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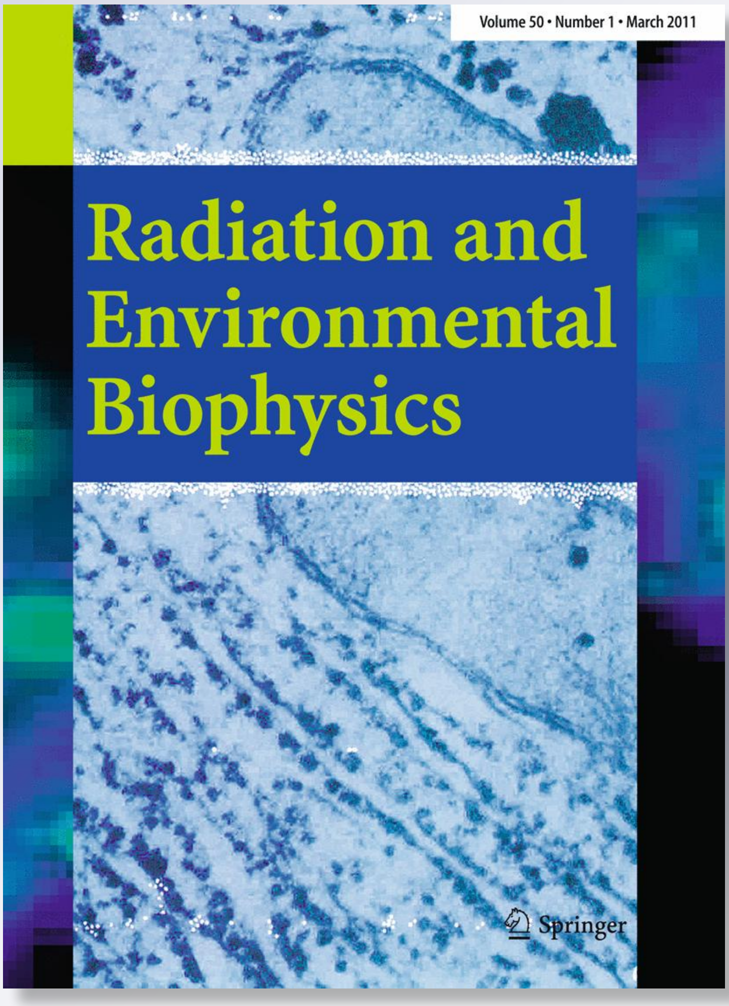

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ORIGINAL PAPER

ReSCA: decision support tool for remediation planning after the Chernobyl accident

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Abstract Radioactive contamination of the environment following the Chernobyl accident still provide a substantial impact on the population of affected territories in Belarus, Russia, and Ukraine. Reduction of population exposure can be achieved by performing remediation activities in these areas. Resulting from the IAEA Technical Co-operation Projects with these countries, the program ReSCA (Remediation Strategies after the Chernobyl Accident) has been developed to provide assistance to decision makers and to facilitate a selection of an optimized remediation strategy in rural settlements. The paper provides in-depth description of the program, its algorithm, and structure.

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Introduction

The accident in the Chernobyl nuclear power plant on 26 April 1986 resulted in a massive radioactive contamination of territories in the Republic of Belarus, in the Russian Federation, and in Ukraine (UNSCEAR 2000; UNDP-UNICEF 2002; IAEA 2006a). In the first years after the accident, the contributions of external and internal exposure pathways to the total radiation dose were rather similar, while in later years, when short-lived radionuclides had decayed and ^{137}Cs became the principal dose-forming radionuclide, internal exposure very often became dominant (Ilyin and Pavlovsky 1988; IAEA 2006a; Fesenko et al. 2007). As a consequence, large-scale agricultural countermeasures (or remedial actions) were and remain to be necessary in the affected countries.

In these areas, agricultural countermeasures have been applied in order to reduce the soil-to-plant transfer of ^{137}Cs (IAEA 2006a). Such measures can be costly, most of them are effective only over a fixed time period, and the degree of reduction in contamination that can be achieved is sometimes limited (Fesenko et al. 2007; Nisbet et al. 2004). Continued application of countermeasures may therefore remain an unavoidable necessity in many areas for a number of years to come and require application of flexible decision support tools, facilitating long-term remediation planning after the Chernobyl accident.

Countermeasures have been most intensively applied in 1987–1992 and encompassed numerous agrotechnical (e.g. removing vegetation, ploughing, and reseeding) and agrochemical (liming and application of mineral fertilizers) countermeasures (Agricultural Radioecology 1992; Alexakhin 1993; Prister et al. 1993; Recommendations 2003). Recommendations on application of these countermeasures have been summarized in the IAEA Technical

Document “Guidelines for agricultural countermeasures following an accidental release of radionuclides”, published by the IAEA (1994).

During the last years, the radiological conditions in the affected countries have changed considerably. For example, an extensive experience on the application of countermeasures in the late period after the Chernobyl accident have been accumulated (Fesenko et al. 2006a, b), and new approaches of planning the rehabilitation of territories and public have emerged (Jacob et al. 2001; IAEA 2006a).

The effectiveness and practicability of countermeasures, their costs and amount of required resources vary considerably depending on local farming practices, time passed after the accident, site-specific environmental conditions, agricultural production management, lifestyle, and dietary habits (Voigt et al. 2000; Howard et al. 2005; Fesenko et al. 2006a, b, 2007).

Common recommendations, which do not account for these multiple factors affecting the efficiency of countermeasures, often result in inadequate decisions when applied at a local scale. These considerations have led to the need for the development of a practical environmental decision support system capable of providing advice on agricultural countermeasure strategies by taking into account local radioecological and social conditions.

Decision support systems (DSS) are popular means to solve complex environmental problems. They are widely applied to various situations where not only numerical aspects of optimal decision are accounted for, but also experience from experts and wide involvement of public or other stakeholders into decision-making process are necessary to be a part of optimal environmental strategy (see e.g. Oughton et al. 2004; Nisbet et al. 2005).

Following the Chernobyl accident, a number of decision support systems have been developed, such as FORCON (Fesenko et al. 1996), AGRO (Recommendations 1998), RESTORE (Van der Perk et al. 1998) and STRATEGY (Gillett et al. 2001; Howard et al. 2005; Cox et al. 2005). At the same time, these codes were developed mainly with the aim to optimize application of countermeasures at large agriculture plants (e.g. collective, state or large private farms) and to produce foodstuffs with low contamination levels; consequently, these codes did not account for the necessity to decrease the dose to the rural population inhabiting affected areas, and for social and economic constraints affecting the effectiveness of long-term remedial actions.

Today, there are still a significant number of rural settlements in Belarus, Russia, and Ukraine where the mean annual effective dose due to the Chernobyl accident exceeds 1 mSv.

Taking into account existing demands in development and realization of appropriate methods and computer codes to support decision making on remediation and on use of radioactively contaminated areas for agriculture production, the IAEA started in 2003 the regional Technical Co-operation Project RER/9/074 “Long-term countermeasure strategies and monitoring of human exposures in rural areas affected by the Chernobyl accident”. The project was run in 2003–2007 in the three most affected countries, i.e., Belarus, Russian Federation, and Ukraine.

Among the principal tasks of the project was the development of a computer code to support decision making by optimization of countermeasures in rural settlements in the late period after the Chernobyl accident. This special-purpose code has been named ReSCA—Remediation Strategies after the Chernobyl Accident. Because, in the late period after the Chernobyl accident, the principal dose-forming radionuclide is ^{137}Cs (UNSCEAR 2000), ReSCA has been developed for optimization of countermeasures that reduce public exposure caused by this radionuclide. The program operates by building a so-called ‘strategy of remediation’, which is thought as a sequence of remedial actions applied in rural settlements in a given geographic or administrative area or in a whole country.

The present paper focuses on details of ReSCA and its algorithm. Other related topics like results of benchmarks in test settlements or end-user reports on experiences gained in the course of software application are not considered here and will be described elsewhere (see e.g. Jacob et al. 2009).

Materials and methods: description of the program

Main terms and basic quantities as used in ReSCA

Principal criteria in the application of remediation practices are the reduction of the annual effective dose to the population and the compatibility with local agricultural and social conditions.

Exposure of rural population

In the late phase after a contamination of the environment with radiocesium, the population exposure is created via two principal pathways: external exposure to radiation emitted from radiocesium deposited on the ground, and internal exposure due to radiocesium uptake via ingestion of foodstuffs. Therefore, the total annual effective dose, D, is expressed as sum of doses due to external, D_E, and internal, D_I, exposure:

$$D = D_E + D_I. \quad (1)$$

Individual doses vary among the population of a settlement. In rural settlements of Belarus, Russia, and Ukraine, the adult population is exposed at higher levels than children and adolescents, mainly due to the larger consumption of locally produced foodstuffs and due to special protective programs of catering in kindergartens and schools. Also, external exposure of adults is higher than that of youngsters.

