Computer modelling – are we making a new generation of professionals stupid?

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Abstract
The paper provides an overview of the problems and errors encountered in computer modelling of both the exposure of workers and of the potential environmental impacts of industries dealing with NORM.
The tendency to rely purely on computer modelling, without understanding the software used, radiation protection principles (and sometimes even basic laws of physics) relatively often leads to situations where either:

- Potential exposures of workers and/or environmental impacts are significantly underestimated, requiring costly and prolonged correction measures in the future, or
- Enormous amounts of funds are spent on 'preventative' occupational radiation protection and protection of the environment – where these actions were certainly not required.

Additional issues are associated with facts that –

- Many representatives of a new generation of radiation protection professionals appear to be generally ignorant of principles and equations, on which the models and calculations are based and, sometimes, cannot recognise an error in the final results of modelling;
- The same model is occasionally used by a mineral processing company, by a radiation protection consultant and by a regulatory authority – with completely different outcomes, with those outcomes appear to have been "pre-programmed" before modelling commences.

The examples of the use of different models in different ways are provided and graded on a following scale:

Stupid → Silly → Adequate → Ridiculous → Ludicrous

The measures to ensure that the new generation of radiation protection professionals is capable of assessing potential impacts of industries dealing with NORM are also suggested.

1. Issues with computer modelling of radiation exposures and environmental impacts

Many representatives of a new generation of radiation protection professionals appear to be generally ignorant of principles and equations, on which the models and calculations are based and sometimes cannot recognise a simple error in the final results of modelling.

Voluminous reports containing detailed predictions of all possible radiological impacts of prospective operations involving radioactive materials are printed, filed and typically no detailed assessment of these reports is undertaken – until such time when the actual radiation monitoring commences.

This is particularly important for the sites where naturally occurring radioactive materials (NORM) are mined and processed. In these cases a very complicated modelling is required:

Firstly, there is a need to fully understand and predict the behaviour of many radionuclides in the processing environment: how every chemical, physical or thermal process affects the deportment of ^{232}Th, ^{228}Ra, ^{228}Th, ^{238}U, ^{234}Th, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po and sometimes also ^{235}U, ^{231}Pa, ^{227}Ac, ^{227}Th, ^{223}Ra, ^{147}Sm, ^{87}Rb and ^{40}K. It is usually also important to understand in which areas ^{222}Rn and ^{220}Rn may be present in significant concentrations.

Secondly, there is a need to estimate how different radionuclides may affect workers' health, through which pathways and to what extent.

Thirdly, a comprehensive site model needs to be developed to understand and estimate the potential impact of different radionuclides on the environment and on the members of the general public, in very different climates and for completely different ecosystems and social structures. Applying default parameters from a model developed for continental United States for a mining and/or processing operation in tropical Africa or South East Asia is as meaningless as using Canadian mining industry guidelines for cold stress (–50°C) at the mine sites in Northern Australia where heat stress (+50°C) is the main issue.

In almost all cases known to the author, the real measurements may differ from those that were modelled by the order or one or two magnitudes, showing that the models significantly overestimated or underestimated radiation risks.

1.1. Training

One of most important issues is that computer software is downloaded and used by untrained people. Even if a computer model provider places certain restrictions on the use of the software, it is often possible to obtain its previous versions and use it on a computer that is not connected to the Internet.

There is only a limited number of people who have attended appropriate training, such as RESRAD workshops. There is not much training offered in other software, such as ERICA, NORMALYSA, etc. either and such training usually consists of a one or two hour presentation demonstrating the software, after which the participants download it and use it at their own risk.

Several cases when only one trained person is (or was) available in an organisation are also known. A personal example can be presented, from a discussion of a radiological impact assessment for a NORM project in South-East Asia:

- "How did you came up with these numbers? These are weird and definitely incorrect."
- "We've had one person that went on the course, he has left now and we simply used the data from his print-out."

That incorrect assessment has resulted in the six-months delay for the project, as the radiological impact assessment needed to be completely re-done.

1.2. Use of default parameters instead of site-specific ones

This problem that is directly linked to the lack of training. Enormous overestimations may happen when the default input parameters are used instead of site-specific ones. The issue can be illustrated by the following example:
At a farm near a radiologically contaminated site the water (after purification) is used for irrigation, the water is sourced from site bores (some of which are contaminated) only 5% of the time and this water almost never used for drinking.

