# Supplementary Material

# Secondary Receptors

## Selection of Secondary Receptors

The list of secondary receptors used in this project is shown in Table 1 below. The agricultural receptor type was not split further due to the absence of data.

Table 1: Secondary receptors used in this study

|  |  |
| --- | --- |
| **Type** | **Name** |
| Agriculture | Agriculture |
| City | Al Wakra |
| Dukhan |
| Al Khor |
| Industrial Area |
| Rayyan |
| Doha |
| Desalination Plant | Ras Abu Fontas |
| Umm Al Houl |
| Dukhan Desalination |
| Gas Field | North Oil Field |
| Industry | Mesaieed |
| Ras Laffan |
| Oil Field | Shaheen Oil Field |
| Al Khalij Oil Field |
| Bul Hanine |
| Idd El Shargi |
| Maydan Mahzam |
| Al Rayyan Field |
| Al Karkara |
| A- Structure |
| Al- Bunduq |
| Dukhan Oil Field |
| Transport Hub | HIA |
| Hamad Port |
| Halul Island | Halul Island |

The author's judgment based on the available population distribution and the anecdotal experience was used to select cities as secondary receptors. The inclusion of every small nonindustrial residential area is infeasible at this study stage. The only international airport (Hamad international airport) ([Airport Technology](#_ENREF_1)) and the main seaport (Hamad Port) ([Walker, 2016](#_ENREF_49)) were selected as transport hubs.

Qatar has three heavy industrial cities. However, only two were selected as secondary receptors. As the Dukhan oil field encompasses the Dukhan industrial city, the larger Dukhan oil field receptor boundary was used. Generally, when an area corresponded to two classifications, only one classification was assigned based on the author's judgment. Finally, Qatar also has a light industrial area within the city classified as a city due to the significant blue-collar population on-site and the nature of work performed ([Shakespeare, 2014](#_ENREF_38)).

Similarly, Qatar has four major desalination plants. However, Ras Laffan industrial city encompasses the Ras Laffan desalination plant. Thus, Ras Laffan was classified as an industry, and only three desalination plants were included as secondary receptors. Special attention was paid to desalination plants, as essentially all potable water in Qatar is obtained from desalination ([Mannan et al., 2019](#_ENREF_26)). In Figure 1, desalination plants are not visible due to their small size relative to the other receptors

As the hydrocarbon industry is the main contributor to Qatar's economy, oil fields and gas fields were also included ([Planning & Statistics Authority, 2018](#_ENREF_32)). Fields on Qatar's mainland and exclusive economic zone (EEZ from ([Al-Qaradawi et al., 2015](#_ENREF_2))) were included ([Al-Siddiqi & Dawe, 1998](#_ENREF_3); ["Qatar Blocks and Fields," 2014](#_ENREF_34)). Finally, Halul Island was given a unique secondary receptor classification as it serves as an army base, industrial site, and environmental protection site ([Qatar Petroleum](#_ENREF_35)). Thus, vital infrastructural areas have been included in the analysis as recommended by FEMA ([FEMA, 2010](#_ENREF_16)). All receptor boundaries were drawn using satellite imagery and district maps obtained from Google Maps as applicable.

## Land Use & Soil Classification

A combined land use/ soil classification map was obtained from Hassan et al. They combined data from the harmonized world soil database (HWSD) and a 2013 Qatari geological study with Google Earth satellite photos to obtain these maps. The soils were classified using reference soil groups of the world reference base for soil resources (WRB) ([Hassan et al., 2020](#_ENREF_20)). The original data had a different format for classification compared to the expected JRODOS input. JRODOS classifies land use as agricultural, forest, urban, water, and grassland/undefined. On the other hand, JRODOS categorizes soil as peaty, sandy, loamy, clay, and no data. QGIS was used to split the original data into two maps for JRODOS use. Then, the data conversion was done, as shown in Table 2 below.

