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Chernobyl heritage and the E40 trans-Europe waterway

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ACRO | 138 rue de l'Eglise – 14200 Hérouville St Clair – France | (+33) 2 31 94 35 34 | acro.eu.org | acro@acro.eu.org

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Association pour le Contrôle de la Radioactivité dans l'Ouest
138, rue de l'Eglise
14200 Hérouville Saint-Clair
France
www.acro.eu.org
phone: +33 (0) 2.31.94.35.34 / email: acro@acro.eu.org
SIRET 950 369 868 00027 | APE 7120 B

Authors	David Boilley, Ala Pigrée, and Pierre Barbey
Cover picture	Pripyat river © Olga Kaskevich

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Summary

The E40 waterway aims to connect the Black Sea to the Baltic Sea, via the Dniepr and Prypiat rivers. But, the whole Dnieper watershed is contaminated by 1986 Chernobyl accident. Furthermore, the Prypiat crosses the Chernobyl Exclusion Zone and passes immediately next to the Chernobyl nuclear power plant. The present study aims to give a first evaluation of the radiologic impact of the construction and maintenance of the E40.

The two important radioelements from a public health perspective are cesium-137 and strontium-90. Cesium-137 binds to clay sediments while strontium-90 is more mobile. In addition, the element americium-241, the daughter nucleus of plutonium-241, is highly toxic and has an increasing contribution that is expected to dominate the radiological impact in the future.

There are two IAEA radiological hotspots at risk. The Pripyat River floodplain within the Chernobyl exclusion zone becomes a threat if inundated by dam construction. The Chernobyl cooling pond becomes a threat in case of a breach in the dam that separates it from the Prypiat river. In addition, the Kyiv reservoir is heavily contaminated with Cesium-137 and risks to become another hotspot if the sediments are disturbed.

Based on the risk analysis, construction workers in the Chernobyl Exclusion Zone would be the most exposed: their external exposure could reach doses higher than 10 mSv/y and be close to the European limit fixed at 20 mSv/y. The contamination of drinking water, fish and the use of dredged material as fertiliser in the fields could lead to additional exposure of the population depending on the Prypiat and the Dnieper.

The Aarhus and Espoo conventions, as well as ICRP radiation protection principle, require environmental and radiological studies, a justification of the project and the participation of the stakeholders and the general public in the decision process, which have not been carried out.

Constructing the E40 will have a radiological impact on the construction workers and the population depending on the rivers. The risks to construction workers in the Chernobyl Exclusion Zone are unacceptable. Moreover, the cooling pond and radioactive waste storage sites close to the Prypiat river have not been decommissioned. Last but not least, the IAEA recommends to leave the contaminated sediments in the Kyiv reservoir in place, to avoid exposure of the population downstream. In this context the construction of the E40 is not feasible.

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1. Introduction

The International Waterway E40 aims to link the Baltic and Black Seas running from Gdansk via Polish, Belarusian and Ukrainian territory down to Kherson. See Fig. 1. Currently the route is navigable only from the Black Sea up to the Polish-Belarusian border. The Dnieper is navigable for large vessels (class V waterway). It only requires some dredging work and modernisation of the locks. The main challenge is to modernise the other sections. Belarus emphasises the importance of E40 and has proposed a programme of modernisation of hydro-technical infrastructure and transport channels.

Figure 1: *Map of the E40 waterway project. Extracted from [UNECE2012].*

There are very few documents available on this huge project. Information mainly comes from a Feasibility Study Report coordinated by the Maritime Institute in Gdansk [MIG2015]. To our knowledge, no exhaustive environmental impact study has been done so far, except an independent study of the impact on hydrological and environmental conditions of neighbouring rivers and wetlands [FZS2019]. The E40 waterway is planned through Polesia that is Europe's largest wilderness area. Its development is likely to pose a high risk of degradation of the most natural stretches of Pripyat in Pripyatsky National Park (Прыпяцкі нацыянальны парк). In addition, a part of the project includes modernisation of the Pripyat river that runs very near the Chernobyl nuclear power plant and through the Polesia State Radioecological Reserve (Палескі дзяржаўны радыяцыйна-экалагічны запаведнік) in the Chernobyl Exclusion Zone that is highly contaminated by various radioelements. Figures 2, 3 and 4 report the surface ground deposition of cesium-137, strontium-90 and plutonium-239+240 that dominate the radioactive contamination. Other maps are available in the annex at the end of the document. Note that plutonium-241 decays into americium-241 that presently reaches significant levels. Downstream of this region, approximately 8 million Ukrainians drink water from the Dnieper River, and as many as 20 million eat foods irrigated with Dnieper River water.

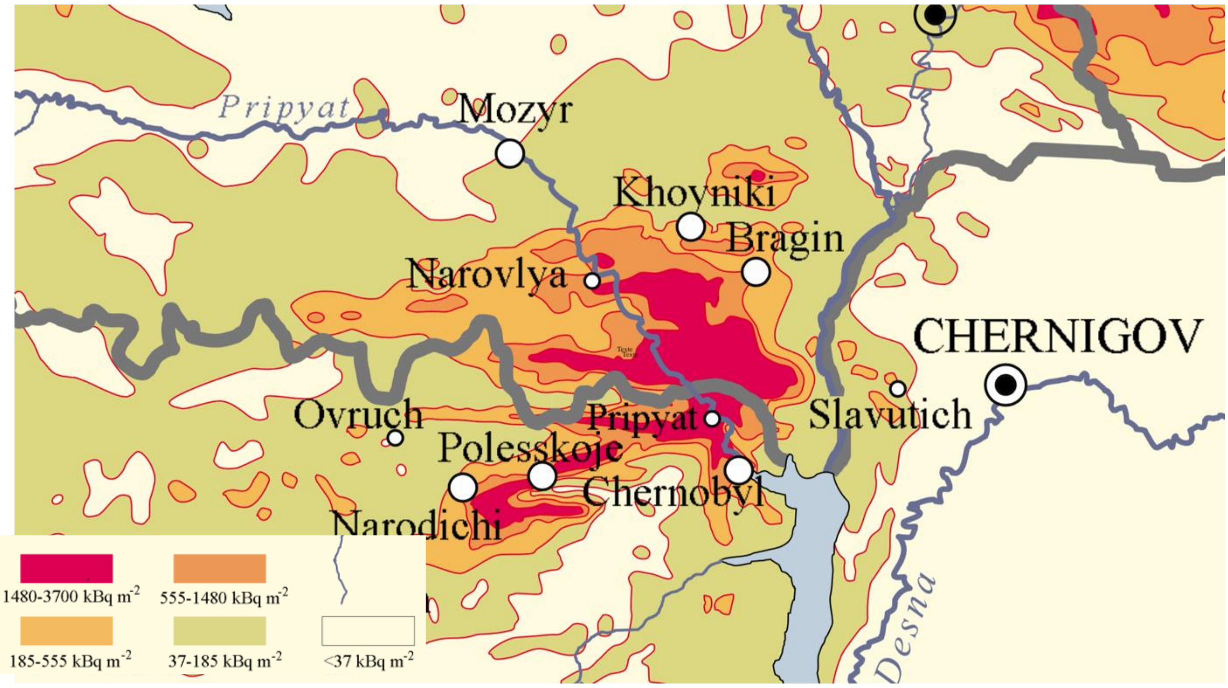

Figure 2: *Map surface ground deposition of cesium-137 along the Pripyat river near the Chernobyl nuclear power plant. Extracted from [UNSCEAR2000].*

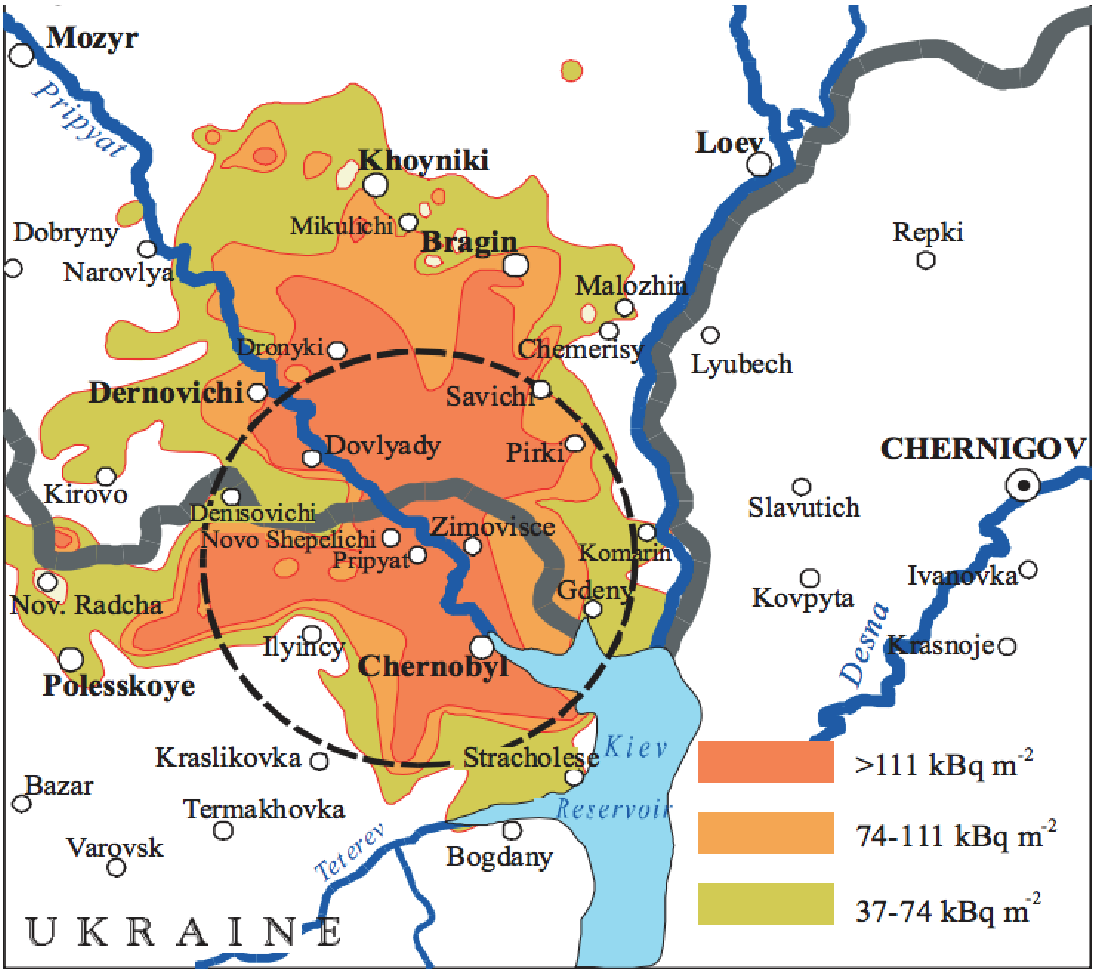

Figure 3: *Map surface ground deposition of strontium-90 along the Pripyat river near the Chernobyl nuclear power plant. Extracted from [IAEA2006b]*