Default and actual RESRAD input parameters are [1]:

- *FDW* Fraction of drinking water that is contaminated. Default = 1, real = 0.1.
- *FGWDW* Fraction of drinking water from groundwater. Default = 1, real = 0.005.
- *FGWIR* Fraction of irrigation water from groundwater. Default = 1, real = 0.05.

The result of modelling using default parameters is a 500% to 2000% overestimation of doses and impacts.

1.3. Over-regulation

The application of the detailed and very strict regulations, particularly when an Australian, Canadian, EU or USA document is copied into the legislation in a developing country could (and most likely will) lead to the diversion of limited funds from other more important health problems of the population as a whole. The modelling is required in many cases to demonstrate regulatory compliance.

Radiation is only one of many low-level risks that is over-regulated [2]. There appears to be an obsession with regulating relatively low risks and an overall blindness to diseases such as measles, malaria and tuberculosis, and to other potentially fatal dangers, such as prescription opioids and alcohol.

Regulating minor or hypothetical hazards (such as low-level radiation from NORM) and using complicated models in an attempt to estimate and then reduce risk from these hazards:

a) Gives elected officials an opportunity to say, “we are here to protect you”,
b) Provides support for the scientific research that may not be needed, and for the government departments that, in some cases, have many more staff that is necessary, and
c) Appeases BANANAs – people of the following opinion: “Build Absolutely Nothing Anywhere Near Anything” [3].

Results of incorrect modelling that significantly overestimate possible radiation exposures and impacts often inflame local population and many projects that would be beneficial for some countries are not going ahead, in many cases only because someone typed a wrong number on a computer.

In two cases known to the author, in Africa and in South-East Asia, the local opposition to a project has not been successful and the subsequent monitoring of actual radiation exposures and impacts during the operational period of the facilities indicated that exposures and impacts were overestimated significantly, in some cases by an order of magnitude.

2. Illustrations of illiterate conclusions and their causes

The lack of training and understanding of basic radiation protection principles contribute to the existing problems.

In one case in West Africa, the laboratory certificate for the analysis of drinking water contained two values, one of which was negative: “– 0.12 Bq/L” for ^{226}Ra, which is an obvious nonsense.
The estimation of radiation exposure of the members of local community was done by consultants and the negative radiation exposure was the result of this assessment.

In another case in Australia, an assessment of different radiological parameters has been carried out for a radioactive waste disposal project.
The modelling indicated that the safe ‘waste acceptance criterion’ for ^{238}U concentration is 100,000 Bq/g – which is another example of a ridiculous error. The specific activity of ^{238}U is 12,384 Bq/g and there were no ‘red flags’ in the software indicating the physical impossibility of the result.
Essentially, the proposal suggests that ^{238}U would be accepted at this waste disposal facility; on a condition that one kilogram packageof such material does not contain more than eight kilograms of uranium.

In a third case in East Africa, the radiation exposure of the members of the general public to the ingestion of drinking water was assessed by simply collecting the water and taking a gamma radiation reading from the bucket.
As this is a high natural background area, the gamma radiation levels were of course above those thought to be “normal required values” by the Government Analyst, further inflaming already tense social problems. No samples were analysed for the concentrations of radionuclides and the actual radiation exposures were found to be zero above naturally existing background at a later stage.

2.1. Reliance on exclusively on computer modelling

The tendency to rely purely on computer modelling, without understanding of the software used, radiation protection principles (and sometimes even basic laws of physics) very often leads to situations where either:

- Potential exposures of workers and/or impacts on the environment are significantly underestimated, requiring costly and prolonged correction measures in the future, or
- Enormous amounts of funds are spent on ‘preventative’ occupational radiation protection and the protection of the public and the environment – where these actions were certainly not needed.

The examples of such situations are presented in part 3 of this paper.

2.2. Pre-programmed outcomes

The same or similar model is sometimes used by a mineral processing company, by a radiation protection consultant or by a regulatory authority – with completely different outcomes, with those outcomes appear to have been "pre-programmed" before modelling commences.

In some cases there is a suspicion that the inputs into a model were manipulated to ensure that the final outcome is what was desired.