Table 2: Reclassification of land use & soil map JRODOS classifications

|  |  |  |
| --- | --- | --- |
| **Original** | **JRODOS Land use** | **JRODOS Soil** |
| Industrial | Urban | Clay |
| Urban & built-up | Urban | Loam |
| Rangeland | Agricultural | Loam |
| Water | Water | No data |
| Barren land (Soil type: Solonchaks) | Grassland/Undefined | Clay |
| Barren land (Soil type: Sand Dunes) | Grassland/Undefined | Sand |
| Barren land (Soil type: Leptosols) | Grassland/Undefined | Loam |
| Barren land (Soil type: Calcisols/in city) | Grassland/Undefined | Loam |
| Barren land (Soil type: Calcisols/out city) | Grassland/Undefined | Loam |

As seen in Table 2 above, the reclassification of land use is relatively straightforward. Industrial areas were also assumed to be urban as they most resemble urban regions in infrastructure and population distribution.

The reclassification of the soil map was a more involved process. The reclassification was done using the USDA soil texture triangle. The sand, clay, and silt composition for the four soil types mentioned above in Table 2 were obtained from the harmonized world soil database by FAO and IIASA and are shown in Table 3 below ([FAO/IIASA/ISRIC/ISSCAS/JRC, 2012](#_ENREF_15)).

Table 3: Composition of soil types in Qatar based on harmonized world soil database ([FAO/IIASA/ISRIC/ISSCAS/JRC, 2012](#_ENREF_15))

|  |  |  |  |
| --- | --- | --- | --- |
| **Soil Type** | **Sand** | **Silt** | **Clay** |
| Calcisols | 51 | 31 | 19 |
| Solonchaks | 31 | 35 | 34 |
| Leptosols | 41 | 36 | 24 |
| Sand Dunes | 86 | 9 | 6 |

These classifications were used to reclassify the soil types into sandy, clay, and loamy based on the soil texture triangle from USDA, as shown in Figure 1 below ([Soil Survey Division Staff, 1993](#_ENREF_41); [United States Department of Agriculture](#_ENREF_46)). The rangelands (agricultural areas) were assumed to be loamy since loamy soil is more fertile than clay or sandy soil ([Lerner, 2000](#_ENREF_25)). No peat was assumed for Qatar because peat is typically found in wet climates with a lot of organic matter such as trees shrubs, and other flora ([Soil Survey Division Staff, 1993](#_ENREF_41)). The industrial and urban areas were assumed to be the same soil type as the predominant soil type surrounding them.

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Calcisols

Solonchaks

Leptsols

Sand dunes

Figure 1: Reclassification of Soil Map based on USDA Soil Texture Triangle ([United States Department of Agriculture](#_ENREF_46))

## Food Consumption

The food consumption data was obtained from the Household Expenditure and Income Survey (HEIS) from 2013 ([Ministry of Development Planning and Statistics, 2013](#_ENREF_28)) with meat consumption data from a study by Al-Thani et al. ([M. Al-Thani et al., 2017](#_ENREF_5)). No data from more recent years was available and remains a key future avenue of research. The food consumption rates available from MDPH were monthly household rates for Qataris and non-Qataris separately ([Ministry of Development Planning and Statistics, 2013](#_ENREF_28)). This rate was converted into an individual daily rate using the average household size provided within the same survey. A weighted average based on the distribution of Qataris and Non-Qataris within Qatar ([Gulf Labour Markets and Migration, 2017](#_ENREF_19)) was used to estimate a unified daily individual consumption rate for each foodstuff. It is to be noted that for larger receptors, more granular data for each receptor should be collected to ensure ingestion dose is accurate.

Only food grown within Qatar was only included in the calculation of the radiation dose through ingestion. It is expected that Qatar would only import food from countries unaffected by the nuclear accident. A similar approach was also followed by Poon et al. when estimating the radiation ingestion dose in Hong Kong, following a hypothetical nuclear accident at Guangdong NPP ([Poon et al., 1997](#_ENREF_33)). However, it is to be noted that Qatar imports a significant amount of food from its neighbors ([World Integrated Trade Solution](#_ENREF_53)). Some of them are also likely to be impacted by the same accident. A future avenue of work would be to include these countries in the simulations to understand Qatar's complete food supply chain better. Such an approach would give the country more tools to minimize disruption to the food supply chain. This approach would require a detailed breakdown of the origin of the imported food and significant receptor data on the neighboring countries.