The program ReSCA addresses the annual effective dose for the "Representative Person" of the population as defined by the ICRP (2006, 2007), where it is the 95%-ile of the individual dose distribution in a settlement. It can be expressed via settlement-average doses, $\overline{D_\mathrm{E}}$ and $\overline{D_\mathrm{I}}$:

$$D_\mathrm{E} = t_\mathrm{E}\,\overline{D_\mathrm{E}}, \quad D_\mathrm{I} = t_\mathrm{I}\overline{D_\mathrm{I}}. \tag{2}$$

For rural settlements in Belarus, Russia, and Ukraine, contemporary values of the factors are $t_\mathrm{E} = 1.8$ and $t_\mathrm{I} = 3.0$ (IAEA 2007).

External exposure is due to radioactivity deposited within the settlement area, and the corresponding annual effective dose for the Representative Person in the settlement can be expressed as follows:

$$D_\mathrm{E} = t_\mathrm{E}\mathrm{DC}_\mathrm{E}q_\mathrm{s}, \tag{3}$$

where DC_E is the mean annual external effective dose per ^{137}Cs ground contamination density (mSv per kBq m^{-2}), and q_s is the average ^{137}Cs ground contamination density in the whole settlement (kBq m^{-2}).

Internal exposure is due to incorporated radionuclides. For the considered conditions (rural settlements in Belarus, Ukraine, and Russia after the Chernobyl accident), the principal pathway for radionuclide intake is ingestion with foodstuffs produced locally. Five principal food products are considered in ReSCA: milk, beef, pork, potato, and mushrooms. Other foodstuffs, e.g. cheese or forest berries, are not considered explicitly, but they are accounted indirectly by increased consumption rates for some of the five principal foodstuffs.

For the rural population of the territories affected by the Chernobyl accident, Jacob et al. (2009) have compared model-calculated internal doses (using model parameters of ReSCA and measured contamination of foodstuffs) with internal doses estimated based on whole body measurements. This comparison has shown that the use of the diet adopted in ReSCA leads to internal doses typical for the Representative Person, i.e., the internal dose values computed using the adopted consumption rates correspond to the 95%-ile of the internal dose distribution. Consequently, the annual effective dose for the Representative Person due to internal exposure in a settlement is evaluated directly via average consumption rates of locally produced principal foodstuffs and of their contamination; therefore, the factor t_I in (2) is not used in (4):

$$D_\mathrm{I} = \mathrm{DC}_\mathrm{I}\sum_f q_f F_f \lambda_f, \tag{4}$$

where DC_I is the mean annual internal dose per ingested ^{137}Cs activity (mSv Bq^{-1}), q_f is the average ^{137}Cs activity concentration in foodstuff f (Bq kg^{-1} or Bq L^{-1}), F_f is the average consumption rate of foodstuff f (L a^{-1} or kg a^{-1}), and λ_f is the fraction of foodstuff f (dimensionless) produced locally. As seen from (4), it is implicitly assumed that foodstuffs produced outside the settlement have a negligible contamination and do not contribute to the internal exposure of the population. This assumption is based on current practices in the three affected countries, where contaminated foodstuffs are not allowed in trade network (shops or markets) because of strict radiological control established in these countries.

Remedial actions

Generally, the effect of a remedial action r is expressed by the so-called reduction factor, i.e., a factor being numerically equal to the ratio of the annual dose for the Representative Person before the remedial action, D, and that after application of the remedial action, D_r:

$$R_r = \frac{\text{Dose before remedial action}}{\text{Dose after remedial action}} = \frac{D}{D_r}. \tag{5}$$

Remedial actions vary widely depending on agriculture practices, types of soil, regulatory norms and others; correspondingly, the number of possible remedial actions and their implementations vary as well (Alexakhin 1993; Prister et al. 1993; Recommendations 2003; Nisbet et al. 2004; Fesenko et al. 2007). Based on previous experience gained after the Chernobyl accident (IAEA 1994, 1997; Jacob et al. 2001; Fesenko et al. 2006a, b), in ReSCA only seven different remedial actions are considered:

1. radical improvement of grassland (RI), which includes removing vegetation, ploughing, liming, fertilization, and reseeding. For areas with wet peat, this action includes also drainage (RI + D);
2. surface improvement of grassland (SI);
3. ferrocyn application to cows (FA);
4. clean feed for pigs before slaughtering (FP);
5. mineral fertilizers for potato fields (MF);
6. information campaign on mushroom consumption (IM); and
7. removal of contaminated soil in the settlement (RS).

In the list of considered remedial actions, RS is the only remedial action that affects external exposure of the population. As it is seen from (3), reduction of external doses can be achieved by either reduction of soil contamination or of the dose coefficient. The dose coefficient is determined by the distribution of ^{137}Cs activity in soil, and certain remediation procedures (e.g. ploughing) can result in a redistribution of the radiation source and subsequent reduction of the dose coefficient (IAEA 2001). In ReSCA, a simplified approach is used to take these procedures into account: all reduction of external dose is formally attributed to the reduction of the soil contamination, and the reduction factor is expressed as the ratio of the average soil contamination in the settlement before and after implementation of the remedial action:

$$R_{\mathrm{s,RS}} = \frac{q_{\mathrm{s}}}{q_{\mathrm{s,RS}}}. \tag{6}$$

From (4), it follows that the reduction factor for internal exposure can be expressed as the ratio of the activity concentration of ^{137}Cs in foodstuff f before and after implementation of the remedial action:

$$R_{f,r} = \frac{q_f}{q_{f,r}}, \tag{7}$$

where r represents one of the following actions: RI, SI, FA, FP, MF, and IM. Concerning the IM remedial action, it should be noted that this action may affect both activity concentration in consumed mushrooms (e.g. due to changes in culinary preparation, exclusion of mushrooms of certain types, and changes of places of collection) and the consumption rate (reduced or stopped consumption). In the present algorithm, all these changes are attributed to an effective change in activity concentrations of consumed food.

A sequence of remedial actions is called here "remediation strategy". There are many possible ways to construct a remediation strategy. Remedial actions may differ in their costs and efficiency in reducing the population dose, and the population's reaction on these actions may vary from enthusiastic to negative. Different strategies will have different costs and result in different dose reductions. Thus, the task to construct and implement the best strategy is very important. Depending on the evaluation criteria, there might be different best strategies. ReSCA has been developed to facilitate construction of a remediation strategy, which ideally should be based on objective environmental and agricultural factors (see detailed description in section "Input data") as well as on subjective stakeholders' attitudes to different remedial actions.

Development of the program ReSCA

The program ReSCA was inspired by earlier work of Jacob et al. (2001). In the course of the ReSCA development, the algorithm has been further developed and improved. The main goal of ReSCA is to build a cost-effective and publicly acceptable remediation strategy, i.e. a sequence of countermeasures in settlements, for which a user has to provide all necessary input data.

ReSCA is written in the Python programming language[1] and distributed to end-users as a stand-alone Microsoft Windows application. The program does not include Windows-dependent solutions and can be easily ported to virtually any computer platform as most of these platforms support the Python language. The program is developed to provide assistance for decision-making authorities in Belarus, Russia, and Ukraine, and its interface language can be either English or Russian. The main interface is organized as a tabbed notebook. Switching different tabs allows the user to choose between different actions, process input data, view and/or edit the model and output parameters, as well as select various execution options and work with output reports. An example screenshot can be seen in Fig. 1.

Input data

Several grasslands can be specified as pasture areas in a given settlement. Therefore, the input data are differentiated between a settlement level and a level of areas. All input data on ^{137}Cs contamination have to be arithmetic means, because costs-per-averted-dose calculations in the algorithm are based on estimates of average dose.

A screenshot of ReSCA including an active editor window is shown in Fig. 1. More detailed information on the input data can be found in Table 1.

The program supports reading the input data from user-supplied files in CSV-format.[2] The input data can be also created using a built-in data editor in the program itself. The built-in data editor allows changing values in the input data fields, adding or removing new settlements or areas, and saving the data for a later use.

The data editor has a built-in functionality to check for plausibility of values typed by the user in the editing fields. To advice the user about plausible values of the input variables, tooltip windows are used to display recommended ranges of values for each entry field in the editor. While some settlement- and area-specific parameters are always required by the optimization algorithm of the program, others (like settlement names and ID codes) are not. In the data editor, input fields for obligatory parameters are indicated by bold font.

In the following, the index i is used to denote settlement-specific values of parameters and variables, while the index j is left for area-specific values.