For example, in one case the input parameters were too precise to be genuine, such as "concentrations in the material are: ^{232}Th = 5.37568 Bq/g, ^{226}Ra = 6.77559 Bq/g", where last three digits are meaningless, as the concentrations cannot be measured with such accuracy.

The impact of this specific site on the members of the general public was estimated to be 0.298 mSv/year, which is just below the locally applicable dose constraint of 0.3 mSv/year.

Then, in the process of further analysis, it was discovered that when the calculations are made using the simplified values of 5.38 Bq/g for ^{232}Th and 6.78 Bq/g for ^{226}Ra, the annual public exposure level would be 0.303 mSv/year, which would require a company to carry out radiation monitoring and possibly take additional measures in the management of NORM on site boundaries.

There are several cases of this kind that are known to the author and all of them may simply be coincidences. However, as a rule:

- Company modelling very often underestimates radiation doses and impacts, as understandably, the limited health, safety and environmental budgets need to take into account all aspects of company operations and radiation typically presents one of the lesser hazards.
- Consultant/government modelling quite often overestimates radiation doses and impacts, as many consultants are always in search for more work and personnel in some government departments may also look for more mining and mineral processing sites to regulate.

Two examples of the modelling carried out for the same mineral processing operation by the company and by the consultant are presented in Parts 3.2 and 3.4 to illustrate the above conclusions.

Many young professionals in both minerals industry and in the relevant government departments believe that the results are correct, as they appear not to have a capacity to understand the correctness of inputs into modelling programs, do not know which equations are used and how the programs work. Therefore, they usually cannot verify the outcomes of the modelling.

3. Examples of modelling

The examples of the use of models in this part are graded on a following scale:

Stupid → Silly → Adequate → Ridiculous → Ludicrous

3.1. Stupid

The assessment of the environmental impact from the disposal of NORM residue containing 7 Bq/g of thorium and 1 Bq/g of uranium was carried out by the mineral processing company and the outcome of this assessment was that there will be no measurable radiological impacts.

The re-assessment of the proposal indicated that the exposure of the members of the general public are likely to exceed the locally applicable dose constraint of 0.5 mSv/year and the exposure to one of "limiting reference organisms" is also above the recommended dose.

The comparison is presented in Table I.

Table I. Assessment of the environmental impact from disposal of NORM residue

Assumption	Actual situation
Particle size = 180-200 μm (assumed no dust and no leaching from mineral surface).	Particle size = 10-15 μm (practically dust + much larger surface of particles). Inhalation is likely.
Acidic material, presence of sulphates, assumed that all radium sulphate is precipitated.	Radium not precipitated, sulphates of thorium (^{232}Th, ^{230}Th, ^{228}Th) also need to be accounted for. Ingestion is likely.
0.5 meter cover thought to be sufficient, radon (both ^{222}Rn and ^{220}Rn) not considered, gamma radiation not considered.	0.5 m only acceptable for grasses and small bushes, several larger trees will destroy this cover by deep roots, ^{222}Rn, ^{220}Rn and gamma radiation above background detectable. Inhalation of radon and exposure to gamma radiation possible.
Modelling indicated that "limiting reference organism" is lichen and bryophytes. No one knew what "bryophytes" were: it was assumed that there were none of those on site.	The presence of the local endangered species of moss on site needed to be considered.
No effects whatsoever	Public exposure above 0.5 mSv/year possible. Specific protection measures may be required for the local endangered species of moss

3.2. Silly

The prediction of the occupational exposures of workers in the separation and processing of zirconium, titanium and rare earth minerals was carried out by the mining company. Several different minerals are processed and their activity concentrations vary from 3 to 15 Bq/g. The individual doses were predicted to be in order of 1.5 mSv/year.

The independent re-assessment of the proposal indicated that the exposure or workers would be around 4.5 mSv/year and some of them would need to be classified as "radiation designated workers" in accordance with the local regulations, stipulating the threshold of 5 mSv/year for such designation. The comparison is presented in Table II.