Subsequently, the food consumption was scaled down using Qatar's agricultural production data obtained from the Planning Statistics Authority. This data included crops grown, animals reared, and agricultural yield ([Planning & Statistics Authority, 2017](#_ENREF_31)). In many cases, the percentage of food produced locally was only available in terms of the primary foodstuff classification such as vegetable, fruit, milk products, and not specific products. In these cases, the uniform scaling factor was assumed for all products under the main category. For example, 16% of vegetables were produced locally. Thus, food consumption of root, leafy, and other vegetables was scaled down evenly by 16%.

These imported foods are considered safe from any fallout from NPP accidents within the GCC. Additionally, the following assumptions were made as part of preprocessing for us in JRODOS:

* Wheat is available and grown within Qatar in spring and winter. This assumption was made based on Qatar's growing nearly all of its food within greenhouses that are less dependent on climate. ([Burdon-Manley, 2017](#_ENREF_12))
* One-fourth of all wheat products were assumed to be whole wheat and the rest as typically processed wheat
* All beef consumed was assumed to be cow meat and not bull or veal meat
* All milk consumed was assumed to be cow milk
* No seasonal intake factors were applied to different foodstuffs as Qatar imports most of its food ([Planning & Statistics Authority, 2017](#_ENREF_31)).
* Cheese consumed local was assumed to be 50% rennet type and 50% acidic type
* Any vegetable not classified as root or leafy vegetable was classified as fruit vegetable. For example, the tomato was considered a fruit vegetable.
* Consumption rates for vegetables only classified as "frozen", "fresh "or "canned" without specific vegetable names were divided into three parts and added to consumption rates of root, leafy, and fruit vegetables each.
* Dates were classified as fruits

The food consumption rates derived by the above methodology and used for estimation of the ingestion radiation dose are shown below in Table 4.

Table 4: Contaminable food input for JRODOS calculations

|  |  |  |  |
| --- | --- | --- | --- |
| **Foods** | **Total adult food intake (g/day)** | **%Self Sufficiency** | **Contaminable food intake (g/day)** |
| **Whole Wheat (Whole)** | 48 | 3.4% | 1.6 |
| **Wheat Flour** | 193 | 3.4% | 6.5 |
| **Potato** | 63 | 16.4% | 10.3 |
| **Leafy veg** | 70 | 16.4% | 11.6 |
| **Root veg** | 179 | 16.4% | 29.3 |
| **Fruit veg** | 89 | 16.4% | 14.6 |
| **Fruits \*** | 316 | 0.5% | 1.5 |
| **Berries** | 0 | 16.4% | 0.0 |
| **Milk** | 148 | 26.8% | 39.7 |
| **Cond Milk** | 55 | 26.8% | 14.7 |
| **Cream** | 37 | 26.8% | 9.9 |
| **Butter** | 5 | 26.8% | 1.4 |
| **Cheese (ren.)** | 10 | 26.8% | 2.7 |
| **cheese (acid)** | 10 | 26.8% | 2.7 |
| **Sheep milk** | 0 | 26.8% | 0.0 |
| **Goat milk** | 0 | 26.8% | 0.0 |
| **Beef (cow)** | 29 | 13.2% | 3.8 |
| **Lamb** | 56 | 13.2% | 7.4 |
| **Chicken** | 73 | 9.5% | 7.0 |
| **Eggs** | 42 | 13.6% | 5.7 |
| **Fish** | 40 | 31.7% | 12.5 |
|  | | | |

## Agricultural Production

The following assumptions were made regarding crops while using the available agricultural production data:

* Wheat and barley are grown both in spring and winter.
* One-fourth of all wheat gown is processed to be whole wheat, and the rest is assumed to be regular wheat flour.
* Half of the green fodder was assumed to be grass and the other half as hay

No direct information was available on the feed water given to animals. However, the number of animals reared within Qatar in 2017 was available ([Planning & Statistics Authority, 2017](#_ENREF_31)). This information was combined with the average daily water intake data for each animal to obtain the overall feed water consumption rates shown in Table 5.