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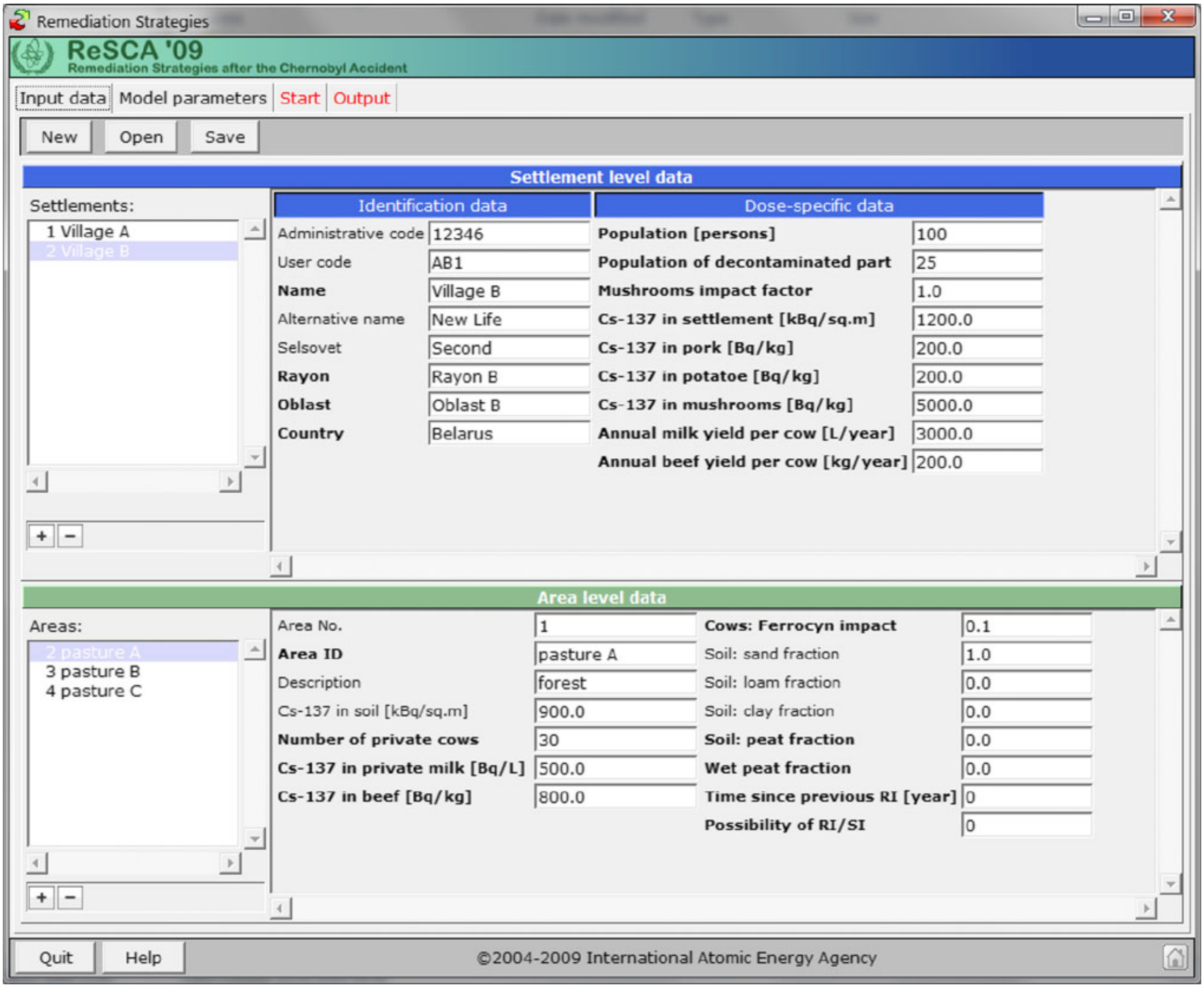
[1] www.python.org.

[2] Input files can be created in a spreadsheet program or a database management system and exported to CSV-format.



Settlements:
1 Village A
2 Village B

Administrative code	12346
User code	AB1
Name	Village B
Alternative name	New Life
Selsovet	Second
Rayon	Rayon B
Oblast	Oblast B
Country	Belarus

Population [persons]	100
Population of decontaminated part	25
Mushrooms impact factor	1.0
Cs-137 in settlement [kBq/sq.m]	1200.0
Cs-137 in pork [Bq/kg]	200.0
Cs-137 in potatoe [Bq/kg]	200.0
Cs-137 in mushrooms [Bq/kg]	5000.0
Annual milk yield per cow [L/year]	3000.0
Annual beef yield per cow [kg/year]	200.0

Areas:
2 pasture A
3 pasture B
4 pasture C

Area No.	1
Area ID	pasture A
Description	forest
Cs-137 in soil [kBq/sq.m]	900.0
Number of private cows	30
Cs-137 in private milk [Bq/L]	500.0
Cs-137 in beef [Bq/kg]	800.0

Cows: Ferrocyn impact	0.1
Soil: sand fraction	1.0
Soil: loam fraction	0.0
Soil: clay fraction	0.0
Soil: peat fraction	0.0
Wet peat fraction	0.0
Time since previous RI [year]	0
Possibility of RI/SI	0

Fig. 1 Screenshot of the program ReSCA showing the input data editor

Settlement-specific data

Settlement-specific data encompass all information that is common for the settlement as a whole. These data are subdivided in two groups, i.e., settlement identification data (Group A data, see Table 1) and dose-specific data (Group B data, see Table 1). The dose-specific part of the data includes the total number of inhabitants N_i in the ith settlement, and the number of inhabitants N_i^d living in a part of the ith settlement, which is already decontaminated.

The factor μ_i accounts for peculiarities of local consumption of mushrooms. This factor (so-called *mushroom impact factor*, *MIF*) is defined as the ratio of the average consumption of locally collected mushrooms in settlement i and the average consumption of mushrooms in the country. For example, if $\mu_i = 0.5$ and the country-specific mushroom consumption rate is equal to 4 kg a^{-1}, the average of the consumption rate of locally collected mushrooms in the settlement is assumed to be 2 kg a^{-1}.

The average ^{137}Cs contamination of soil in settlement i is $q_{i,s}$ (kBq m^{-2}), where the index s stands for “soil”. This quantity is used in calculation of external exposure of the settlement population. The average ^{137}Cs activity per unit fresh mass is $q_{i,f}$ (Bq kg^{-1}), where $f = 3$ is for locally produced pork, $f = 4$ for potatoes, and $f = 5$ for locally collected mushrooms. Finally, the annual yield of milk is $Y_{i,1}$ (L a^{-1}) per cow, while that of beef is $Y_{i,2}$ (kg a^{-1}) per cow.

Area-specific data

The grassland used by the inhabitants of a settlement for feeding private cows is subdivided into areas. In general, there can be several areas in a settlement. The corresponding area-specific input data (Group C data, see

Table 1 Description of the ReSCA input

Code	Parameter	Dimension	Allowed range or values
Settlement level			
Part A (identification data)			
A1	Administrative code (optional)		
A1	User code (optional)		
A3	Settlement name		
A4	Alternative settlement name (optional)		
A5	Selsovet (optional)		
A6	Rayon		
A7	Oblast		
A8	Country		Belarus, Russia, Ukraine
Part B (dose-specific data)			
B1	Population		10 … 10^4
B2	Population in decontaminated part		0 … 10^4
B3	Mushrooms impact factor μ_i		0 … 5
B4	Contamination of soil in settlement by ^{137}Cs	kBq m^{-2}	10 … 1,500
B5	Contamination of pork by ^{137}Cs	Bq kg^{-1}	1 … 1,000
B6	Contamination of potato by ^{137}Cs	Bq kg^{-1}	1 … 500
B7	Contamination of mushrooms by ^{137}Cs	Bq kg^{-1}	1 … 5×10^4
B8	Annual milk yield per cow	L a^{-1}	500 … 6,000
B9	Annual beef yield per cow	kg a^{-1}	20 … 200
Area level			
C1	Area No. (optional)		
C2	Area ID		
C3	Area description (optional)		
C4	Contamination of soil in area by ^{137}Cs (optional)	kBq m^{-2}	10 … 1,500
C5	Number of grazing private cows		5 … 10^4
C6	Contamination of milk by ^{137}Cs	Bq L^{-1}	1 … 1,000
C7	Contamination of beef by ^{137}Cs	Bq kg^{-1}	2 … 2,000
C8	Ferrocyn impact factor		0 … 1
C9	Soil: sand fraction (optional)		0 … 1
C10	Soil: loam fraction (optional)		0 … 1
C11	Soil: clay fraction (optional)		0 … 1
C12	Soil: peat fraction		0 … 1
C13	Peat: fraction of wet peat		0 … 1
C14	Previous application of RI		0 (no previous RI) or The number of years since last RI
C15	Possibility of RI and SI		0,1,2,3

Table 1) include (a) the average contamination of soil by ^{137}Cs $q_{j,s}$ (kBq m^{-2}) in area j; (b) the number of private cows N_j^c, which are pastured in area j (if the number of cows grazing in the area is unknown, then it is recommended to distribute the total number of cows in the settlement proportionally to the area of the grasslands); (c) the average ^{137}Cs concentration in milk $q_{j,1}$ (Bq L^{-1}) and beef $q_{j,2}$ (Bq kg^{-1}); (d) the fraction φ_j of private cows for which the measured activity concentrations in milk and in beef were reduced due to application of ferrocyn to cows at the time of measurements; (e) the sand, loam, clay, and peat fractions of soil (adding up to 1) and the wet peat fraction of peat; of these, only the peat and wet peat fractions v_j and v_j^{w} are mandatory parameters, as they are needed for the calculation of area-specific values of reduction factors for radical improvement; other parameters describing soil structure are optional and can be used together with the value of the area contamination by ^{137}Cs for derivation of surrogate values of ^{137}Cs concentrations in foodstuffs, if no measured data exist (see sub-section "Use of generic

transfer factors"); (f) the parameter ρ_j providing information on any previous application of RI in the given area; this parameter is set to zero if RI was never applied, or to the number of years since the last RI application; if any previously applied RI is still effective, then the new application of RI or SI would be inefficient and, consequently, the remedial action for the given area is excluded from the list of possible actions for the remediation strategy being built; g) the parameter "Possibility of RI/SI" allowing the user to specify explicitly whether RI or SI is ever possible in the given area (e.g. impossible in forest pastures) or whether either RI or SI or both should be considered for the area.