Figure 4: *Map surface ground deposition of plutonium along the Pripyat river near the Chernobyl nuclear power plant: areas (orange) where the surface ground deposition of plutonium-239,240 exceeds 3.7 kBq/m*^{2}*. Extracted from [IAEA2006b].*

Therefore, a radiological impact assessment of the E40 waterway project should have been carried out by its promoters and supporters and should have been submitted to the stakeholders and to the public, as required by the Aarhus convention[1] on access to information, public participation in decision-making and access to justice in environmental matters. Such a consultation should be transboundary, as required by the Espoo convention[2], accepted by Belarus and ratified by Poland and Ukraine[3]. Since this has not been done so far, the main purpose of the present report is to provide a first evaluation of the radiological impact of the E40 waterway project.

The UN "Blue Book" identifies the bottlenecks in the network of European main inland waterways of international importance, but never mention radioactivity for the E40: the only problem seems to be a low maximum draught [UNECE2017].

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[1] https://www.unece.org/fileadmin/DAM/env/pp/documents/cep43e.pdf

[2] https://www.unece.org/env/eia/about/eia_text.html

[3] https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-4&chapter=27&lang=en

2. State of the radioactive contamination along the E40 route

This section is mainly inspired by Refs. [IAEA2006a, IAEA2006b, Onishi2007].

2.1. The whole Dnieper watershed is contaminated by Chernobyl accident

The Chernobyl nuclear power plant site lies along the Pripyat river in northern Ukraine within the Dnieper River basin and very close to the border with Belarus. The Chernobyl accident on 26 April 1986 released large amounts of radioactivity into the air and into the cooling pond. The pond, now separated from the Pripyat River by a dam, was heavily contaminated during the accident and by subsequent dumping of radioactive liquid waste. Radionuclide fallout was concentrated in the upper Dnieper watershed in Russian and Belarusian territory and in the whole Pripyat watershed. See maps in annex. Many research and remediation efforts have been focused on minimising radionuclide transfer from the Chernobyl Exclusion Zone to the nearby Dnieper River to reduce radiological risks from water use.

The Dnieper River, the largest river in Ukraine, supplies 64 percent of Ukraine's water needs and is widely used for irrigation. About 30 percent of the water consumed in the Dnieper River Basin is used for agriculture (Irrigation water taken from the Dnieper is almost 4 700 million m^3 annually). The Dnieper irrigates about 1.6 million of the 2.6 million hectares (ha) of land in Ukraine (mid-1990s).

The largest areas of irrigated lands are used for growing grain (rice, winter and spring wheat, and barley) and fodder (corn, peas, sugar beet, clover, and alfalfa). Vegetables (potatoes, tomatoes, cucumbers, cabbage, onions, carrots, red beets…) and fruits are grown less in the irrigated areas.

Kyiv Reservoir is the uppermost reservoir of the Dnieper cascade, which consists of 6 reservoirs, and the most contaminated by the 1986 accident. As a result, fish in Kyiv Reservoir have the greatest contribution to the individual effective exposure dose of the population.

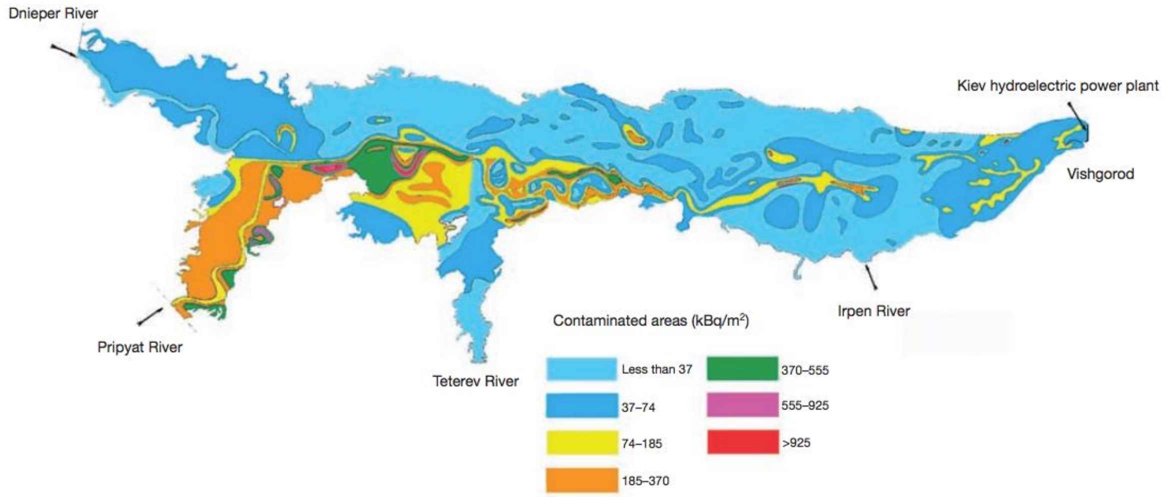

Figure 5: *Cesium-137 in the bottom sediments of the Kyiv reservoir. Reproduced from [IAEA2006b]*

2.2. Characteristics of the environmental contamination

2.2.1. Main radioelements

Nowadays, cesium-137 (^{137}Cs, half-life 30 years) and strontium-90 (^{90}Sr, half-life 29.1 years) are the most important radioelements from an environmental and public health perspective[4]. According to the IAEA [IAEA2006a], the estimated inventories in the main rivers and tributaries of the Dnieper River catchment area are about 19 PBq of ^{137}Cs and 2.2 PBq of ^{90}Sr (1 PBq = 10^{15} Bq). These two elements behave differently in the environment and the human body. Cesium behave like potassium and strontium like calcium (hence strontium is a 'bone seeker'). Thus, cesium has an affinity for clay minerals frequently occurring in natural soils. Binding of cesium to soil retards its lateral and vertical migration. Strontium is less firmly bound to mineral sites and is consequently more mobile in the environment.

Cesium-137 tends to become fixed to clay sediments, which are deposited in the deeper sections of the reservoirs, especially the Kyiv reservoir. Very little ^{137}Cs flows through the cascades because of this process and consequently the present concentration entering the Black Sea is indistinguishable from background. However, although ^{90}Sr concentration decreases with distance from the source (mainly due to dilution), about 40 - 60% passes through the cascade and reaches the Black Sea.

As depicted in Figure 4 and in annex maps, plutonium contamination also affects the Chernobyl exclusion zone. Plutonium-241 decays into americium-241 with a half-life of 14 years. Americium-241 (^{241}Am) is an alpha-gamma emitter with a half-life of 432 years that gradually accumulates in the environment due to the differences in half-lives. In turn, as a result of the alpha-decay of ^{241}Am, the formation of Neptunium-

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[4] Cesium-137, with its short-lived daughter, ^{137m}Ba, emits beta and gamma radiation; ^{90}Sr, with its short-lived daughter, ^{90}Y, emits strong beta radiation.

237 (^{237}Np) with a half-life of $2.1x10^6$ years is taking place at a slower pace. These are all highly toxic radionuclides, classified as the most dangerous with two harmful effects: the radioactivity and the heavy metal poison effects. Americium-241 is more dangerous when inhaled than when ingested and it accumulates in the liver and the bone marrow, after being transported by the blood. It has a considerably higher damaging effect, than ^{90}Sr and ^{137}Cs, especially in case of internal contamination.

Maximum plutonium concentrations observed in the Pripyat River in the first days after the accident were about 370 mBq/L (10pCi/L) but decreased to 7,4 mBq/L (0.2 pCi/L) by August 1986. They were four orders of magnitude lower than the maximum permissible level of soluble plutonium for drinking water. Up to 98% of the plutonium in the waterbodies was associated with suspended and bottom sediments. Therefore, the emphasis of the field and experimental studies on radioactive contamination of water bodies was on strontium-90 and cesium-137 [PLN1994].

Americium-241 has been measured in aquatic biota and its concentration is forecasted to increase until 2070 where it is expected to become the most important dose-related factor. Its mobility in the water environment is higher than in the soil, which facilitates its rapid incorporation into the trophic nets of water bodies [Golubev2011]. However, americium is ignored by most of the grey literature on the radiological impact of the Chernobyl accident and in dose assessments. Considering the timeframe of the E40 project, it has to be taken in account.

Moreover, so-called hot particles, that are small in size but are intense sources of radiation, were dispatched by the accident. Although there were detected in at least 11 countries, most of them fell down in the vicinity of the Chernobyl nuclear power plant: within the 30-km exclusion zone, up to 10^5 particles per square metre were observed. The total mass of small radioactive particles emitted from the reactor was probably 6-8 tonnes. Two types of micro-particles were identified: the majority had a composition very similar to that of fuel in the core and were probably just fragments of that fuel; other particles of higher specific activity with only one or two radionuclides [Sandalls1993]. Sizes of deposited fuel particles ranged from hundreds of microns to a fraction of a micron. Deposition of fuel particles diminished with increasing distance from the reactor site. In soils, fuel particles had virtually disintegrated within 10 years. The opposite situation was observed in the cooling pond of the Chernobyl NPP, where the vast majority of long-lived radioactivity was deposited as fuel particles: the majority of ^{90}Sr activity still occurs in the form of fuel particles. However, at the present time these conditions are changing since the pond is being drained and a significant part of the sediments is being exposed to the air. This significantly enhances the dissolution rate of fuel particles in exposed sediments, and hence, it is anticipated that the mobility and bioavailability of radionuclides will increase with time. Model calculations have shown that in newly exposed sediments fuel particles will be almost completely dissolved in 15-25 years, while in parts of the pond which remain flooded, fuel particle dissolution will take about 100 years [Onishi2007, Beresford2016].