Table II. Assessment of the exposure of workers at a heavy mineral sands operation

Assumption	Actual situation
Working hours = 1000 hours/year.	Working hours = 1800 hours/year.
Respiratory protection factor = 100 (the use of 'airstream' helmets).	Respiratory protection factor = 5 (a simple P1 dust mask).
Dust particle size = 15 μm.	Dust particle size = 5.5 μm.
Split of worker's time between supervised, controlled and restricted areas:	Split of worker's time between supervised, controlled and restricted areas:
90% – 8% – 2%.	75% – 15% – 10%.
^{222}Rn Equilibrium Factor = 0.2	^{222}Rn Equilibrium Factor = 0.5
^{220}Rn Equilibrium Factor = 0.003	^{220}Rn Equilibrium Factor = 0.010
Monazite tailings dispersion: grain size 150 μm	Monazite tailings dispersion: grain size 50 μm
Drinking water not checked, assumed to be from municipal supply	Some (~25%) drinking water from site bores, elevated ^{226}Ra, ^{228}Ra and ^{228}Th
Worker's exposure = 1.1 mSv/year	Worker's exposure = 4.5 mSv/year

The illustration of the same modelling undertaken by a consultant is presented in part 3.4.

3.3. Adequate – correct

The adequate prediction of radiation doses and impacts is considered to be an extremely rare case, as the author is not aware of any situation where those were predicted correctly, especially in the situations involving NORM.

The modelling is always carried out at the stage of planning of a site where NORM will be mined and/or processed and there are always factors that are not taken into account. Even if the best possible care is taken to account for all exposure situations, all radionuclides, all possible pathways of radiation exposure and all input parameters are also correct, some of those would always be different in the future due to the changes which could not have been foreseen at the modelling stage.

3.4. Ridiculous

The prediction of the occupational exposures of workers in the separation and processing of zirconium, titanium and rare earth minerals at the same facility mentioned in part 3.2 was carried out by a consultant. Several different minerals are processed at the facility and their activity concentrations vary from 3 to 15 Bq/g. The individual doses were predicted to be in order of 28.7 mSv/year. As in case described in part 3.2, the independent re-assessment of the proposal indicated that the exposure or workers would be around 4.5 mSv/year. The comparison is presented in Table III.

Table III. Assessment of the exposure of workers at a heavy mineral sands operation

Assumption	Actual situation
Working hours = 2500 hours/year.	Working hours = 1800 hours/year.
No respiratory protection at all.	Respiratory protection factor = 5 (a simple P1 dust mask).
Dust particle size = 3 µm.	Dust particle size = 5.5 µm.
Split of worker's time between supervised, controlled and restricted areas:	Split of worker's time between supervised, controlled and restricted areas:
50% – 30% – 20%.	75% – 15% – 10%.
^{222}Rn Equilibrium Factor = 0.8	^{222}Rn Equilibrium Factor = 0.5
^{220}Rn Equilibrium Factor = 0.010 [correct]	^{220}Rn Equilibrium Factor = 0.010
Monazite tailings dispersion: grain size 20 µm	Monazite tailings dispersion: grain size 50 µm
All (100%) drinking water from site bores, elevated ^{226}Ra, ^{228}Ra and ^{228}Th	Some (~25%) drinking water from site bores, elevated ^{226}Ra, ^{228}Ra and ^{228}Th
Worker's exposure = 28.7 mSv/year	Worker's exposure = 4.5 mSv/year

The illustration of the same modelling undertaken by a company is presented in part 3.2.

3.5. Ludicrous

The prediction of the exposures of the members of the general public at a remediated large uranium exploration site (previously containing numerous workings and a pilot plant) was carried out by a government department and it was estimated that radiation exposure may be around 3 mSv/year.

The site is in a very remote area and nearest members of the public reside in a small village approximately 40 kilometres away; the actual situation was not taken into account and, as a result, millions of dollars were spent on overseas modelling, consulting and remediation teams, despite the fact that over 50% of people in that particular country live in poverty.

An independent re-assessment of the work indicated that there was no need for any remedial action whatsoever, as doses to members of general public were very unlikely to exceed 0.05 mSv/year. The comparison is presented in Table IV.