If RI had been recently (less than 4 years ago) applied to a part of the considered area, then any new RI or SI remedial actions will be blocked; however, they can still be applied in the other, non-improved part. In this case, the user should split the area into two parts and consider them separately: one part where remediation is possible and the other part where radical improvement should not be done and its consideration in the program is blocked.

Use of generic transfer factors

Sometimes it may happen that information on food contamination is incomplete and, therefore, not all mandatory input fields can be filled. In such situations, a user can estimate foodstuff contamination by using data on the ^{137}Cs activity in soil of various agricultural fields and pastures in the settlement, and of generic aggregated transfer factors (TF) specific to the soil structure in agricultural lands pertinent to the given foodstuff.

Values of generic TF values are listed in Table 2 for five major soil groups: sand, loam, clay, and peat (including wet peat). These values are not used in ReSCA, but given here as a reference for the user on how to calculate surrogate ^{137}Cs concentrations in foodstuffs if there are no measured data to input.

Table 2 Soil-specific ^{137}Cs aggregated transfer factors (Bq kg^{-1} fresh mass per kBq m^{-2}) from soil to agricultural products and mushrooms (IAEA 2006b)

Product f	$TF_{f,t}$ for soil type t				
	Sand	Loam	Clay	Peat	Wet peat
Milk	0.2	0.07	0.03	0.6	5
Beef	0.6	0.25	0.1	2	10
Pork	0.3	0.1	0.05	1	4
Potato	0.06	0.04	0.015	0.2	1
Mushrooms	13	4	1	20	–

Evaluation of the ^{137}Cs contamination q_f, of foodstuff f based on a value of the ^{137}Cs, contamination of an agriculture field relevant for the specific foodstuff, q_l, can be done according to (8):

$$q_f = q_l \sum_t \mathrm{TF}_{f,t} B_t \tag{8}$$

where index t stands for the various soil types shown in Table 2, and B_t is the fraction of soil type t in the given agriculture field.

Model parameters

Besides the user-provided input data describing the settlements and the areas, ReSCA uses a number of so-called 'model parameters', which are parameters immanent to underlying model assumptions. The ReSCA user can review and modify (if necessary) the model parameters, thus influencing the process of the optimization. The program starts from assigning all model parameters by standard (generic) values.

The model parameters are divided into six groups: (a) consumption habits: country-dependent consumption rates $\tilde{F}_{c,f}$ (L a^{-1} or kg a^{-1}) of food f and corresponding fractions of locally produced food in the diet $\tilde{\lambda}_{c,f}$ (rel. units); (b) reduction factors for remedial actions R_r (rel. units) and the number of people ΔN_{RS} for implementing a single RS remedial action (see "Appendix"); (c) country-dependent effective times of remedial actions $\tilde{T}_{c,r}$ (a); (d) country-dependent costs of remedial actions $\tilde{C}_{c,r}$ (€),[3] including a limiting value of maximum acceptable cost per averted dose CD^{max}(k€ person-Sv^{-1}); (e) degree of acceptability of remedial actions DA$_r$ (rel. units); and (f) dose coefficients DC$_I$ and DC$_E$ for internal and internal exposures to ^{137}Cs, and factors t_E and t_I corresponding to the ratio of the dose (external or internal) for the Representative Person and of the average dose in the settlement, and the reference annual dose limit RAD (mSv a^{-1}).

These standard values are based on extended analyses of radionuclide transfer from soil to plants (IAEA 2006b) and on expert estimates. Because these values are pertinent to average conditions for the whole country, it may well be that the standard model parameters are not appropriate for a specific settlement. In such case, the user can alter the model parameters and create his/her own sets of model parameters for later use. The model parameters are described and explained in the following sub-sections.

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[3] There are different national currencies in all three countries; therefore, Euro has been selected as a unit to express countermeasure costs in different countries.

Consumption habits

Parameters pertinent to the diet are treated as country dependent. The diet is defined for five principal foodstuffs (milk, beef, pork, potato, and mushrooms) as an annual consumption rate $\tilde{F}_{c,f}$ (kg a^{-1} or L a^{-1}) and a fraction $\tilde{\lambda}_{c,f}$ (dimensionless) of consumed food that is produced locally. Default values (Table 3) are the average consumption rates in the three countries (IAEA 2006b). It is assumed by default that all consumed foodstuffs are produced locally, i.e., the generic values of the fraction of local food equals to 1.0 for all foodstuffs and all countries.

Reduction factors of remedial actions

Procedures, equipment, and materials necessary to perform remedial actions are described in (IAEA 2006b). In ReSCA, values of the reduction factors are taken to be country independent and based mostly on (Jacob et al. 2001; IAEA 2006b). Standard values of the reduction factors for the remedial actions are summarized in Table 4.

In the current version of the program, the algorithm of soil removal action previously used in (IAEA 1994; Jacob et al. 2001) has been expanded and generalized. Namely, as a new functionality it is introduced that RS can be applied stepwise starting from the most contaminated part of the settlement. The reduction factors for these actions have been derived (see "Appendix" for details) assuming that partial decontamination is always performed in the highest contaminated part of the settlement.

Experience has shown that, if radical improvement is considered to be applied in an area, change to another meadow may turn out to be a more effective action to reduce radiocesium contamination of milk and beef. In order to explore this option, the user can replace in the input data the corresponding area by the new area. If no more information is available, the contamination of milk and beef in the new area may be assessed from the contamination in the old area and the ratio of the soil contaminations of the two areas.

Table 3 Country-dependent consumption rates of various foodstuffs in rural settlements (BRIR 1990; Jacob et al. 2001)

Foodstuff *f*	Consumption rates $\tilde{F}_{c,f}$ (kg a^{-1} or L a^{-1})		
	Belarus	Russia	Ukraine
Private milk	260	200	234
Beef	6	8	3
Pork	50	20	48
Potato	240	190	131
Mushrooms	4	5	3.5

Three of the seven remedial actions (RI, SI, and FA) are applicable at area level to grasslands or to cows (see Table 5). In these cases, costs and averted doses are proportional to the number of private cows, for which the area is used. For the other four remedial actions, an application at settlement level is assumed. In these cases, costs and averted doses are proportional to the number of inhabitants (see below for details on calculation of the averted doses).

Time periods of the remediation actions

Remedial actions can be effective during certain time periods (see Table 5). Currently, RI and SI are assumed in all countries to be effective for 4 years, and IM for 2 years. Doses averted by these remedial actions are therefore calculated for a period of four or 2 years, respectively. FA is assumed to be applied for 1 year; FP is applied to all pigs, which are slaughtered during 1 year. An application of MF is also assumed to be effective for 1 year.

Once implemented, the decontamination of settlement (RS) is effective permanently. Taking into account radioecological half-lives, it is assumed that the whole external averted dose after RS is the 27-fold of the external dose averted in the first year after the removal of soil. This is derived from the assumption that the external exposure decreases without soil removal due to radioactive decay and migration with an effective half-life of 18.8 years (Jacob et al. 2001).

Degrees of acceptability and costs of remedial actions

Default values for degrees of acceptability DA_r and costs $\tilde{C}_{c,r}$ of the remedial actions can be found in Table 6. For RI, SI, and FA, costs are given per cow, while for FP, MF, IM, and RS costs are given per inhabitant. Based on current agriculture practices for areas with wet peat, an open drainage is assumed in Ukraine, and a closed drainage below ground surface is assumed in Belarus; thus, their costs are essentially different.

Acceptance of various remedial actions by the population varies considerably (see e.g. Fesenko et al. 2007) from enthusiastic in case of radical improvement of pastures to sceptic or negative in case of decontamination of settlement's territory. In ReSCA, the degree of acceptability is an expert estimate and varies from 0 to 1. The value 1 is applied for remedial actions that are most accepted by the members of public. Default values of the degree of acceptability are specific to conditions in Belarus, Russia, and Ukraine. As other model parameters, the values of the degree of acceptability can be modified by the user if the program is applied to other populations or in different social and economical conditions.