2.2.2. Maps and databases

In Japan, following the Fukushima accident, official contamination maps were made available on line[5], as well as database collecting measurement results from grassroot movements[6]. There are also many local maps with a smaller mesh drawn by local authorities and/or citizen. This is not the case in Belarus and Ukraine where detailed contamination maps are not available on line. Measurement data of the official

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[5] https://ramap.jmc.or.jp/map/eng/

[6] https://en.minnanods.net/

monitoring are not available neither. A few data related to some specific studies could be found in scientific publications, but they are too scarce to evaluate the impact of the radioactive pollution.

The Aarhus convention, accepted by Belarus and ratified by Ukraine[7], requires that *"each Party shall ensure that environmental information progressively becomes available in electronic databases which are easily accessible to the public through public telecommunications networks."* Moreover, *"each Party shall, at regular intervals not exceeding three or four years, publish and disseminate a national report on the state of the environment, including information on the quality of the environment and information on pressures on the environment."* Belarus and Ukraine should comply to their international commitments and publish all available data on the radioactive contamination.

2.2.3. Contamination along the Dnieper cascade

The 6 reservoirs in the Dnieper River were significantly affected by both atmospheric fallout and input from the contaminated zone. These reservoirs are essentially huge sedimentation tanks as the slow passage of water through the cascade creates ideal conditions for accumulation of radionuclides and other pollutants in all components of the ecosystem of the reservoirs. As a consequence, the cesium-137 concentration in the river water is reduced by two orders of magnitude along the way from the upper part of the Dnieper cascade to the Dnieper mouth. For the entire post-accident period in the ecosystem of the reservoirs and the Dnieper–Bug estuary, more than 99% of the cesium-137 that entered the Pripyat and upper Dnieper Rivers was removed on to sediments. See Fig. 3.

Owing to the higher mobility of strontium-90, the degree of its deposition (50–70%) within the Dnieper reservoirs is significantly lower than that of cesium-137. One of the main reasons for the non- exchangeable behaviour of strontium-90 from the water column is its strong chemical fixation in the shells of growing molluscs (strontium is the chemical analogue of calcium). This is why the maximum content of strontium-90 in the bottom sediments was observed on the sites of mollusc colonies and in sediments containing shell debris.

The strontium-90 concentration in the Dnieper River water is reduced by a factor of 1.5–3 from Chernobyl to the Kakhovka reservoir (according to data averaged over a year). This is determined mainly by the dilution of Pripyat waters with clean waters from the upper Dnieper River and the side tributaries. The mixing action of the Dnieper reservoirs as the strontium-90 passes along the cascade becomes apparent by the gradual reduction of the peak concentrations and by the offset of this peak with time. Even very high peak concentrations of strontium-90 in the waters of the Pripyat River and the Kyiv reservoir are suppressed by the time the peak reaches the Kremenchug reservoir, and in the Kakhovka reservoir one may observe only gradual fluctuations in the concentration of strontium-90. See Fig. 6.

Most of the suspended sediment released from the river to the reservoir is deposited on the bottom of the upperparts of the reservoirs. However, some of the finest particles (usually with a size of less than 50 µm) could be carried away by flow to the next reservoir and on down to the lower parts of the cascade. A considerable flux of radionuclides into the lower reservoirs has been observed during storms and in periods of high water. Up to 50% of the cesium-137 influx to the reservoirs is carried with the fine sediment

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[7] https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-13&chapter=27&clang=_en

particles, and up to 80% of the river suspended sediments are deposited in the upper parts of the cascade [PNL1994].

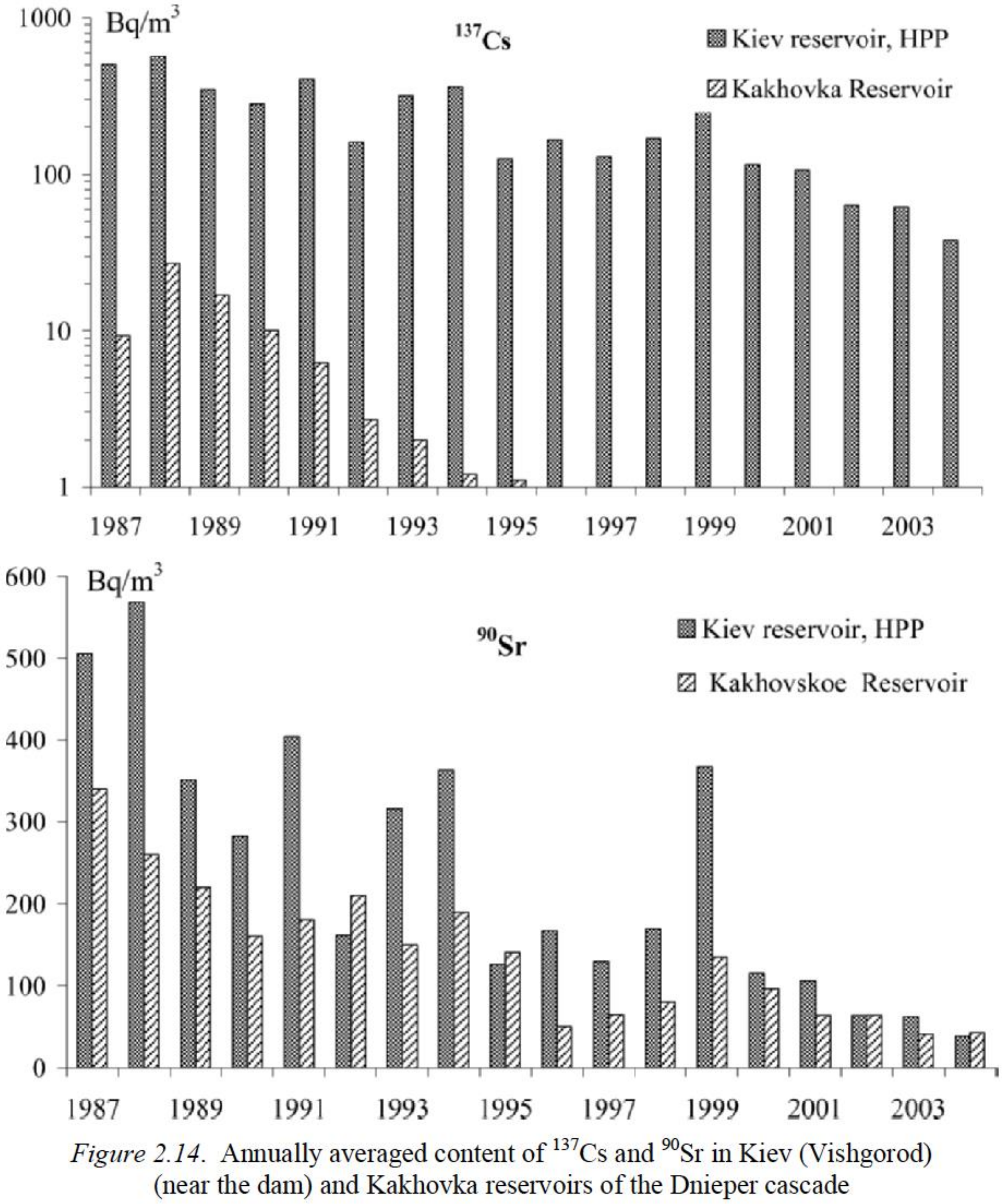

Figure 6: *Annually average content of ^{137}Cs and ^{90}Sr in Kyiv (Vishgorod, near the dam) and Kakhovka reservoirs of the Dnieper cascade. Reproduced from [Onishi2007].*

Plutonium isotopes transported by the rivers down to the Black Sea were measured in the sediments of the irrigation channels of Northern Crimea [Polikarpov2015]. However, there are very few studies on the transfer of plutonium and americium in the Dnieper watershed. Reviews ignore these radioelements. There are relatively few data of americium-241 accumulation in aquatic biota.

2.3. Impact of the flooding of the Pripyat floodplain and remediation measures

Within the catchment area of the Dnieper River basin, an area of about 85 000 km^2 has a surface contamination of cesium-137 above 37 kBq/m^2. The floodplain along the Pripyat River is highly contaminated from the Chernobyl accident, especially with strontium-90, where concentrations exceed 4 000 kBq/m^2 over large areas. See maps in annex. This zone is regularly inundated, especially during spring floods. Moreover, some of the waste burial sites are located within the floodplain. IAEA considers the Pripyat floodplain area within the Chernobyl exclusion zone as a transboundary hot spot with a current impact and a greater impact during times of high flooding [IAEA2006a].

The Pripyat river is surrounded by marshes, and a large number of closed lakes, oxbow lakes, in which the concentration of cesium-137 (and to a lesser extent of strontium-90) in water and fish is much higher than in the nearest rivers. These are the most contaminated areas after the Chernobyl accident. These closed lakes and their inhabited surroundings are considered as actual local hot spots by the IAEA. The radioelements concentrations do not significantly decrease with time, and in many lakes still exceed the permissible levels for drinking water and especially for fish. In case of flooding, there are some additional transfers of contaminants to the Dnieper River basin. At times of flooding of the Pripyat floodplain, dose rates increase somewhat due to washout of strontium-90.

The peaks of strontium-90 activity in the reservoirs of the Dnieper cascade seen in Fig. 6 were caused by flooding of the most contaminated floodplains in the Chernobyl Exclusion Zone. For instance, flooding of the Pripyat caused by ice dams in the river in the winter of 1991 led to temporary but significant increases in strontium-90 concentrations but did not affect cesium-137 concentrations. Concentrations of strontium-90 increased from about 1 to 8 Bq/L for a 5 –10 days period during the winter of 1991. Similar events took place during the summer rainfall in July 1993, the winter flood of 1994, and the high spring flood in 1999.