Table 5: Feedwater consumption rates for animals reared in Qatar in 2017

|  |  |  |  |
| --- | --- | --- | --- |
| **Animals** | **Number of Animals** ([Planning & Statistics Authority, 2017](#_ENREF_31)) | **Water consumed per animal daily (L/day\*animal) (**[Ehrlenbruch et al., 2010](#_ENREF_14)**;** [Ward & McKague, 2019](#_ENREF_50)**)** | **Water consumed annually (m3/year)** |
| **Cows** | 24958 | 155.00 | 1.41E+06 |
| **Sheep** | 932472 | 8.14 | 2.77E+06 |
| **Goats** | 382423 | 7.90 | 1.10E+06 |
| **Camels** | 105387 | 39.00 | 1.50E+06 |
| **Horses** | 7333 | 39.00 | 1.04E+05 |
| **Poultry** | 10524315 | 0.73 | 2.80E+06 |
|  |  | **Sum** | 9.69E+06 |

The following assumptions were made while deriving the annual water consumption rate:

* The maximum water consumption rate was used as Qatar's hot climate necessitates a higher water consumption rate
* All cows were assumed to be of the Holstein variety as most local cows are of the Holstein variety. While 700 liters are used per cow in Qatar, most of this is misting to control the temperature ([Castelier, 2019](#_ENREF_13)). As a result, the cow only consumes around 155 liters ([Ward & McKague, 2019](#_ENREF_50)). Thus, the water consumption rate was calculated based on the 155-liter consumption rate.
* The exact distribution of sheep between feeder lambs, ewes, etc., was not known. Thus, the feed rates of sheep throughout all stages of life were averaged to determine the water consumption rate
* The local breed of horses was assumed to be all Arabian horses with an average weight of 800-1000 pounds ([Mascarenhas, 2014](#_ENREF_27)).
* Camel water consumption was assumed to be the same as a horse in the absence of data.
* The water consumption rate of poultry in fall, spring, winter, and summer was averaged to derive a daily water consumption rate.

## Skin Area

The average skin area was estimated using the formulation proposed by Yu et al.. This formula was obtained by studying 135 people of each gender using 3D body surface scans and was shown to have a smaller estimation error than the standard procedures used nowadays, such as the Du Bois and Du Bois formula. The formula is shown in Eq. 1 below ([Yu et al., 2010](#_ENREF_60)).

|  |  |
| --- | --- |
|  | Eq. 1 |

Where BSA is Body surface area (cm2)

H is height (cm)

W is weight (kg)

Height and weight data for men and women in Qatar from Qatar biobank ([A. Al-Thani et al., 2017](#_ENREF_4)) were used to obtain an average skin area of 1.87 m2, as shown in Table 6 below.

Table 6: Height, Weight and Skin Area of Men & Women within Qatar

|  |  |  |
| --- | --- | --- |
|  | **Men** | **Women** |
| **Height (cm)** ([A. Al-Thani et al., 2017](#_ENREF_4)) | 172.60 | 158.00 |
| **Weight (kg)** ([A. Al-Thani et al., 2017](#_ENREF_4)) | 85.90 | 73.90 |
| **Skin Area(m2)** | 1.99 | 1.75 |
| **Average Skin Area (m2)** | 1.87 | |

## Population Distribution and Behavior

Population distribution maps for 2017 were obtained from the Ministry of Public Health ([Hassan et al., 2020](#_ENREF_20)).

The fraction of time spent indoors (occupancy rate) was estimated to be 90% based on EPA guidelines and recommendations by Andrade et al. in their review of indoor air quality for sports ([Andrade & Dominski, 2018](#_ENREF_7); [U.S. Environmental Protection Agency, 1989](#_ENREF_43)). This assumption also is in line with the author's anecdotal observations of this factor within Qatar. Indeed, some factors, such as bathing frequency (assumed daily) and the fraction of skin covered by clothes (assumed 80%), were assumed based on anecdotal observations due to the lack of data.