Table 4 Reduction factors of the various remedial actions

Pathway	Reduction factors of the remedial actions:						
	RI	SI	FA	FP	MF	IM	RS
Milk	$4 \times S$[a]	1.5	3	–	–	–	–
Beef	$4 \times S$[a]	1.5	2	–	–	–	–
Pork	–	–	–	3	–	–	–
Potato	–	–	–	–	2	–	–
Mushrooms	–	–	–	–	–	1.5	–
External exposure (Jacob 2003)	–	–	–	–	–	–	1.5

[a] Factor *S* modifies the reduction factor of radical improvement depending on the amount of peat or wet peat, and on whether any previously applied RI is still effective. The values of *S* are (Jacob et al. 2001): 2, wet peat soil, no previously applied RI; 1, peat soil, no previously applied RI; 0.75, non-peat soil, no previously applied RI; 0.5, peat soil, previously applied RI is still effective; 0.425, non-peat soil, previously applied RI is still effective

Table 5 Levels on which remedial actions are applied, and the time periods for which costs and dose reduction factors are calculated

Remedial action			Level	Time (year)
RI	Radical improvement of	Wet peat[a]	Area	4
		Other soil groups	Area	4
SI	Surface improvement		Area	4
FA	Ferrocyn application		Area	1
FP	Clean feed for pigs		Settlement	1
MF	Mineral fertilizers for potatoes		Settlement	1
IM	Information campaign on mushrooms		Settlement	2
RS	Removal of soil—decontamination		Settlement	27[b]

[a] Includes drainage

[b] Assuming an exponential decrease of the external exposures with a half-life of 18.8 years, the total averted dose corresponds to the 27-fold of the dose averted in the year following the decontamination

Table 6 Default values for degrees of acceptability and costs of the remedial actions

Remedial action	Degree of acceptability	Cost per …	Cost (€)[b]		
			Belarus	Russia	Ukraine
RI	1	Cow	350	390	450
D[a]	–	Cow	2,000	–	1,000
SI	1	Cow	300	340	400
FA	0.75	Cow	30	60	40
FP	0.6	Inhabitant	6	7	20
MF	1	Inhabitant	0.8	2.5	1
IM	0.5	Inhabitant	3	3	3
RS	0.1	Inhabitant	325	325	325

[a] Drainage (used only in connection with RI on wet peat soil)

[b] Costs relate to the year 2004

The default value of maximum accepted cost per averted dose CD^{max} is equal to 100 k€ × person-Sv^{-1}, and the range of allowed values spans from 5 to 10^4 k€ × person-Sv^{-1}. This parameter is used to exclude automatically those remedial actions that are too inefficient.

Dose coefficients and reference annual doses

Based on (ICRP 1993), the average effective dose of internal exposure per unit intake of ^{137}Cs is assumed as $DC_I = 1.2 \times 10^{-5}$ mSv Bq^{-1} (IAEA 2007). However, it was found (Jacob et al. 2009) that the use of adopted average consumption rates results in internal dose values higher than the average internal dose values derived from whole body measurements. Jacob et al. (2009) have shown that internal doses calculated using the adopted diet structure result in average annual effective doses typical for the Representative Person of the population.

For external exposure, the following value of the average effective annual dose per unit contamination is adopted: $\mathrm{DC_E} = 1.2 \times 10^{-3}$ mSv per kBq m^{-2} of ^{137}Cs (Golikov et al. 2002, IAEA 2007).

As recommended by ICRP (2007), for the purposes of radiation protection the annual effective doses for the Representative Person have to be used; however, another important quantity to be considered in remediation practices is the averted collective dose. Averted collective doses are calculated based on the average doses in the settlements and the number of affected persons. Correspondingly, to get the average doses in the settlement the annual effective doses for the Representative Person due to external and internal exposure have to be reduced by appropriate factors t_E and t_I[see (2)], correspondingly.

ReSCA considers remedial actions in those settlements where the computed average annual effective dose to the Representative Person exceeds a certain reference value. This value is another model parameter and it is called hereafter “reference annual dose”, *RAD*. The *RAD* value can be varied in a range from 0.2 to 5 mSv; the default value is set up to 1 mSv.

Initialization

Given user-provided input data for a specific country *c*, the consumption rates and local food-consumption fractions are initialized by using appropriate country-dependent values (9):

$$F_f = \tilde{F}_{\mathrm{c},f}, \lambda_f = \tilde{\lambda}_{\mathrm{c},f}. \tag{9}$$

Based on user-input data, the previously decontaminated fraction of the settlement is calculated for each settlement (10):

$$\theta_i = \frac{N_i^d}{N_i}. \tag{10}$$

The next initialization step is to assign weights to all pasture areas according to their contributions to population exposure. Area contributions are computed by taking into account the number of cows grazed in the given area (11):

$$W_j = \frac{N_j^\mathrm{c}}{\sum_{j \in i} N_j^\mathrm{c}}. \tag{11}$$

Settlement- and area-level costs for country *c* are assigned to all settlements and areas and create a cost matrix (12):

$$C_{i,j,r} = \begin{cases} \tilde{C}_{\mathrm{c},r} + \tilde{C}_\mathrm{c}^\mathrm{w} v_j v_j^\mathrm{w}, & r = 1 \\ \tilde{C}_{\mathrm{c},r}, & r > 1 \end{cases} \tag{12}$$

where $C_\mathrm{c}^\mathrm{w}$is the cost of wet peat drainage in country *c*.

As seen from (11), costs per cow for radical improvement ($r = 1$) are calculated according to the fraction of wet peat, because for fields with wet peat it is assumed that a drainage system built as a part of RI increases the remediation cost.

Country-dependent times for remedial actions are initialized by a simple assignment (13):

$$T_r = \tilde{T}_{\mathrm{c},r}. \tag{13}$$

In the next stage of the initialization, data on activity in foodstuffs are processed and assigned to respective matrices. A matrix of initial activities, $Q_{i,j,f}$, is created from the user-input data accounting for peculiarities of various foodstuffs. The matrix includes activities of all foodstuffs as well as the soil contamination in the settlement. For this, the value of soil activity is stored in the matrix under the fictitious index value $f = 6$.

For exposure pathways relevant to a settlement level ($j = 0$), i.e. pork ($f = 3$), potatoes ($f = 4$), mushrooms ($f = 5$) for internal and soil contamination by ^{137}Cs for external exposures ($f = 6$), the initialization proceeds as follows (14):

$$Q_{i,0,f} = \begin{cases} q_{i,f}, & f = 3, 4 \quad \text{(pork and potato)} \\ q_{i,f}\frac{\mu_i}{\mathrm{RCM}}, & f = 5 \quad \text{(mushrooms)} \\ q_{i,s}, & f = 6 \quad \text{(soil in settlement)} \end{cases} \tag{14}$$

where the activity in mushrooms ($f = 5$) is adjusted to local settlement-specific consumption rates with factor μ_i and additionally reduced by the factor *RCM* (default value is 2), in order to account for any activity reduction due to typical culinary preparations.

Data for ^{137}Cs activity in milk ($f = 1$) and beef ($f = 2$) are area-dependent. Therefore, they are processed separately and, if ferrocyn application had taken place at the time of the milk and beef measurements, then initial estimates of the ^{137}Cs activity in milk and beef before ferrocyn application ($r = 3$) are restored (Jacob et al. 2001) using (15):

$$Q_{i,j,f} = \frac{q_{j,f}}{1 - \phi_j + \frac{\phi_j}{R_{3,f}}}, \quad \text{for} f = 1, 2. \tag{15}$$

Matrices of activities reduced due to application of remedial actions are created and initialized by assigning their values equal to initial activities:

$$Q^*_{i,j,f} = Q_{i,j,f}. \tag{16}$$

These matrices track changes in activities due to application of the remedial actions in the process of construction of the current remediation strategy.

Reduction factors are initiated simply by assigning country-independent values to all settlements and areas, taking into account local area conditions for RI ($r = 1$):

$$R_{i,j,r} = \begin{cases} R_r \times S_j, & r = 1, \\ R_r, & r > 1, \end{cases} \qquad (17)$$

where the area-specific multiplier S_j is calculated by taking into account the fraction of peat or wet peat soils in the area and previously applied RI (if any). The values of the modifying factor are shown in Table 4.

Initial values of the average annual effective doses for the Representative Person in the settlement due to ingestion of contaminated food and due to external exposure, before any remediation, are computed according to (18):

$$D_i = \mathrm{DC}_\mathrm{I} \sum_f F_f \lambda_f \sum_j W_j Q^*_{i,j,f} + t_\mathrm{E} \mathrm{DC}_\mathrm{E} Q^*_{i,0,6}. \qquad (18)$$

The remediation matrix includes information necessary to build the strategy. A zero value in the remediation matrix means that the specific remedial action is not yet used and can be considered in construction of the strategy. If the specific action is selected, then the value of the matrix element is set to I_a, i.e. to the number of the action in the current strategy. The remediation matrix RM is initialized by zero values:

$$\mathrm{RM}_{i,j,r} = 0. \qquad (19)$$

After initialization, additional checks are made to identify actions that are impossible. If a certain action in a specific settlement/area is impossible, then the corresponding remediation matrix element is assigned to a negative value (e.g. −1).

At the final stage of the initialization process, an output report is created and the standard report header, including initial doses in the considered settlements, is displayed in the output window.

Optimized remediation strategy

Optimization criterion

The remediation strategy is built as a sequence of remedial actions in different settlements and areas. An optimization is achieved by arranging all possible remedial actions according to a certain optimization criterion and implementing the action with the highest value of the criterion.