During the January 1991 flood, the strontium-90 concentrations reached 9 – 11 Bq/L (250-300 pCi/L) at Yanov Bridge located at the downstream end of the floodplain, exceeding the local drinking water limit of 3.7 Bq/L (100 pCi/L). The total amount of strontium-90 transported by the Pripyat River increased from 18 to 370 GBq (0.5 to 10 Ci, 1 GBq = 10^9 Bq) per day, and the total amount of strontium-90 released from the floodplain through the Pripyat River into the Kyiv Reservoir during this period exceeded 3 TBq (90 Ci, 1 TBq =10^{12} Bq). Fortunately, the impact of this release to the Kyiv Reservoir was reduced thanks to dilution of the Pripyat River water by the cleaner Dnieper River water and dispersion of contamination in the reservoir. As a result, the maximum concentration on the way from the Pripyat River mouth to the Kyiv Reservoir dam (a distance of more than 80 km) diminished from 7.4 to 1.1 Bq/L (200 to 30 pCi/L) [PNL1994].

Consequently, in 1993 a dyke was constructed around the highly contaminated floodplain on the left bank of the Pripyat, just upstream of Chernobyl Nuclear Power Plant. This prevented flooding of this area and the IAEA considers that this proved effective in reducing strontium-90 wash-off to the river during flood events. However, in July-August 1993, heavy rainfall over the Pripyat River catchment in Belarus and Ukraine caused severe flooding, significantly raising strontium-90 concentrations in the river, triggering public concern about radionuclide levels in the river and an emergency response from the Ukrainian government. The peak strontium-90 concentration in the Kyiv Reservoir was 0.44 Bq/L (12pCi/L). It would have been much higher without the 10-km dyke [PNL1994]. No impact is given about the construction work of the dykes.

In 1999, significant quantities of strontium-90 were again washed out into the cascade from regions of significantly contaminated flood prone sites beside the Pripyat River in the near zone of the Chernobyl nuclear power plant. The signal of radioactively contaminated waters was followed to the Kakhovka reservoir during 1999. Owing to the high river flow rates in March–June 1999, fast movement of the contaminated water down the Dnieper River was observed, and, by mid-July 1999, this front had reached the Black Sea. The maximum value of ^{90}Sr activity measured during that period in the Dnieper River at Novaya Kakhovka was 0.3 Bq/L, being three to four times higher than the levels of contamination observed during the previous years. This observation further demonstrates the flood prone territories of the Pripyat River and other sources of contamination in the near zone of the Chernobyl nuclear power plant remain the main source of radioactive contamination of the Dnieper waters.

A second dyke was constructed on the right bank of the Pripyat in 1999. The annual average strontium-90 activity concentration in the Kyiv reservoir water, however, was below 1 Bq/L in all years from 1987 onwards.

It is worth noticing that, according to the IAEA, numerous countermeasures put in place in the months and years after the accident to protect water systems from transfers of radionuclides from contaminated soils were, in general, ineffective and expensive and led to relatively high exposures of the workers implementing the countermeasures [IAEA2006b].

2.4. Radiological hot spots

The IAEA expert group has selected a list of hot spots that require a special attention [IAEA2006a]. Among them, the following ones might be affected by the construction work associated to the E40 waterway project: the Pripyat River floodplain within the Chernobyl exclusion zone, the Chernobyl cooling pond, the Chernobyl exclusion zone as a whole (both in Belarus and Ukraine), highly contaminated areas outside the Chernobyl exclusion zone, especially closed lakes and ponds in Belarus, the Russian Federation and Ukraine and, contaminated sediments in the Kyiv reservoir.

According to the IAEA, the hottest spot in the Chernobyl affected area along the Pripyat River is the heavily contaminated floodplain upstream of the Chernobyl nuclear power plant (within a distance of 10 km upstream of the Yanov bridge) near the city of Pripyat. The floodplain can be inundated by a flood of 25% probability (on average once per four years).

The Chernobyl cooling pond is a threat to the Pripyat river in case of a breach in the dam, leading to the release of a large amount of contaminated water and sediment. The total inventory of radionuclides in the pond is in excess of 200 TBq [IAEA2006b]. According to the IAEA [IAEA2006a], the results of the simulation of a dam break can be compared with the results of the last large flood in 1999. This pond should be decommissioned and the heavily contaminated sediments removed. Decommissioning has started in 2013.

Note that the IAEA's analysis shows that the sediments in the Kyiv reservoir are not considered as a hot spot because the contamination is largely held in bottom sediments, which are not available for significant uptake into biota under normal or flood conditions. However, dredging works were not considered in this analysis. The map of cesium-137 in the bottom sediments of the Kyiv reservoir is given in Fig. 5. Depending on the dredging place, the sediments could be classified as a potential hot spot.

2.5. The IAEA's conclusions and recommendations

Regarding the contaminated bottom sediments in the reservoirs of the Dnieper River, the IAEA notes that they do not influence significantly the secondary radioactive contamination of the water and aquatic organisms. Almost all the cesium-137 washed out from contaminated areas is immobilised in bottom sediments within the reservoirs of the Dnieper River. The impact of these sediments is low and will decline further with decay and further deposition of sediments on top of the contaminated sediments. Thus, the IAEA considers that the general rule for exploitation of the reservoirs (mainly Kyiv) is to minimise scooping and mechanical operations at the places with increased bottom contamination. The overall strategy should be to leave these sediments as is and avoid processes that will lead to their resuspension [IAEA2006a].

Regarding the lakes with no regular inflows and outflows, they still present a radiological problem that will continue for some decades. There is a need for improved understanding of processes occurring within these lakes, especially transfer to fish. There is also a need for improved understanding of the strontium-90 inventory in sediments and strontium fixation processes. Strontium-90 becomes more important with time because of its greater mobility.

Here are some of the IAEA recommendations issued in 2006 [IAEA2006a]:

- A diversionary canal should be constructed along the Belarus–Ukraine border between the settlements of Krasne and Zimovische to prevent inundation of the heavily contaminated areas on the Pripyat River's left bank.
- The heavily contaminated Chernobyl cooling pond should be safely decommissioned.
- Technical measures should be taken to prevent significant radionuclide dispersion from the sites of temporary radioactive waste storage in the floodplain of the Pripyat River.

More than 10 years on, to our knowledge, none of these recommendations have been achieved. The cooling pond decommissioning has started in 2013 and the completion date in unknown [SSEChNPP2019].

3. Construction and maintenance works related to the E40 waterway

3.1. Description

The entire length of the Dnieper Cascade is of water class V and no bottlenecks within the Ukrainian section of the E40 waterway are reported. The main problems consist of a very poor technical condition of the locks and route markings and the presence of local shoal patches. This would require technical measures, such as dredging and reducing the draught of vessels. The feasibility report [MIG2015] mentions that about 68 000 m^3 of dredging work would be necessary every year in the Kyiv reservoir.

The Pripyat River flows slowly, meandering through wide floodplains, frequently breaking into and rejoining branches over 250 km. The large homogeneous floodplain of the river consists of oxbow lakes, marshes, bush, and coppice. The river freezes in mid-December and thaws in late March. The goal of the project is to create conditions to ensure the permanent parameters of the fairway during the entire shipping season for fully loaded vessels.

From the mouth of the Pripyat river (in the flooded riverbed of the Dnieper River by the Kyiv Reservoir) to the Ukrainian-Belarusian border, the length of the waterway along the Pripyat River is 64.5 kilometres. Practically the whole section is artificial; it underwent a number of changes, due to the construction of the Kyiv Reservoir, the construction of the cooling reservoir for Chernobyl power plant, as well as the construction of protective structures along the river after the disaster of Chernobyl and in connection with the operation of the waterway. A characteristic feature of the estuary section of the Pripyat river is a constant flow of suspensions and movement of sediment material, resulting in the formation of peninsulas and islands along the river, followed by sanding fairways. This process is particularly intense during the spring floods. The feasibility report [MIG2015] mentions requirements to deepen the river Pripyat on 13 shallows and the annual volume of dredging in the Ukrainian part of the river is 580 000 m^3.

Upstream, in the Belarussian territory, the river is mostly flowing freely. It meanders and frequently breaks into oxbow lakes and rejoining branches. In order to maintain the navigability, the necessary works consist of annual dredging, strengthening of river banks, and cleaning of riverbed. In order to upgrade the navigation conditions, additional dredging works, strengthening of the river banks, cleaning of riverbed will be necessary, as well as alignment and straightening of some river sections. This will also require the construction of additional dams and locks.

The feasibility report [MIG2015] mentions zero lock between the Ukrainian border and Mikachevitchy (Мікашэвічы) in Belarus. However, in a presentation, the secretary of the Commission on the development of the E40 waterway on the Dnieper-Vistula section mentions that 6 or 7 dams will be necessary to ensure the control of the Pripyat river: see figure 7. In particular, one dam should be built near Narowlia (Нароўля) at the entrance of the the Polesia State Radioecological Reserve (Палескі дзяржаўны радыяцыйна-экалагічны запаведнік) and another one just upstream of Pripyat city, within the Chernobyl exclusion zone [E40Com2015].