## Radionuclide Transfer within a Desert Ecosystem

Experimental data on radionuclide transfer within a desert ecosystem was sparse and was not changed from the default values. These defaults are based on the HARMONE research project results, which were a part of the EU's OPERRA project.. This project sought to improve the environmental modeling and human dose assessment capabilities of JRODOS ([NERIS, 2016](#_ENREF_30)). Updating these values for a desert ecosystem is another significant avenue for future research. The default inhalation rate within JRODOS for the EU was adopted for Qatar as no significant difference in breathing rate is expected between the EU and Qatar. Another parameter of note is the resuspension factor used to estimate the resuspension dose. The resuspension factor is estimated as a function of time. The coefficients are estimated based on the Chernobyl accident and are chosen to avoid underestimating the dose ([Müller et al., 2003](#_ENREF_29)). Any other factors not mentioned above were left as JRODOS default due to lack of data.

# Details of Selected Nuclear Plants

**Iran**

Iran currently has one operational nuclear plant, Bushehr. The reactor has one unit, with details in Table 7 below. Plans are in place to expand the Bushehr plant in four phases and build nuclear plants at other sites like Makran coast ([World Nuclear Association, 2020a](#_ENREF_55)).

Table 7: Details of the Reactor at Bushehr Nuclear Power Plant in Iran ([Jafarikia & Feghhi, 2018](#_ENREF_24); [World Nuclear Association, 2020a](#_ENREF_55))

|  |  |
| --- | --- |
| **Reactor Model** | VVER-1000/V-446 (PWR) |
| **Thermal power production (MWt)** | 1 x 3000 |
| **Electrical power production (MWe)** | 1 x 915 |
| **Startup Date** | May 2011 |
| **Commercial Operation** | September 2013 |
| **Containment Chamber Dimension** | 56 m (Spherical) |

**UAE**

UAE is building one nuclear power plant, Barakah, in collaboration with South Korea. The reactor has four identical units, with their details given in Table 8 below.

Table 8: Details of the Reactor at Barakah Nuclear Power Plant in UAE ([UAE Federal Authority for Nuclear Regulation, 2012](#_ENREF_44), [2014](#_ENREF_45); [World Nuclear Association, 2020b](#_ENREF_56))

|  |  |
| --- | --- |
| **Reactor Model** | APR-1400 (PWR) |
| **Thermal power production (MWt)** | 4000 |
| **Electrical power production (MWe)** | 4 x 1390 |
| **Startup Date** | August 2020 (Reactor 1) |
| **Commercial Operation** | -- |
| **Containment Chamber Dimension** | 70 m (Dome height) |

**KSA**

KSA currently has no commercial operating reactors, and none are under construction. However, KSA has committed to developing local nuclear power generation capability. Towards this end, it has signed agreements with several companies to explore reactor technologies. Some of the larger reactor units considered are GE Hitachi's ESBWR, Toshibas ABWR, and Toshiba/Westinghouse's AP1000. The first two are boiling water reactors (BWR), with the last being a PWR. In addition, two smaller reactors are also being considered. The first is the South Korean SMART reactor, and the second is the Chinese High-Temperature Reactors (HTR) ([World Nuclear Association, 2019](#_ENREF_54)). However, KSA has one research reactor under construction in Riyadh([Brumfiel, 2019](#_ENREF_11)).

# Sampling Method

## Key Equations and Explanation for the Tests Used

### Mann-Whitney Test

The Mann-Whitney test as part of the R package (wilcox.test function with paired=FALSE in R stats package v3.6.2) was used to conduct the test for this study{Hollander, 2015 #5369;Hollander, 2015 #5368;Siegel, 1988 #5370} . The basic calculation procedure to obtain the key test parameter (U) is as follows :

1. Assign ranks to observations within each sample. In case of ties, assign ranks that correspond to the midpoint values of the tied observations.
2. Determine the sum of the ranks for each sample (Ri). Subtract the minimum value from the ranks. *(This is a special adjustment found within the R. Other software such as SPSS do not subtract the minimum value from the ranks.)*
3. Calculate the U value for both samples using the equation below.

Where: i = Sample number

Ri = Rank Sum

ni = sample size

1. Calculate z-statistic from the U value using the equation below from which the p-value can be calculated using the correlation tables commonly used and programmed within different statistic packages.