In ReSCA, the process of optimization is governed by two criteria. The first criterion is the cost efficiency of a remedial action, while the second criterion accounts for the public attitude toward this action. The user may wish to change the balance between these criteria, thus giving more preference either to cost efficiency or to population friendliness. The cost efficiency is characterized by the value of cost per averted dose $\mathrm{CD}_{i,j,r}$, while the public attitude is expressed via the degree of acceptability DA_r of the remedial action. To perform an optimization accounting for both criteria, a combined criterion α is introduced as follows:

$$\alpha_{i,j,r} = \beta \frac{\min(\mathrm{CD})}{\mathrm{CD}_{i,j,r}} + (1 - \beta)\mathrm{DA}_r. \qquad (20)$$

where β represents the relative importance of cost efficiency and can be varied by the user in the range from 0.01 to 1.0. For the maximal value, $\beta = 1.0$, the remedial actions are ranked according to the costs per averted dose, only. By decreasing the value of β, the importance of the degree of acceptability is increasing. For given input and model parameters, various strategies can be calculated by changing the amount of available funds and/or the parameter β.

The next remedial action r in the strategy being built will be selected in settlement i and area j, which corresponds to the maximal value of the criterion $\alpha_{i,j,r}$. A flowchart of the optimization process is given in Fig. 2. The remediation strategy starts if there are both funds and settlements where the mean annual effective dose to the Representative Person exceeds the reference annual dose value (*RAD*).

Starting new strategy

A new strategy is started by resetting initial (Q) and reduced (Q^*) concentration matrices and the remediation (RM) matrix. The number N_RA of vacant remedial actions, i.e. the number of zeroes in matrix RM, is counted. The total cost (C_Σ), the total averted dose (AD_Σ), and the remedial action counter (I_a) are zeroed. The value of β is set to the user-specified value.

The process of building the remediation strategy continues as long as the total cost does not exceed the available funds (M) and as long as there are still unused remedial actions to be implemented:

$$C_\Sigma < M \quad \text{and} \quad N_\mathrm{RA} > 0. \qquad (21)$$

Starting new remedial action

A new remedial action to be inserted in the strategy must be an action showing the maximal value of the optimization criterion (20). First, the matrices of costs per averted dose are recomputed (see details below). Then, the optimization criterion values $\alpha_{i,j,k}$ [see (20)] are computed and the combination of the indices "settlement-area-action" (i,j,r) corresponding to a maximum is searched for. After such combination is found, the remedial action counter, I_{ra}, is incremented and the remediation matrix is updated:

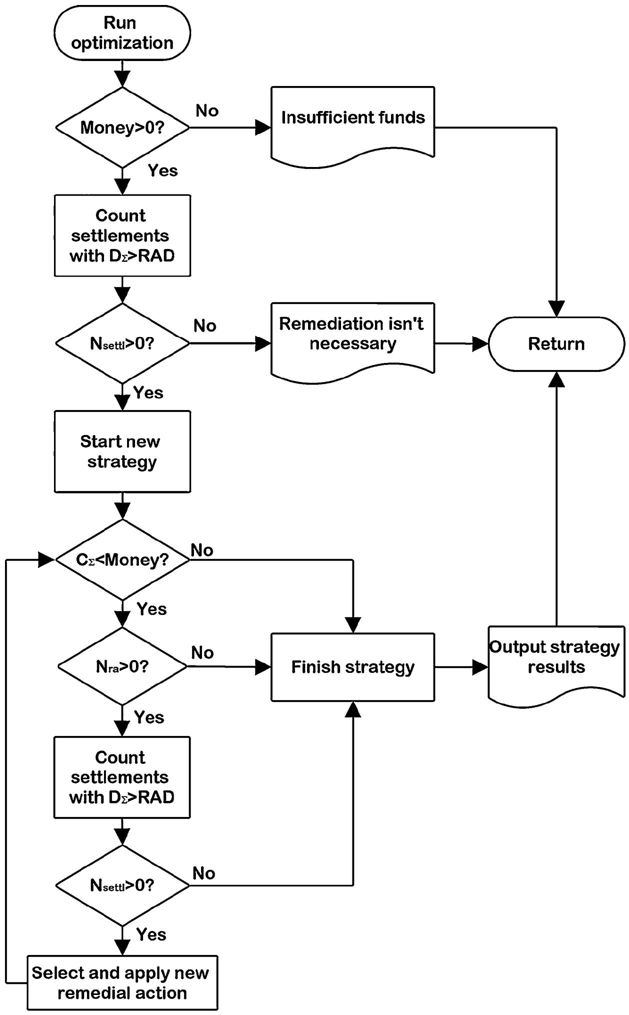

Fig. 2 Flowchart of optimization of a remediation strategy

$$RM_{i,j,r} = I_{\mathrm{a}}. \tag{22}$$

For the selected remedial action r, the elements of the reduced concentration matrix are recalculated to account for the effect of the action:

$$Q^*_{i,j,f} = \frac{Q_{i,j,f}}{R_{i,j,r}} \tag{23}$$

and so are the doses [see (18)].

The total cost, C_Σ, and the total averted dose, AD_Σ, for the whole strategy are updated with values computed for the selected action. The output report is updated with results from the new action, and the number of unused actions, N_{RA}, is counted again.

Costs per averted dose are re-computed at the beginning of every new remedial action. Remedial actions with cost-per-averted dose exceeding the allowed maximum value $\mathrm{CD}^{\max}$ are blocked in the remediation matrix. On the settlement-level, the costs of the remedial actions are computed based on the settlement population, while on the area-level actions they are calculated based on the number of cows:

$$CT_{i,j,r} = C_{i,j,r} \times \begin{cases} \Delta N_i^{RS}, & r = \mathrm{RS} \\ N_i, & r = \mathrm{FP,\ MF,\ IM} \\ N_i^c, & r = \mathrm{RI,\ SI,\ FA} \end{cases} \tag{24}$$

The effect of a remedial action, i.e. the averted collective dose, is calculated depending on the remedial action to be taken and on actions that already took place in the settlement/area. Calculation of the averted dose accounts for effects of preceding remedial actions and their validity periods. For example, if the FA action has already been taken and then the RI/SI action is selected for the same area, then the total dose averted by RI/SI accounts for milk and beef activity reduction due to ferrocyn application in the first year, while applying non-reduced activity values in the subsequent years when FA has no effect.

The only remedial action to reduce external exposure is the removal of soil in the settlement. This remedial action is considered in the program stepwise, starting from the initial value $\theta_{i,1}$ that describes the fraction of a settlement area already decontaminated. Decontamination in the settlement results in expanding the decontaminated part to occupy the fraction $\theta_{i,2}$ of the settlement, and the dose averted due to decontamination is evaluated as follows:

$$\mathrm{AD}_{i,\mathrm{RS}}\left(\theta_{i,1} \to \theta_{i,2}\right) = \mathrm{DC_E} N_i \left(1 - \frac{R_{\mathrm{RS}}\left(\theta_{i,1}\right)}{R_{\mathrm{RS}}\left(\theta_{i,2}\right)}\right) Q^*_{i,0,6} T_{\mathrm{RS}}. \tag{25}$$

Details of the calculation of reduction factors $R_{\mathrm{RS}}(\theta_i)$ for an arbitrary value of the parameter θ_i can be found in the Appendix, where a derivation of the new algorithm is given.

Averted collective internal doses are estimated differently for the settlement- and area-level remedial actions. The averted internal dose for the settlement-level remedial actions (FP, MF, and IM) is computed using food consumption rates as follows:

$$\mathrm{AD}_{i,0,r} = \mathrm{DC}_I N_i \sum_f \left(1 - \frac{1}{R_{i,0,r}}\right) Q^*_{i,0,f} \frac{F_f}{t_I} \lambda_f T_r. \tag{26}$$

The area-level remedial actions (RI, SI, and FA) reduce the ^{137}Cs activity in milk and beef only; therefore, the averted internal dose is computed using total milk and beef yields:

$$\mathrm{AD}_{i,j,r} = \mathrm{DC}_I N_j^c \sum_f \left(1 - \frac{1}{R_{j,r}}\right) Q^*_{i,j,f} W_j Y_f T_r. \tag{27}$$

Finally, the matrix CD is filled up with the values of cost per averted dose for all possible combinations of indices (i, j, and k):

$$\mathrm{CD}_{i,j,r} = \frac{\mathrm{CT}_{i,j,r}}{\mathrm{AD}_{i,j,r}}. \qquad (28)$$

Termination of the strategy

Building of the strategy is finished when either of the three following termination conditions is met: (a) there are no more funds left ($M \leq 0$), (b) doses in all settlements are below the reference annual dose *RAD*, or (c) there are no more remedial actions to undertake ($N_{\mathrm{RA}} = 0$).

When the termination is triggered, the program finalizes the output report, processes all additional output requests set-up by the user, and deletes temporary data. At this stage, the user can inspect the window with the output report, produce and save plots of the remediation strategy results for later use, and save the output report as a formatted text file or as a document in RTF format.

The final remediation costs can become higher than the funds initially available for the remediation. This may happen because the algorithm treats all remedial actions as a whole and does not sub-divide them to fit the available rest of the funds. That is, if there is still 1€ available, then the program will proceed with remediation further and will select a new remedial action based on the optimization criterion (20). Then, after completion of this action, the total remediation cost exceeds the allowed funds and the remediation process is finished.