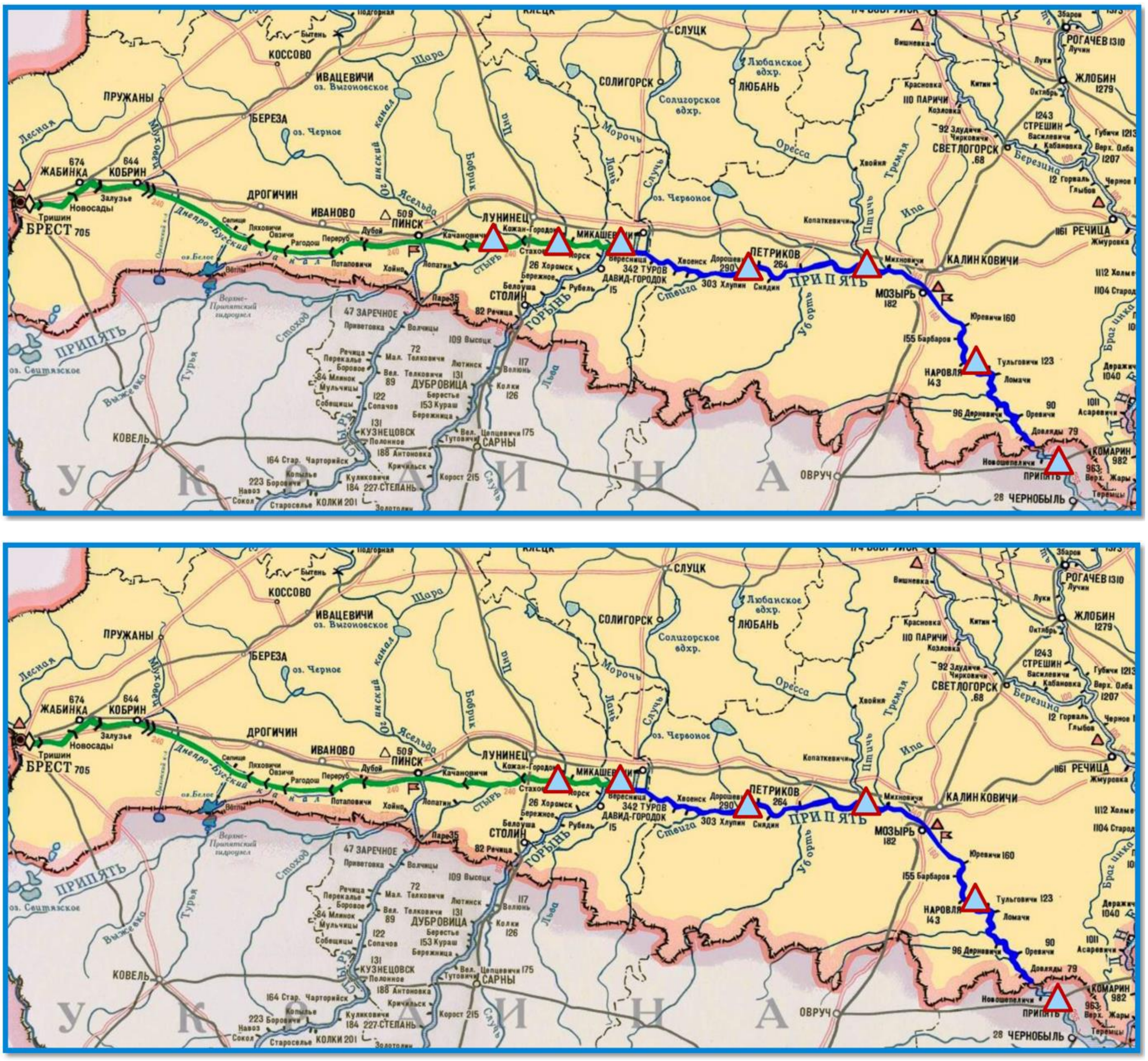

Figure 7: *Location of the dam (triangles) according to Ref. [E40Com2015]: variant 1 and 2. Reproduced from [E40Com2015].*

Dam construction, together with works necessary to enlarge and align the river, mean dredging a large amount of contaminated soils and building other facilities such as roads. Once the infrastructures are constructed, maintenance work is still necessary to maintain navigability. The total volume of dredging works on the Dnieper-Bug channel and the Pripyat river (the route length - 315.1 km), required to ensure a guaranteed depth of 2.6 m, will be approximately 6.3 million m^3. The part of the Pripyat river that runs through the Chernobyl exclusion zone has a length of about 50 km.

The feasibility study explains that the construction of cargo handling port is planned in the vicinity of Nizhniya Zhary (Ніжнія Жары) in Belarus, along the Dnieper River. The port could accept vessels with maximum draft of up to 3.0 m, and smaller feeder vessels would transport the cargo further transhipment. The site lies in between the Polesia State Radioecological Reserve and the Mizhrichynskyi Regional Landscape Park in Ukraine (Міжрічинський регіональний ландшафтний парк). The section of the waterway in the Upper Dnieper River from the mouth the Pripyat up to this planned port is situated within the area of water accumulation of the Kyiv Reservoir. No other information is given on the extend of the port.

From a purely radiological point of view, the most complicated section is in the vicinity of the Chernobyl nuclear power plant and all through the Chernobyl exclusion zone as it is the most contaminated zone along the E40 project. According to the feasibility study [MIG2015], in the vicinity of the Chernobyl plant, reconstruction of the international waterway E40 requires the complete decommissioning of the cooling pond, which can take years. Moreover, the study warns that *"if no compensatory works are implemented, deep-water transport artery is impossible to be created"*, but does not say anything on the *"compensatory work"*.

Before detailing the potential radiological impact of such works, it is worth stressing that dam construction within the Chernobyl exclusion zone will induce a permanent flooding of very contaminated land, marshes, lakes and annihilate some of the countermeasures and remediation efforts to reduce the impact of flooding. Works necessary to enlarge and align the river, will also induce removing contaminated soils, which will contaminate the rivers. Last but not least, annual dredging goes against the IAEA's recommendation to leave bottom sediments in place.

3.2. Dredging

As sediments accumulate at the bottom of the rivers and channels, regular dredging work is necessary to maintain the navigability of the waterways. The feasibility study [MIG2015] gives an estimate of the annual dredging work once the E40 waterway is built or rehabilitated:

- At the Kyiv Reservoir four most sanded sections of the waterway are indicated. The annual size of the dredging material is 68 000 m^3.
- The section of the waterway in the Upper Dnieper River from the mouth of the Pripyat up to Niznij Zary village is situated within the area of water accumulation of the Kyiv Reservoir. 41 annual dredging works are necessary in the six most sanded places. The total amount of dredged sediments is expected to be 480 000 m^3/y.
- The Ukrainian part of the Pripyat river has to be deepened on 13 shallows. The annual volume of dredging 580 000 m^3.
- For the Belarussian part of the Pripyat river that goes through the most contaminated part of the waterway route, annual dredged volume of sediments up-stream of Mikachevitchy (Мікашэвічы) is evaluated at about 200 000 m^3. No information is given for the most contaminated part of the Pripyat river.

Fine-grained bottom sediments tend to accumulate contaminants due to their sorptive nature. Given that deep sediment layers are commonly more contaminated than surficial layers, dredging will result in higher surficial contaminant concentrations than before dredging.

The resuspension of anoxic sediment results in alterations in particle water interactions and in desorption of contaminants. Hence, remobilisation of sediment-associated contaminants can occur during natural events, such as storms, or during human activities such as dredging. Dredging leads to the mixing of anoxic sediments with biologically active surface sediment. Moreover, sediment resuspension has been shown to accelerate desorption, partitioning, and bacterial degradation. Of course, dredge-related bioavailability is mainly site-specific and dependent on the degree of contamination, the amount of suspended sediment, the duration of the disturbance and the organism [Eggleton2004].

Resuspension rates have been reported ranging from less than 0.1 % to over 5 % as it depends heavily on the specific nature of the dredging operation. Then sediment resuspended by dredging operations is available for transport by ambient and induced currents. Modelling should include an initial mixing zone where the induced currents are more important than the ambient currents, a near-field zone with a sediment plume and a far-field zone [ERDC2008].

Modelling of the impact of dredging is extremely complicated as it depends on many parameters that can vary from site to site. Work conducted on the impacts of sediment resuspension during dredging activities has focused on contaminant bioavailability. Little work has been conducted on the processes affecting contaminant release. It is apparent from the data reviewed that there is a significant gap in our understanding of the processes and factors that control the release and bioavailability of contaminants during sediment disturbance events [Eggleton2004]. Specific studies are necessary to estimate the transfer to fish resources.

No information is given about the disposal of the sediments dredged from the waterway. Private information sources mentioned that in Ukraine the sediments are disposed nearby the Dnieper without any specific protection.

Both temporal and spatial characteristics of the entire project should be factored into the evaluation of short-term release and the impact of such release on long-term consequences and risk.

3.3. Main radiological impact

The main radiological impact will be during the long construction work within the Chernobyl exclusion zone. Workers are expected to receive the highest radiation exposure. Part of the contamination will be carried by the Pripyat river down to the Dnieper, increasing the radiological impact through the various aquatic pathways. As already mentioned, cesium-137 will be fixed in the upper-sediments of the Kyiv reservoir, while strontium-90 will affect the whole Dnieper cascade. New layers of sediments contaminated by cesium-137 will be resuspended annually during dredging operations.

Up-stream the Chernobyl exclusion zone, dam construction together with works necessary to enlarge and align the Pripyat river will also have a radiological impact but at a lesser level than within the Chernobyl exclusion zone. However, agriculture and fish farming will be highly affected [FZS2019].

No impact is expected on Poland and other European countries.

4 Exposure scenarios and doses

4.1. Radiation protection principles

4.1.2. ICRP principles

The latest recommendations for a system of radiological protection were published in 2007 by the International Commission on Radiological Protection (ICRP) [ICRP2007]. We shall briefly recall here the main points.

Radiation exposure (or exposure in short) is the process of being exposed to both radiation or radionuclides. Radiation exposures are harmful: high doses will cause deterministic effects, often of an acute nature, which only appear if the dose exceeds a threshold value. Both high and low doses may cause stochastic effects (cancer or heritable effects), which may be observed as a statistically detectable increase in the incidences of these effects occurring long after exposure.

Exposures considered here result in low doses for which the increase in the incidence of stochastic effects is assumed in proportion to the increase in radiation dose over the background dose. This is the so-called linear-non-threshold (LNT) model considered by the Commission to be the best practical approach to managing risk from radiation exposure.

The major policy implication of the LNT model is that some finite risk, however small, must be assumed and a level of protection established based on what is deemed acceptable. This leads to the Commission’s system of protection with its three fundamental principles of protection:

- The Principle of Justification: Any decision that alters the radiation exposure situation should do more good than harm.
- The Principle of Optimisation of Protection: The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.
- The Principle of Application of Dose Limits: The total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed the appropriate limits specified by the Commission.

Moreover, the Commission recognises three types of exposure situations which are intended to cover the entire range of exposure situations:

- Planned exposure situations, which are situations involving the planned introduction and operation of sources.