Where:





### Kruskal Wallis Test

The Kruskal Wallis test as part of the R package (kruskal.test function in R stats package v3.6.2 ) was used to conduct the test for this study {Hollander, 2015 #5368}. The basic calculation procedureto obtain the key test parameter (H) is as follows:

1. Assign ranks to observations within each sample. In case of ties, assign ranks that correspond to the midpoint values of the tied observations.
2. Determine the sum of the ranks for each sample (Ri).
3. Calculate H as per the following formula



Where: N= Total size of the sample

### Dunns Test

The Dunns test with Bonferroni correction as part of the FSA package (dunnTest function in FSA package v0.9.1 <https://github.com/fishR-Core-Team/FSA> ) was used to conduct the test for this study. The test is conducted pairwise after the Kruskal Wallis test to see which pair of samples are statistically different. The basic equation to obtain the z-statistic (zi) which can be used to derive p-values to compare the two samples is as follows:



Where:



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## Result of Dunns Test

The results of the pairwise comparison between the four datasets (V4-V7) of S=1 sampling and three datasets of S=2 sampling (V1-V3) of S=2 sampling using Dunns test are shown below in Table 9 and Table 10.

Table 9: Comparison of samples by Dunns test for S=1 sampling rates for all three NPPs

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **NPP** | **% of receptors with stat. diff datasets (S=1 Sampling)** | | | | | |
| **V4 - V5** | **V4 - V6** | **V5 - V6** | **V4 - V7** | **V5 - V7** | **V6 - V7** |
| **Barakah** | 0% | 0% | 0% | 0% | 0% | 0% |
| **Bushehr** | 0% | 0% | 0% | 0% | 0% | 0% |
| **Umm Huwayd** | 8% | 4% | 0% | 4% | 12% | 4% |

Table 10: Comparison of samples by Dunns test for S=2 sampling rates for all three NPPs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **NPP** | **% of receptors with stat. diff datasets (S=2 Sampling)** | | | |
| **V1-V2** | **V1-V3** | **V2-V3** |
| **Barakah** | 0% | 0% | 0% |
| **Bushehr** | 4% | 0% | 0% |
| **Umm Huwayd** | 4% | 2% | 8% |

In all samples, less than 25% of receptors have statistical differences in the associated data. Thus, both sampling rates can be used depending on needs and available resources.

# Modules/Software Used

## JRODOS

JRODOS is a DSS developed by the EU after the Chernobyl disaster for addressing off-site emergency management after nuclear accidents. JRODOS is an integrated DSS that includes several simulation modules such as atmospheric & aquatic dispersion, atmospheric deposition, dosage estimation, and countermeasures testing. The system has been developed over three decades with the involvement of multiple institutions across the EU. It operates in more than 20 institutions across 16 nations in the EU and Asia at national and local levels ([Ievdin et al., 2012](#_ENREF_23); [Wengert, 2017](#_ENREF_51)). The use of JRODOS across multiple countries lends confidence to its accuracy and versatility. The latter is especially important since Qatar (primary receptor) is a desert with a different climate to many other countries, as explained later. Furthermore, ARGOS and JRODOS share many common modules, which only increase the confidence in the use of JRODOS ([Raskob et al., 2016](#_ENREF_36)).

## Dispersion/Deposition Modules

RIMPUFF is a Lagrangian mesoscale puff model that was designed to overcome the shortcomings of the Gaussian plume model. These shortcomings include the inability to handle inhomogeneous flows and turbulent flows ([Thykier-Nielsen et al., 1999](#_ENREF_42)). DIPCOT is a Lagrangian particle model used to simulate the dispersion of pollutants over complex terrains in both homogenous and inhomogeneous conditions ([Andronopoulos et al., 2002](#_ENREF_8)). Finally, LASAT is also a Lagrangian particle model with a diagnostic wind field model present in the pre-processor to calculate dispersion when buildings are present.