Results: examples of program output

The results of a program run are prepared as a report in plain text format and displayed in the output window. The content of the output window can be saved as a plain text or as a document in RTF format (commonly supported by existing word processing software). Main results of the remediation can be presented as plots and can be saved as images in bitmap (PNG) or vector (EPS) formats. The content of the output window is dynamic and flexible with different levels of details, depending on the options selected by a user. If requested by the user, extended summaries of input data and model parameters might be added to the output report. These parts are optional and, by default, not shown in the output report.

The output report shows also a list of settlements and their corresponding areas. For every settlement, annual effective dose values for the Representative Person as computed from the input data are included. Shown in the table are external, internal, and total annual effective doses.

The strategy recommended by the program consists of a sequence of single remedial actions arranged according to the applied optimization criterion. A table with the description of the strategy can be prepared and shown in two ways: standard and expanded. In its standard form, the strategy table starts from explanations of all acronyms used in the table, and for every remedial action in the strategy it displays information on (a) IDs and descriptions of the settlements and the areas, (b) type and cost of the selected remedial action, (c) annual effective doses for the Representative Person in the settlement before and after implementation of the remedial action, and (d) the dose averted by the selected remedial action and a value of the cost per averted dose.

The strategy table ends with the values of total averted dose, total cost, and average cost per averted dose for the complete strategy. This short form of the table is a default and always included in the output report.

If requested by the user, the standard strategy table is enlarged by supplementary information on relevant food or soil activities before and after the remedial action. The activity concentrations to be shown are selected based on the level of the remedial action: settlement- or area-specific action. This expanded form of the strategy table is optional. It can be recommended for in-depth investigation into how specific certain remedial actions may influence contamination of food and environment. In routine operation, the expanded table is less convenient due to its large size, and this functionality is therefore deactivated in the report saved in RTF format. However, the expanded strategy table can be saved in plain text format.

Main results of the strategy can be presented graphically in a popup window that displays two different plots (see Fig. 3). The first (top) plot shows a number of settlements where the average dose exceeds the *RAD* limit as a function of money invested into the remediation (i.e. the total cost of the remediation). The second (bottom) plot shows the total dose averted due to remediation vs. cost of the remediation. These plots can be saved in either bitmap-based (PNG) or vector-based (EPS) formats.

For all settlements found in the input data file, summary tables can be generated and placed in the output report if this functionality was activated by the user. The settlement summary table contains the number and name of the settlement, rayon and oblast to which it belongs, list of remedial actions (if any), their costs and averted doses as well as average annual doses. Similarly to the main table of the strategy results, the data included in the settlement summary tables can be plotted and shown separately (see example in Fig. 4). These plots show the total dose in the settlement (upper plot) and the cost of the remediation (bottom plot), both as a function of sequential application of the remedial actions.

Additionally, the output report includes summary tables for rayons and oblasts, which show the total costs and averted doses of the selected remediation strategy as well as the ratio of the above—cost per averted dose—to

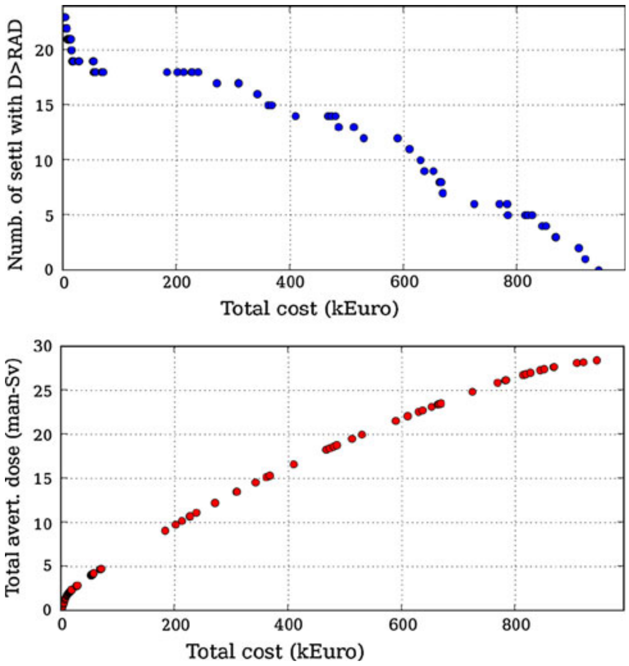

Fig. 3 Example summary plots of the strategy results: number of settlements with dose higher than *RAD* (*top*) and total averted dose due to remediation (*bottom*) vs. total cost of the strategy (data shown are exemplary and not related to any real country)

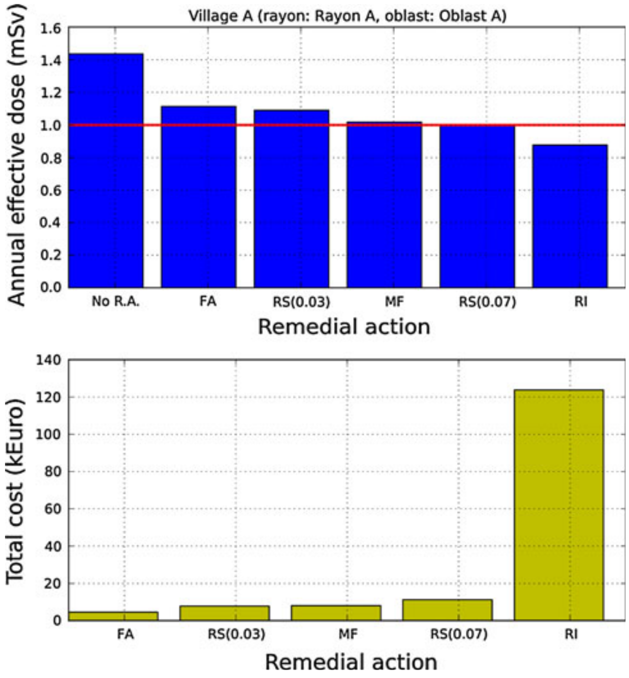

Fig. 4 Example of the graphical output for a settlement. The value of *RAD* is set to 1.0 mSv. The remedial actions shown have been selected based on criterion (20) for the given settlement (the data shown are exemplary and not related to any real settlement)

provide information on average economical efficiency of the remediation in the given administrative units (rayon or oblast).

Conclusions

As a result of the IAEA-supported projects of technical co-operation with countries most affected by the Chernobyl accident, the Republic of Belarus, the Russian Federation, and Ukraine, the software tool ReSCA has been developed and distributed to agriculture specialists and decision-making authorities in these countries. The acronym ReSCA abbreviates "Remediation Strategies after the Chernobyl Accident". As implied by its name, the program aimed to facilitate development of optimized strategies of rehabilitation of rural settlements contaminated after the Chernobyl accident. The software is based on contemporary data on contamination of agricultural products, settlements and pasture areas as provided by respective authorities from the countries.

Besides settlement-specific data, the program uses a set of generic country-dependent parameters, so called "model parameters". These parameters are based on expertise level gained during remediation activities in the affected countries. The user can adjust the model parameters to different values, provided the contemporary radiological situation demands it. The model parameters describe country-specific diet, costs and reduction factors of remedial actions, time of their validity as well as parameters pertinent to dose calculations. Annual doses of population, as calculated in ReSCA, are in agreement with the concept of the Representative Person recently introduced by ICRP (2006). However, averted collective doses are computed based on average doses in the settlement.

The main output of the program is an optimized strategy of remediation, i.e. of successive application of various countermeasures. The strategy can be optimized by minimizing the costs of averted collective dose. Because not all remedial actions are popular among inhabitants of the affected settlements, the program provides the possibility to shift priorities from less to more popular, although more expensive, remedial actions.

The program has already been proved to be a valuable and convenient tool in planning remediation activities. In Ukraine, for example, ReSCA is recommended for official use by the National Commission on Radiological Protection. In Belarus and in Russia, the program is on its way to become an officially approved decision-support tool.

Examples of application of ReSCA are given by Jacob et al. (2009), who performed an extensive analysis of possible remediation strategies and how they improve the

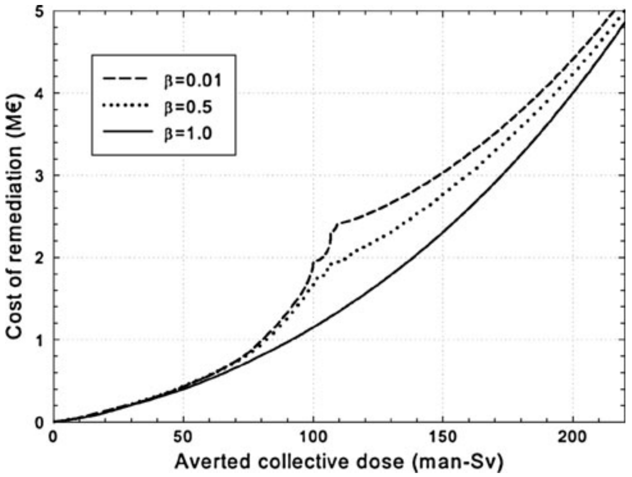

Fig. 5 Remediation costs vs. averted collective dose of three strategies: social-oriented ($\beta = 0.1$, *dashed line*), economically based ($\beta = 1$, *solid line*), and intermediate ($\beta = 0.5$, *dotted line*)

radiological situation in the three countries, including recommendations derived from those.