Table IV. Assessment of the exposure of members of the public at the uranium exploration site

Assumption	Actual situation (NOT taken into account)
Occupancy factor – 100% (8,760 h/year).	Maximum of 100 h/year (random hunters).
All samples uncovered, trenches not filled.	Everything disposed of properly and covered.
Contradictory, at the same time:	Measured:
(a) No wind – $^{222}Rn = 300\ Bq/m^3$,	$^{222}Rn = 15\ Bq/m^3$ (background)
(b) 10 m/sec wind, dust generation = 1 mg/m^3.	Dust concentrations = 0.01-0.02 mg/m^3
Cooking of local game in/on the ground, uranium fully soluble, ingestion coefficients for less than 1 y.o. child used.	No cooking on site, uranium mostly insoluble, no children on site and < 1 y.o. child will not normally eat meat – even if present on site
Public exposure = 3 mSv/year, large scale remediation carried out.	There was no need for any remedial action whatsoever.

4. Suggestions

4.1. Results interpretation

The following suggestions can be made in regards to the interpretation of the results of computer modelling:

- Never accept modelling results as correct without at least a simple check, i.e. an estimate of possible gamma exposure can be done with a pen and a piece of paper in a couple of minutes.
- Always inquire as to who actually did the assessment and using which software: some examples of errors are from “reputable consulting firms” or from government departments.
- Always verify the data: any document to which a reference is made may contain incorrect values:
  - Australian Safety Guide on the occupational radiation doses in mining and mineral processing [4] contains, in part 4.2.3, an Equilibrium Factor for ^{220}Rn that is 300-500 times higher than it typically is;
  - IAEA Technical Document on the detection of radioactive materials at borders [5] contains, in Annex I, ^{232}Th concentration in monazite that is 20 times lower than it normally is.

Be very careful in the evaluation of conclusions of any assessment, especially those concerning public health, as some assessments contain unreasonable conclusions based on irrational assumptions [6-9].

The data contained in official documents can sometimes be misinterpreted, to suit the views of the person that carries out the modelling and/or the views of the organisation, on whose behalf the modelling is being carried out. An example of the use of US EPA FGR-13 [10] can be presented.
The document establishes radiation risk coefficients for mortality and morbidity for about 100 radioisotopes, which are to be used in regulatory programs and in the preparation of environmental impact assessments.
Mortality – you die from the radiation-induced illness before you die from something else. *Morbidity* – you recover from the radiation-induced illness or you die from something else before radiation will finish you off.

Of course, the document is “not intended for application to specific individuals and should not be used for this purpose”. But the document may still be used for exactly that purpose, as follows:

- A facility is proposed on the outskirts of a town with 100,000 people, and it is proposed to operate for 25 years;
- Due to the facility processing NORM, an Environmental Impact Assessment (EIA) was developed and it was demonstrated that the maximum public exposure would be around 0.1 mSv/year – only 10% of the public exposure limit;
- The local media is mostly unaware of the situation and the general attitude of the interested local public is: “no problems, everything is way below limits, more jobs for us”;

- Then an organisation with certain interests (as a rule, from "out-of-town") carries out the assessment using FGR-13 coefficients, stating that nine people could get a non-lethal cancer and eight could die from radiation-induced cancer.
- After the local media gets a copy of such assessment, the construction of this facility is likely to be halted and it may take years of arguments and public debates for it to re-commence.

4.2. Students

How do we make students interested in modelling? Not only in the use of the software, but also in understanding the principles of radiation protection, physics, chemistry, geology, hydrology, etc. on which the software is based?

- Try to make students interested in what is behind the computer models, don't just teach them to blindly use those. Most of them can easily download the software, read the manual and use it without anyone showing them how to do it.
- Make it COOL and encourage individual students: "Everyone can type on the keyboard, a much brighter mind is needed to understand what is behind it all, I think you are one of those people".
- Make it FUN and ATTRACTIVE: introduce deliberate errors into exercises on modelling, some easy to find, others much better hidden.
  Tell students that there are, say, seven errors – and those who can find all of them will get a credit for the semester (or something of this kind).

4.3. Employment

During an interview with a prospective employee (whom you would want to work on computer modelling) produce a relatively complex mathematical equation, such as a Gaussian plume model for the dispersion materials from stacks. Then ask if a candidate knows what it is:

- If the answer is no, possibly consider employing someone else.
- If the answer is yes (or even "I've seen this before, just don't remember right now what it is exactly"), pick up an easy calculation example from, for example, Annex IV of the IAEA Safety Report No.19 [11], or a similar exercise.
- If the exercise is done correctly, you may have found a good technical specialist for the modelling.

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