- Emergency exposure situations, which are unexpected situations such as those that may occur during the operation of a planned situation, or from a malicious act, requiring urgent attention.
- Existing exposure situations, which are exposure situations that already exist when a decision on control has to be taken, such as those from past events and accidents.

Emergency exposure situations are obviously not relevant in the present case. Exposure of workers sent to the Chernobyl exclusion zone for activities related to the E40 waterway should be considered as planned exposure situations. However, local people in non-evacuated zones affected by the radioactive contamination are facing existing exposure situations. In this type of situation, protection strategies will often be implemented in a progressive manner over the years with the aim to decrease exposures.

The principles of justification and optimisation apply in all three exposure situations whereas the principle of application of dose limits applies only for doses expected to be incurred with certainty as a result of planned exposure situations.

Justification implies determining whether a planned activity involving radiation is, overall, beneficial to individuals and to society and outweigh the resulting harm. In case of existing exposure situation, introducing or continuing the remedial action should outweigh its cost and any harm or damage it causes. This position may be in conflict with the individual right to health of the Universal Declaration of Human Rights: *"Everyone has the right to a standard of living adequate for the health and well-being of himself and of his family"* [ACRO2019]. It has also been criticized by Anand Grover, Special Rapporteur to UN Human Rights Council, who noted in his report on Fukushima: *"ICRP recommendations are based on the principles of optimisation and justification, according to which all actions of the Government should be based on maximizing good over harm. Such a risk-benefit analysis is not in consonance with the right to health framework, as it gives precedence to collective interests over individual rights. Under the right to health, the right of every individual has to be protected. Moreover, such decisions, which have a long-term impact on the physical and mental health of people, should be taken with their active, direct and effective participation"* [HRC2013].

Thus, the radiological impact study of the E40 waterway project that remains to be done by its promoters and supporters should include its justification in comparison to other means of transportation such as railroad. It should also explain how the optimisation principle is applied, and provide individual dose assessment of the most exposed people to guaranty that each individual is sufficiently protected.

ICRP Publication 111 provides guidance on the application of the Commission's recommendations to the protection of people living in long-term contaminated areas after a nuclear accident [ICRP2009]. Although it does not explicitly consider the case of a large project that significantly affects the radiological impact of the existing contamination, the ICRP's cornerstone recommendations still apply. In particular, efforts should be maintained to reach exposures close or similar to those in normal situations. The ICRP does not consider any increase of the exposure in post-accidental situation. Moreover, the Commission stresses that authorities should involve stakeholders.

In particular, in the case of an existing exposure situation, the Commission recommends that the individuals concerned should receive general information on the exposure situation and the means of reducing their doses. This is justified by the fact that individual lifestyles are key drivers of the exposure. This supposes that affected individuals are fully aware of the situation and well informed. Thus, any change in exposure should be well advertised.

Similarly, the radiological quality of foodstuffs can be managed by many protective actions aimed at reducing the transfer of radionuclides in the food chain from farm to fork.

4.1.2. Stakeholders involvement and public participation

The Aarhus convention on access to information, public participation in decision-making and access to justice in environmental matters, requires that *"each Party shall provide for early public participation, when all options are open and effective public participation can take place."* Moreover, *"each Party shall ensure that in the decision due account is taken of the outcome of the public participation"*. Such a participation should be transboundary, as required by the Espoo convention.

Regarding the particular case of a so-called existing situation that occurs after a nuclear disaster, the ICRP has just submitted an update of its publications 109 and 111 to the public consultation [ICRP2019] in which it emphasises the crucial importance of involving stakeholders in implementation of the optimisation process. For protection of the public and the environment during the recovery process, the Commission recommends a 'co-expertise' approach in which authorities, experts, and stakeholders work together to share experience and information in affected communities, with the objective of developing a practical radiological protection culture to enable individuals to make informed decisions about their own lives. In the process of selecting protective actions, the Commission recommends that stakeholders' views and concerns should be considered.

During the recovery process, the evolution and sustainability of economic activities require that the radiological monitoring of employees, the working environment, and products should be maintained and adapted according to the expectations of the different stakeholders. This monitoring should contribute to vigilance in the long term, allowing confirmation of the quality of working conditions and production, as well as implementation of protective actions if necessary.

These recommendations are very binding on the States which must apply them in the context of the E40 waterway project for its part that runs in contaminated territories.

4.1.3. Dose limits and reference levels

Effective dose is intended for use as a protection quantity. The equivalent doses of the reference person are used for the calculation of the effective dose by multiplying these doses by the corresponding tissue weighting factors.

The reference level for the optimisation of protection of people living in contaminated areas should be selected in the lower part of the 1–20 mSv/year band recommended in ICRP Publication 103 [ICRP2007]. Where such recommendations should be applied? The ICRP does not give any clear indication. However, it claims that past experience has demonstrated that a typical value used for constraining the optimisation process in long-term post-accident situations is 1 mSv/year.

Moreover, the ICRP adds that the fact that exposures have been reduced below the reference level is not a sufficient condition to discontinue protective actions as long as there is room to reduce exposures further in conformity with the optimisation process. The continuation of such actions would probably be a prime mechanism to maintain exposures close or similar to those in normal situations as recommended by the Commission [ICRP2009]. Therefore, in this study, we shall retain a reference level of 1 mSv/y, keeping in mind that justification and optimisation have to be considered first.

For workers exposed to planned exposures, international recommendations limit the effective dose to 100 mSv in any period of five consecutive calendar years subject to a maximum equivalent dose of 50 mSv in any single calendar year. European Union[8] has strictly limited workers' exposure to 20 mSv/y, except in special circumstances. In this study, we shall retain the European limit.

4.2. Current dose estimation due to the contamination of the Dnieper River catchment

The pathways of human exposure include external exposure from deposited gamma emitting radionuclides and internal exposure via ingestion of contaminated food and drinking water as well as inhalation of airborne radionuclides. Here, we shall focus on the aquatic pathway resulting from consumption of drinking water, fish and agricultural products which are grown using irrigation water from contaminated water bodies. Use of water bodies as a source of drinking water for livestock and flooding of agricultural land can also lead to human exposure via terrestrial pathways. All these pathways have to be taken into account to evaluate the dose due to the contamination of the Dnieper River catchment.

Assessment of individual doses from known environmental concentrations is relatively straightforward. The dose is the product of concentration, consumption, and dose factor. Dose estimation is more difficult when the environmental concentration is not known and must be estimated. This is generally the case for the Chernobyl dose/risk assessment case studies. In general, most radiation dose estimates were calculated by computer codes based on the recommendations and parameters established internationally.

In a 1994 study [PNL1994], it was noted that none of the past studies analysed integral dose and risk to the population's health due to total water use and water consumption from the Dnieper cascade system. The main differences among previous studies reflect the large uncertainty related to contamination of different fish species. The 1994 study [PNL1994] does not analyse all these issues. However, it has evaluated some methodological problems and sources of uncertainty to mitigate these problems for future Chernobyl studies.

The IAEA [IAEA2006b] reports that estimated doses due to cesium-137 and strontium-90 in the Dnieper River reservoir system were made on the basis of monitoring data and predictions of flood frequencies. A worst-case scenario of a series of high floods during the first decade after the accident (1986–1995) was assumed. Estimates were that individual doses via aquatic pathways would not have exceeded 1–5 µSv/y.

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[8] COUNCIL DIRECTIVE 2013/59/EURATOM of 5 December 2013, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32013L0059

However, as we shall see below, such a statement is contradicted by results of the dose assessment for the year 1999 that gives higher values.

The most important aquatic system (the Dnieper River basin) occupies a large area with a population of about 32 million people who use the water for drinking, fishing and irrigation. Thus, estimates have been made of the collective dose to people from these three pathways for a period of 70 years after the accident (i.e. from 1986 to 2056).

Collective dose estimates consist in calculating the dose of a reference person and multiplying it with the number of exposed people. Such an evaluation is based on modelling that does not require a great accuracy since fluctuations are smoothed by averaging over time and populations. Individual dose calculation requires more refined evaluations in order to estimate the range of possible values according to the assumptions used. Thus, scientific literature and reviews mainly provide collective doses. This also prevents the publication of doses received by the most at-risk groups.

According to the IAEA [IAEA2006b], dose estimates for the Dnieper River system show that if there had been no action to reduce radionuclide fluxes to the river, the collective dose commitment for the population of Ukraine could have reached 3 000 man.Sv for a period of 70 years after the accident. The contribution of ^{137}Cs to the exposure dose is mostly restricted to Ukraine's northern regions. But due to the relatively uniform ^{90}Sr distribution in the Dnieper cascade of reservoirs, the ^{90}Sr contribution to the expected collective dose of the population is relatively uniform. Protective measures carried out during 1992–1993 on the left bank floodplain of the Pripyat River decreased exposure by approximately 700 man.Sv. Other protective measures on the right bank in the Chernobyl exclusion zone (during 1999–2001) further reduced collective doses by 200–300 man.Sv. Thus, the collective dose over 70 years estimated by the IAEA is about 2 000 man.Sv. Note that no indication is given on the impact of the construction work itself.

Three aquatic pathways contribute to the collective dose: drinking water, fish consumption and irrigation. According to the IAEA [IAEA2006a], the percentage breakdown according to water use pathway for the Kyiv region population gives an equal share of these three pathways. For the Crimea population, the impact of fish consumption is negligible as compared to the other two pathways. In the Poltava region, fish consumption pathway dominates the collective dose associated to the aquatic pathways. In 2006, the annual collective dose was about 8 man.Sv for the Kyiv region, 4 man.Sv for the Poltava region and 5 man.Sv for the Crimea region.

Such results show the importance that any construction works in the contaminated areas can have on the collective dose of the inhabitants of the Dnieper watershed. The works mentioned in the IAEA study were designed to reduce the doses. Construction works related to the E40 project will increase the doses. Thus, a dose assessment related to the works that are expected to be performed for the E40 waterway is necessary.

4.3. Dose assessment of exposures related to the E40 waterway

4.3.1 Workers in the Chernobyl exclusion zone

Heavy works related to the E40 waterway in the most contaminated part of the Chernobyl exclusion zone, such as dam construction, will require many workers who will be exposed to high levels of ground contamination by several radioelements. Exposure pathways are dominated by external exposure and radioactive dust inhalation.