## Food Contamination Modules

FDMT first estimates the contamination of plant products such as fruits, vegetables, hay, and wheat as a function of time. It calculates the contamination for plants used as human food as well as animal feed. FDMT considers contamination of the leaves, contamination due to root uptake, and resuspension. FDMT already has the required parameters such as weathering rate, translocation factors used for this calculation. It also requires a soil map of the simulation domain ([Müller et al., 2003](#_ENREF_29)).

Next, the contamination of animal products such as milk, poultry, and eggs is calculated. The livestock exposure pathways considered here are inhalation of radionuclides and ingestion of contaminated feed. After this, factors for the radioactivity enrichment or dilution depending on the type of food processing and storage time are applied to estimate the level of contamination foodstuff ([Müller et al., 2003](#_ENREF_29)).

# Short Term Threshold

On the other hand, there is no agreement on the threshold to prevent the long-term consequences of radiation exposure, such as cancer and birth genetic defects. ICRP recommends keeping the lifetime dosage below 1 Sv. However, this guidance is challenging to implement given the significant uncertainty involved. Epidemiological studies on populations exposed to radiation suggest a significant increase in cancer incidences rate at doses above 100 mSv. At the same time, some other studies suggest a possible increase in cancer rate in the 50-100 mSv range ([Vaiserman et al., 2018](#_ENREF_48); [WHO, 2016](#_ENREF_52)). In contrast, ICRP and US NRC use a 1 mSv/yr threshold under the controversial linear no-threshold (LNT) assumption ([USNRC, 2018](#_ENREF_47); [Vaiserman et al., 2018](#_ENREF_48)). Since typical background radiation in North America can reach 3 mSv per year with an abdominal/pelvic CT scan alone, resulting in a 10 mSv dose, the 1 mSv dose was considered to be too conservative for this study ([IAEA, 2016](#_ENREF_21); [World Nuclear Association, 2020c](#_ENREF_57)). Thus, the 50 mSv threshold was chosen for long-term cancer risk to balance the costs and potential benefits to the public.

# Countermeasure Classification

The countermeasures were classified based on literature review as described below.

**Emergency countermeasures** primarily refer to mitigation measures implemented during the pre-deposition and emergency phase after detecting a radioactive cloud. These include closing windows and air ducts to reduce air flow, covering precious objects, sheltering, and evacuation. These countermeasures tend to be implemented immediately after detecting an accident. These methods protect the population by reducing their exposure to radionuclides in the environment but not directly targeting the contamination ([Brown et al., 2007](#_ENREF_10)). Thus, these methods primarily reduce exposure through inhalation, cloudshine, groundshine, and skin exposure.

**Agricultural countermeasures** are countermeasures that reduce radioactive exposure from ingestion of contaminated food. This category includes short-term measures like food restriction and food processing and long-term measures such as physical and chemical treatment of soil ([Segal, 1993](#_ENREF_37)). A significant amount of work has been done in this specific field. For example, Alexakhin and Segal independently identified and examined the effects of several agricultural countermeasures to mitigate the impact of the Chernobyl disaster ([Alexakhin, 1993](#_ENREF_6); [Segal, 1993](#_ENREF_37)). Yatsalo et. al created a DSS to assess and choose an agricultural countermeasure strategy to rehabilitate the land after the Chernobyl disaster ([Yatsalo, 2007](#_ENREF_58); [Yatsalo et al., 1997](#_ENREF_59)). Similarly, Fesenko et. al retroactively studied the countermeasures applied in Chernobyl using the ReSCA tool (**R**emediation **S**trategies after the **C**hernobyl **A**ccident) to justify the countermeasures applied ([Fesenko et al., 2010](#_ENREF_17)). Likewise, JRODOS & ARGOS have also created a module, AgriCP, for reviewing the impact of agricultural countermeasures after a nuclear accident ([Gering et al., 2010](#_ENREF_18)). Shinano studied reducing contamination in food grown from farmlands surrounding the Fukushima Daichi plant ([Shinano, 2016](#_ENREF_39)). Interested readers can find more information from the joint IAEA/FAO technical workshop held on the same topic ([IAEA & FAO, 2020](#_ENREF_22)).