It was shown by Jacob et al. (2009) that implementation of different strategies might result in sufficiently different averted collective doses, number of settlements with annual doses exceeding reference levels, and costs of averted doses. As an example illustrating the latter, Fig. 5 demonstrates an exemplary calculation of remediation costs for three different strategies. One strategy, which can be called, as "socially oriented" maximizes the public acceptance of a remedial action, i.e. the parameter β [see (20)] is minimal and equals to 0.1. The second strategy is based purely on the cost-per-averted dose criterion and ignores the public attitude toward remedial actions. This economically based strategy is built using a maximal value for β of 1.0. The third strategy shown in Fig. 5 is derived for intermediate conditions when both the degree of acceptability and the cost per averted dose have equal impact, i.e. $\beta = 0.5$. As seen from the figure, the difference between those strategies varies considerably. For example, averting approximately 110 man-Sv might cost 2.4 M€ in the socially oriented strategy, while averting the same collective dose in the economically based strategy can be achieved after investing approximately 1.3 M€. It is also seen from the figure that investing large funds results in a small difference between socially oriented and economically based strategies, although the latter one obviously costs less.

Acknowledgments The program ReSCA was developed within the framework of the International Atomic Energy Agency Technical Co-operation Projects RER/9/074 "Long-term countermeasure strategies and monitoring of human exposures in rural areas affected by the Chernobyl accident" and RER/3/004 "Radiological support for the rehabilitation of the areas affected by the Chernobyl nuclear power plant accident" in 2003–2008.

Appendix

Derivation of algorithm and parameters for partial decontamination of settlement

During the development of ReSCA, the need had emerged to improve the algorithm that describes settlement decontamination (RS remedial action). This remedial action can be very difficult to consider as a part of a remediation strategy when applied to the whole settlement. Settlements vary in size of population, and so do the costs of decontamination work. On the other hand, decontamination practices (IAEA 2001; Golikov et al. 2002; Golikov 2003; Jacob 2003, 2005) showed that decontamination can also be applied only to a part of the settlement depending on its contamination and availability of funds.

The algorithm described here is based on earlier developments (Jacob et al. 2001, Jacob 2005), and it is designed to allow consideration of a step-wise decontamination of a settlement in ReSCA. As such, the algorithm allows evaluation of external dose reduction, averted doses, and costs required when only an arbitrary fraction of a settlement is decontaminated.

The main assumptions of the algorithm are (a) the settlement population is uniformly distributed over the settlement area, (b) the whole territory of the settlement can be split in two parts where part A is the higher-contaminated part (fraction θ of the settlement area), while part B is the lower-contaminated part (fraction $(1-\theta)$ of the settlement area, (c) inhabitants of both parts are assumed to permanently residing in their respective parts, (d) average annual doses due to external exposure are related—for both parts—through the ratio X_S of soil contamination levels:

$$\frac{D^{\mathrm{B}}}{D^{\mathrm{A}}} = \frac{q_{\mathrm{s}}^{\mathrm{B}}}{q_{\mathrm{s}}^{\mathrm{A}}} = X_{\mathrm{S}}. \tag{29}$$

The population of a settlement is exposed to external radiation depending on location, occupational activities, and life style. The location factor Λ_l expresses the dose at location l in terms of that over undisturbed soil, D. According to age, social, and professional activities, the population can be split in different groups, e.g. pre-school children or outdoor workers. These groups are characterized by their relative sizes p_g. People from different groups can spend their time at different locations; this is expressed by matrix $T_{g,1}$, which characterizes the time spent by group g at location l. Following these definitions, the average dose for population group g is

$$D_g = \mathrm{DC}_E q_S \bar{\Lambda}_g, \tag{30}$$

where $\mathrm{DC_E}$ is the dose conversion coefficient (mSv a^{-1} kBq^{-1} m^2), q_S is the average ^{137}Cs soil contamination in the settlement, and $\bar{\Lambda}_g = \sum_l T_{g,l} \Lambda_l$ is the average location factor for population group g.

If decontamination starts from the higher-contaminated part A of the settlement, then the reduction factor for such partial remedial action is by definition [see (5)] by:

$$R(\theta) = \frac{D_\mathrm{A} + D_\mathrm{B}}{D_\mathrm{A}^* + D_\mathrm{B}}, \tag{31}$$

where

$$D_\mathrm{A} = \mathrm{DC_E} q_\mathrm{S}^\mathrm{A} \sum_g \theta p_g \bar{\Lambda}_\mathrm{l} \quad \text{and}, \tag{32}$$

$$D_\mathrm{B} = \mathrm{DC}_E q_S^B \sum_g (1-\theta) p_g \bar{\Lambda}_l \tag{33}$$

are the average external doses without remediation in parts A and B, respectively; and

$$D_\mathrm{A}^* = \mathrm{DC_E} \frac{q_\mathrm{s}^A}{R_\mathrm{RS}} \sum\nolimits_g \theta p_g \bar{\Lambda}_g \tag{34}$$

is the average external dose in part A after application of the remedial action RS, and R_RS is the reduction factor for decontamination of the whole settlement.

Substitution of (32–34) into (31) and accounting for (29) lead to the following expression for the reduction factor of partial decontamination:

$$R(\theta) = \frac{\theta X_\mathrm{S} + (1-\theta)}{\frac{\theta X_\mathrm{S}}{R_\mathrm{RS}} + (1-\theta)}. \tag{35}$$

In the above equation, the only unknown parameter is X_S. This parameter can be derived using results obtained in field studies. It was observed (Golikov et al. 2002) that generally the most exposed group in a settlement (group H) consists of outdoor workers living in wooden houses, while the least exposed group (group L) is formed by pre-school children living in part B. For these groups, average location factors were found (Golikov 2003) to be 0.304 and 0.173, respectively. Correspondingly, the average sizes of these population groups were found to be $p_H = 0.34$ and $p_L = 0.08$.

If decontamination is applied to the higher contaminated part of the settlement (part A), then the size of group H is θp_H and the size of group L is $(1-\theta)p_\mathrm{L}$. The ratio of average doses for the groups L and H,

$$\frac{D_\mathrm{L}}{D_\mathrm{H}} = \frac{q_\mathrm{s}^\mathrm{B}}{q_\mathrm{s}^\mathrm{A}} \frac{\bar{\Lambda}_\mathrm{L}}{\bar{\Lambda}_\mathrm{H}} = X_\mathrm{S} \frac{0.173}{0.304}, \tag{36}$$

allows assessment of the ratio of the contamination levels in parts A and B, which is necessary to calculate the reduction factor (35).

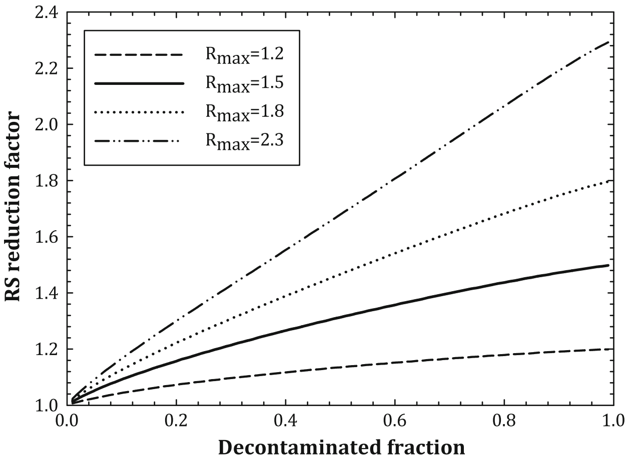

Fig. 6 Reduction factor for partial RS remedial action as a function of the decontaminated fraction of a settlement, for different values of RS in the whole settlement (R_max)

Finally, assuming that the doses of external exposure follow a log-normal distribution $f_\mathrm{LN}(x, \mu, \sigma)$ with GSD = 1.5 (Golikov 2003; IAEA 2007), this ratio (36) can be estimated using:

$$\frac{D_H}{D_L} = \frac{\int_{d_\mathrm{H}(\theta)}^{\infty} x f_\mathrm{LN}(x,\mu,\sigma)\mathrm{d}x}{\int_{d_\mathrm{H}(\theta)}^{\infty} f_\mathrm{LN}(x,\mu,\sigma)\mathrm{d}x} \times \frac{\int_0^{d_\mathrm{L}(\theta)} f_\mathrm{LN}(x,\mu,\sigma)\mathrm{d}x}{\int_0^{d_\mathrm{L}(\theta)} x f_\mathrm{LN}(x,\mu,\sigma)\mathrm{d}x}, \tag{37}$$

where quantiles of the groups are computed as:

$$\begin{aligned} d_\mathrm{H}(\theta) &= F_\mathrm{LN}^{-1}(1-\theta p_\mathrm{H}, \mu, \sigma) \quad \text{and} \\ d_\mathrm{L}(\theta) &= F_\mathrm{LN}^{-1}((1-\theta) p_\mathrm{L}, \mu, \sigma). \end{aligned} \tag{38}$$

Equation 37 expresses the ratio of doses for an arbitrary fraction of the settlement being decontaminated. This algorithm is currently implemented in ReSCA.

Examples of the reduction factors for a fractional RS remedial action are shown in Fig. 6. The example values have been derived for different values of the RS reduction factor applicable to the whole settlement.

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