External exposure is largely dominated by the cesium-137 ground contamination because it is a gamma emitter. Americium-241, that is also a gamma emitter, has lower ground contamination levels and a smaller dose factor due to its low energy. Radiation protection estimates for workers are generally based on a workload of 2 000 hours per year. Surface ground contaminations observed in the Chernobyl exclusion zone are ranging from 555 to 3 700 kBq/m^2 for cesium-137. They will induce exposure levels ranging from 2 to 15 mSv/y. Conversion factors were taken from [Saito2012, ICRP2018].

To evaluate the exposure related to dust inhalation, we have to choose a resuspension factor to convert the surface deposition contamination in Bq/m^2 into the concentration in air arising from resuspension in Bq/m^3. Resuspension factors measured in the zones contaminated by the Chernobyl accident [Hatano2003] do not include mechanical disturbance. A review [Sehmel1980] mentions that mechanically caused resuspension factors span seven orders of magnitude from 10^{-10} to over 10^{-2} m^{-1}. In this study, we have retained 10^{-6} m^{-1} that is used in France in case of mechanical disturbance such as ploughing. This also corresponds to the early resuspension factor recommended by Public Health England after a nuclear accident [PHE2019].

With a breathing rate of 1.2 m^3/h and the conversion factors of [ICRP2012], the estimated annual effective doses for the dominating contaminants are given in Table 1.

Table 1: *Annual effective dose due to the inhalation pathway of workers in the Chernobyl exclusion zone*

Radioelement	Cesium-137	Strontium-90	Plutonium	Americium-241
Surface ground contamination	550 to 3 700 kBq/m^2	200 to 750 kBq/m^2	1 to 40 kBq/m^2	1 to 100 kBq/m^2
Effective dose	9 to 60 µSv/y	14 to 54 µSv/y	72 to 2 880 µSv/y	72 to 7 200 µSv/y

Owing to the large uncertainty in the resuspension factor, the inhalation exposure could be higher. With more pessimistic resuspension factors, inhalation pathway could dominate the workers exposure. However, it could be reduced with protection masks. This is not the case for the external exposure.

Finally, workers external exposure could reach levels higher than 10 mSv/y and be close to the European limit fixed at 20 mSv/y. Pessimistic scenarios including internal contamination could lead to values close to the limit. Such values are large in comparison to the exposure of nuclear workers:

- French nuclear workers had an average external exposure dose of 1.4 mSv in 2018. 236 out of 86 702 nuclear workers were exposed to an external dose higher than 10 mSv in 2018 [IRSN2019].
- At the Fukushima daiichi nuclear power plant in Japan, workers have been exposed to an average dose of 1.6 mSv/y since April 2016. The highest recorded dose is 79.90 mSv over 42 months (3.5 years) [TEPCO2019].

4.3.2. Water contamination of the Dnieper

Population living downstream the Pripyat watershed will get additional exposures during the construction works in the Chernobyl exclusion zone. Once the infrastructures are finished, annual dredging will increase the contamination level of the Dnieper water. Modelling such activities is almost impossible without any detail on the planned works and the precise dredging location. Therefore, we shall consider that heavy work in the Chernobyl exclusion zone will have an impact similar to the flooding of 1999 that washed out radionuclides from the Pripyat floodplain.

The IAEA report [IAEA2006a] gives the estimates of the collective dose from three pathways for 1999. Strontium-90 dominates the tap water, irrigated food and fish ingestion pathways, except for the Kyiv reservoir where cesium-137 dominates the fish ingestion pathway. Tap water and fish ingestion pathways can be easily checked from the concentration data available in IAEA reports.

On the one hand, the IAEA reports [IAEA2006a] that in 1999 tap water drunk by 8.25 million people led to a collective dose of 4.5 man.Sv. At the two extremes of the Dnieper cascade, the average individual dose in 1999 deduced from the IAEA collective doses are 1.32 µSv in Kyiv and 0.52 µSv in Kakhovka. On the other hand, figure 6 indicates that strontium-90 is dominating the water contamination of the Kyiv reservoir. Considering an average concentration of 50 Bq/m^3 as a reference level and 400 Bq/m^3 for 1999, a Kyiv resident drinking 2 litres per day, including cooking, would be exposed to an annual dose of 1 µSv in an ordinary year and 8 µSv in 1999 for strontium-90 alone. Doses should be similar at the other extreme of the cascade. Conversion factor of [ICRP2012] was used. These simple estimates lead to higher doses than the ones from the IAEA. For the population drinking water from the Kyiv reservoir, the contribution of cesium-137 should be added: figure 6 indicates an average concentration of 30 Bq/m^3 as a reference level and 150 Bq/m^3 for 1999. These contamination levels lead to an additional dose of 0.28 µSv for an ordinary year and 1.4 µSv in 1999.

As for fish consumption, the IAEA [IAEA2006a] mentions a total catch of 25 000 tons in 1999 that led to a collective dose of 0.95 man.Sv. The IAEA estimates that cesium-137 in the 1 520 tons of fish from the Kyiv reservoir led to a collective dose of 0.15 man.Sv. Assuming that only half of the total weight is eaten, this means that each kilogramme of fish flesh from the Kyiv reservoir led to a dose of 0.2 µSv.

Figure 8, reproduced from [IAEA2006b], indicates the averaged ^{137}Cs activity concentrations in fish caught in the Kyiv reservoir over the years. The same report says that in 2002–2003, ^{90}Sr in fish in reservoirs of the Dnieper cascade was only 1–2 Bq/kg. In the Dnieper cascade in Ukraine, commercial fisheries catch more than 20 000 t of fish per year [IAEA2006b]. In 2017, fishermen caught more than 1 200 tons of fish in the Kyiv Reservoir.

Cesium-137 concentration ranges from 50 Bq/kg in nonpredatory fish in 2000 to 300 Bq/kg in predatory fish in 1999. Assuming an average concentration of 100 Bq of cesium-137 per kg of fresh fish, the conversion factor of [ICRP2012], and an annual consumption of 10 kg of fish (200 g per week), we get an effective dose of 14 µSv/y. Large fish consumers such as fishermen may eat 40 kg of fish per year (annual intake retained for fishermen in France) and be exposed to an internal dose of 56 µSv/y. With this calculation, each kilogramme of fish flesh leads to a dose of 1.6 µSv. Once again, this is more than the IAEA result. Our calculation shows that the fish ingestion pathway can be significative for a part of the population. Works for the E40 waterway and dredging activities will lead to even higher doses.

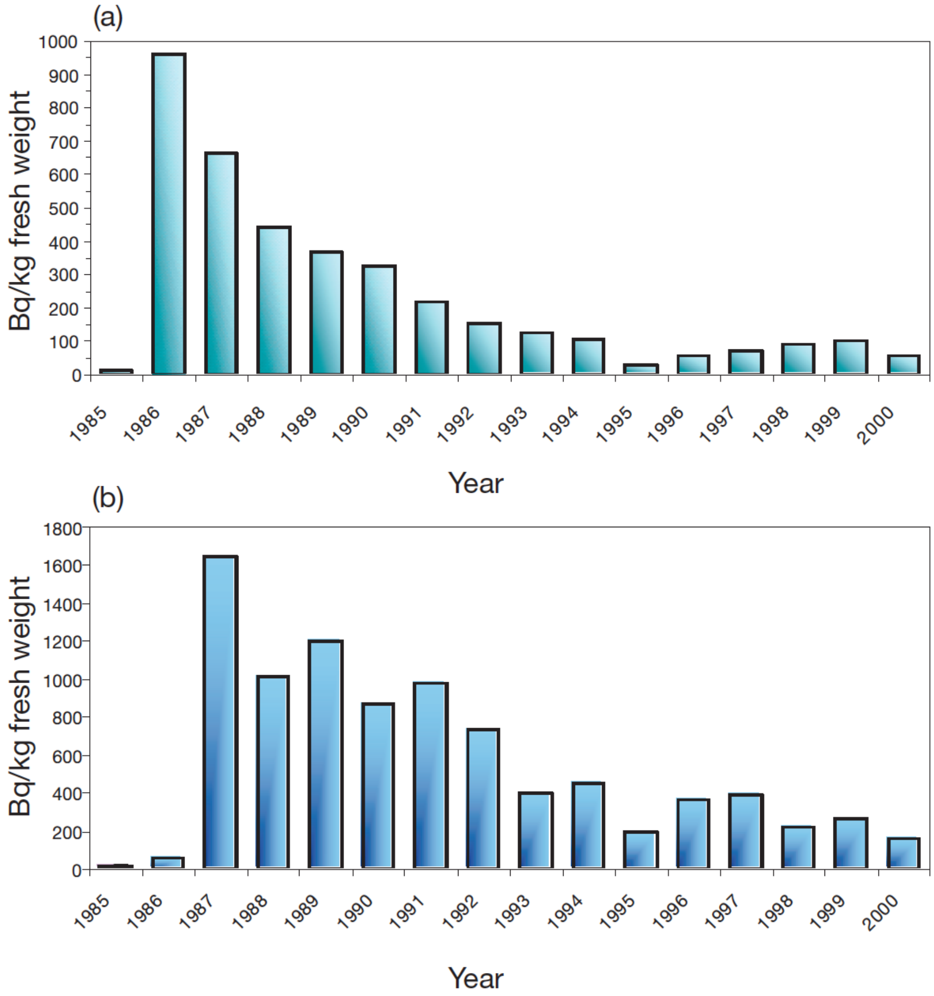

Figure 8: *Averaged ^{137}Cs activity concentrations in nonpredatory (bream (a)) and predatory (pike (b)) fish; the fish are from the Kyiv reservoir. Figure reproduced from [IAEA2006b].*

Without specific data related to the agricultural practices and consumption, we cannot evaluate the pathway related to irrigation. However, the IAEA estimate [IAEA2006a] shows that this is the dominating pathway due to the large number of exposed people: crop and milk production along the Dnieper river cascade during 1999 led to a collective dose of 21.9 man.Sv. As about 20 million Ukrainians eat irrigated food, such a value corresponds to an average individual dose of 1 µSv. Depending on diets, individual doses could be far larger. Moreover, the IAEA estimate only considers strontium and cesium in crops and milk. Other kinds of food also contribute. In the future, americium-241 will also contribute. Hence, individual doses of the order of 10 µSv/y due to irrigation are credible. They could be even larger for farmers.