**Hydrological countermeasures** are countermeasures that reduce radiation exposure from ingestion of contaminated water or marine fauna. This category includes methods such as water restriction, blending of contaminated & freshwater supplies, wetland liming, and use of activated charcoal in water treatment plants. Interested readers can find more detailed information in the review by Smith et. al on methods to reduce the radiation contamination in water supplies following a nuclear accident ([Smith et al., 2001](#_ENREF_40)). These countermeasures were not considered as hydrological dispersion of radionuclides was not conducted in this study.

**Urban countermeasures** are countermeasures that reduce contamination on surfaces such as walls, pavement, trees, and shrubs. Thus, they primarily target groundshine exposure and reduce exposure through the skin and inhalation of resuspended radionuclides. Some examples include fire hosing surfaces, sandblasting surfaces, deep plowing, topsoil removal, and tree/shrub pruning. While these methods directly address the contamination issue, they also have several disadvantages. These create waste and can negatively impact the environment. Second, these methods can potentially be very disruptive and expensive. EURANOS has an excellent guide to urban countermeasures, albeit focused on Europe, which can be adopted modified for other countries ([Brown et al., 2007](#_ENREF_10)).

Finally, **medical countermeasures** aim to reduce effective radiation exposure by using drugs such as prophylactics and other medical procedures. These can be used before expected exposure or even after the person is exposed. The most popular medical countermeasure used is Potassium Iodine which protects the thyroid gland from I-131. Some other examples (with their use) are calcium gluconate (Sr-90, Ra-226), sodium bicarbonate (U-235), Prussian blue (Cs-137, TI-201), melatonin (general), and genistein (general). Other methods include gastric lavage and stem cell transplantation. Interested readers can read more in the review by ([Arora et al., 2010](#_ENREF_9)).

# Food Guideline levels

The calculated guideline is shown in Table 11 below, with the lowest GL level for each radionuclide in bold.

Table 11: Guideline values for iodine contamination of food

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **I-131** | **I-132** | **I-133** | **I-134** | **I-135** |  |
| **Adult Dose Factor (Sv/Bq)** | 2.20E-08 | 2.90E-10 | 4.30E-09 | 1.10E-10 | 9.30E-10 |  |
| **Guideline Level (Bq /kg)** | **681** | 51652 | 3483 | 136173 | 16106 |  |
|  | | | | | | |
|  | **Cs-134** | **Cs-134m** | **Cs-135m** | **Cs-136** | **Cs- 137** | **Cs-138** |
| **Adult Dose Factor (Sv/Bq)** | 1.90E-08 | 2.00E-11 | 1.90E-11 | 3.00E-09 | 1.30E-08 | 9.20E-11 |
| **Guideline Level (Bq /kg)** | **788** | 748951 | 788370 | 4993 | 1152 | 162816 |
|  | | | | | | |
|  | **Sr-89** | **Sr-90** | **Sr-91** | **Sr-92** |  | |
| **Adult Dose Factor (Sv/Bq)** | 2.60E-09 | 2.80E-08 | 6.50E-10 | 4.30E-10 |
| **Guideline Level (Bq /kg)** | 5761 | **535** | 23045 | 34835 |

Table 12: Food guideline used in this study to select potential foods to restrict

|  |  |  |
| --- | --- | --- |
| **Foods** | **Iodine median Contamination (Bq/ kg)** | **Cesium median Contamination**  **(Bq/ kg)** |
| **Acidic Cheese** | 53.55 | 7.46 |
| **Beef** | 0.45 | 19.97 |
| **Butter** | 30.51 | 3.00 |
| **Chicken** | 0.22 | 5.39 |
| **Condensed Milk** | 96.87 | 29.06 |
| **Cream** | 44.82 | 9.23 |
| **Eggs** | 106.55 | 5.53 |
| **Fruits** | 110.33 | 1.48 |
| **Lamb** | 0.021 | -- |
| **Leafy vegetables** | 18286.37 | 8604.48 |
| **Milk** | 69.66 | 12.86 |
| **Other Veg** | 28.59 | 0.48 |
| **Potato** | 56.97 | 0.47 |
| **Rennet Cheese** | 4.79 | 7.81 |
| **Root vegetables** | 72.12 | 0.95 |

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