If sediments from dredging are applied as a fertilizer in the fields, they will also contribute to the internal dose. To estimate the impact of such a pathway, we assumed that the sediments are in equilibrium with the water contamination. Only considering leafy vegetables and root crops and the transfer coefficients recommended by the IAEA [IAEA2010], we get a dose of 14 µSv/y for strontium-90 plus cesium-137. We have also considered a diet with 60% self-consumption. This calculation over-estimates the dose as we have not taken into account the dilution of the applied sediments into the soil, but it also under-estimates it by neglecting other kinds of food like crops, dairy products and meet.

Finally, the three aquatic pathways could lead to individual doses greater than 10 µSv in a single year affected by flooding or heavy work in contaminated areas. 30 µSv is a credible value. Considering an initial exposure of 10 µSv/y, the cumulated 15-year exposure would then be of about 126 µSv, considering the radioactive decay of cesium-137 and strontium-90 that both have a half-life of 30 years. Thus, for an initial dose of 30 µSv/y accounting for the three aquatic pathways, the cumulated 15-year exposure would then reach almost 400 µSv.

4.3.3. Up-stream the Chernobyl exclusion zone

Up-stream the Chernobyl exclusion zone, we have selected a zone nearby the village of Lakhva (Лахва) for two reasons: a dam might be built nearby and the cesium-137 ground-contamination level ranges from 40 to 185 kBq/m^2. See the most recent map of the Brest oblast in the annex.

Water of the Pripyat river is not used for consumption. Thus, the only pathway to the internal exposure is related to fish consumption.

Fishing is well-developed in the Pripyat river. Several parts of the river are controlled by state companies which carry out commercial fishing and sell licenses for recreational fishing. The largest of such companies (Gomel union of fishing companies) catches up to 500 tons of fish per year (both in the Pripyat and Dnieper basin). Fishing in rivers accounts for 20% of all commercial fishing. The rest of the fish is caught in fish farms, also state owned. The fish is grown in artificial lakes created for this purpose. Before selling, the radioactivity levels are checked in the fish, but data are not available.

In 2018 the fish farming company in Lakhva has produced 211 tonnes of fish[9]. However, the contamination level is not public. A considerable amount of fish, difficult to estimate, is caught by non-professional fishermen (amateurs), local population and poachers directly in the Pripyat river. According to the Ministry of statistics and analysis of Belarus, the volume of fish caught by the non-professional fishermen is estimated up to 8 000 tonnes in 2010 [FII2014].

In the Pripyat river, contamination levels of ^{137}Cs in fish remain between 5 and 250 Bq/kg. Fish from closed lake could have higher concentrations. The maximum allowed level for commercial food in Belarus is 370 Bq/kg. Fish caught by amateurs are not controlled and may have a higher concentration. An annual consumption of 10 kg of fish (200 g per week) at this maximum allowed level of contamination would lead

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[9] https://media-polesye.by/news/opytnyy-rybhoz-lahva-stremitsya-vyyti-na-bezubytochnuyu-rabotu-55752

to an effective dose of 50 µSv/y. And with an annual intake of 40 kg of fish generally considered for fishermen, the effective dose would be of 200 µSv/y.

It is difficult to evaluate the impact of construction work on the contamination of the fish in the Pripyat river, however, the effective exposure dose due to the fish consumption pathway should remain below the previous values if the maximum allowed contamination in food is respected. This dose is added to the order contributions such as the external dose due to the ground contamination and to the internal dose due to the other food. Local populations are already exposed to these pathways.

5 Conclusions

Chernobyl is the most severe industrial accident in history. More than 30 years later, residual radioactive contamination is such that it forbids living in an extended exclusion zone. Nowadays, the contamination is dominated by cesium-137, strontium-90 and various isotopes of the highly toxic plutonium. Americium-241, the daughter nucleus of plutonium-241, is also highly toxic and has an increasing contribution that is expected to dominate the radiological impact in the future. The general strategy is to wait for the slow radioactive decay and rehabilitation of the Chernobyl exclusion zone remains impossible for decades. Decommissioning of the Chernobyl cooling pond – the most radioactive hot spot – is the only exception. There are also about 90 radioactive waste storage sites in the Chernobyl exclusion zone that remain to be decommissioned.

Beyond the exclusion zone, the daily life of millions of people is still affected by the residual contamination. The whole Pripyat-Dnieper watershed was contaminated by the fallouts and direct transfers to the river. Downstream of the Chernobyl exclusion zone, approximately 8 million Ukrainians drink water from the Dnieper River, and as many as 20 million eat foods irrigated with Dnieper River water. Dominating contaminants are the cesium-137 that tends to be fixed in bottom sediments and the strontium-90 that is continuously transported down to the Black Sea through the Dnieper cascade. Sediments contaminated by cesium-137 have been slowly covered by less contaminated and clean sediments in the bottom of the Kyiv reservoir, offering a natural shield to this pollutant. The IAEA recommends, as an overall strategy, to leave these sediments as is and avoid processes that will lead to their resuspension. For strontium-90 nothing can be done.

Upstream of the Chernobyl exclusion zone, there are zones along the Pripyat river that were contaminated by the radioactive fallouts at the time of the accident. Cesium-137 is the dominating contaminant. The overall strategy there is also to wait for the slow radioactive decay.

The ICRP considers these situations as existing situations for which it recommends an optimisation process intended to recover the exposure levels prevailing before the accident. Protection measures mainly consist in adapting the daily life of the inhabitants of the contaminated territories because individual lifestyles are key drivers of the exposure. This supposes that affected individuals are fully aware of the situation and well informed.

The Aarhus convention also requires that States ensure that environmental information is available in electronic databases which are easily accessible to the public. Presently, this is not the case. It is very difficult to access to data about the radioactive contamination in order to assess the exposure doses.

In such a context, the projected E40 inland waterway, which is supposed to pass nearby the Chernobyl nuclear power plant and go through the Chernobyl Exclusion Zone, will necessarily have a radiological impact on both construction and maintenance workers, as well as on the population depending on the water of the Pripyat and Dnieper rivers. Although this project requires heavy works such as dam construction and alignment of the river course in the most contaminated part of its route, no radiological impact study is available.

ICRP principles for radiation protection, Aarhus and Espoo conventions require environmental and radiological studies, a justification of the project and the participation of the stakeholders and the general public in the decision process.

The present study shows that the construction works for the part of the E40 waterway route that crosses the Chernobyl exclusion zone and passes nearby the Chernobyl nuclear power plant are not feasible. The forecasted exposure of the workers would be too high to be accepted. Moreover, the heavily contaminated Chernobyl cooling pond and temporary radioactive waste storages in the floodplain of the Pripyat River have not been decommissioned yet, preventing any construction work. The IAEA also recommends a list of other protective actions that remain to be done.

The portion of the E40 waterway that lies upstream the Chernobyl exclusion zone would then be useless without a connection to the Dnieper river. This also means that development works that consist of several dam construction and alignment of meandering Pripyat river to accept class V vessels are not justified.

Finally, the portion of the E40 route from the Black Sea to the Kyiv reservoir mainly requires regular dredging work. The feasibility study mentions 68 000 m^3 of dredging work every year in the Kyiv reservoir, that stocks cesium-137 in its bottom sediments. Such an activity is contrary to the IAEA's recommendations to leave the sediments in place because it will increase the dose of people who depend on the water from the Kyiv reservoir for their water and food supply.

Bibliography

Grey literature:

[ACRO2019] ACRO, Radiological Protection of People and the Environment in the Event of a Large Nuclear Accident, ACRO's comments on the ICRP draft report, 2019
https://www.acro.eu.org/protection-radiologique-des-personnes-et-de-lenvironnement-en-cas-daccident-nucleaire-grave-radiological-protection-of-people-and-the-environment-in-the-event-of-a-large-nuclear-accident/#en

[E40Com2015] Andrey Rekesh, Secretary of the Commission on the development of the E40 waterway on the Dnieper-Vistula section, Restoration of the international waterway E40, presentation to the 59th session, November 2015
https://www.unece.org/fileadmin/DAM/trans/doc/2015/sc3wp3/Presentation_S3_59th_session_-_Restoration_of_the_international_waterway_E40.pdf

[ERDC2008] Todd S. Bridges, Stephen Ells, Donald Hayes, David Mount, Steven C. Nadeau, Michael R. Palermo, Clay Patmont, and Paul Schroeder, Engineer Research and Development Center, Dredging Operations and Environmental Research Program - The Four Rs of Environmental Dredging: Resuspension, Release, Residual, and Risk, prepared for the U.S. Army Corps of Engineers, ERDC/EL TR-08-4, 2008
https://semspub.epa.gov/work/01/287028.pdf

[FII2014] Fish Industry Institute (Институт рыбного хозяйства), Belarus Fish Industry Problems: collection of scientific papers (ВОПРОСЫРЫБНОГО ХОЗЯЙСТВА БЕЛАРУСИ: Сборник научных трудов), 2014
http://agris.fao.org/agris-search/search.do?recordID=BY2017000750

[FZS2019] Mateusz Grygoruk, Ewa Jabłońska, Paweł Osuch and Paweł Trandziuk, Analysis of selected possible impacts of potential E40 Inland Waterway development in Belarus and Ukraine on hydrological and environmental conditions of neighbouring rivers and wetlands, Frankfurt Zoological Society, March 2019
https://bahna.land/files/5d0b65c02a5d4238eedc5191.pdf

[HRC2013] Human Rights Council, Report of the Special Rapporteur on the right of everyone to the enjoyment of the highest attainable standard of physical and mental health, Anand Grover, Mission to Japan (15 – 26 November 2012), 2 May 2013 (A/HRC/23/41/Add.3)
http://www.ohchr.org/Documents/HRBodies/HRCouncil/RegularSession/Session23/A-HRC-23-41-Add3_en.pdf

[IAEA2006a] International Atomic Energy Agency, Radiological Conditions in the Dnieper River Basin - Assessment by an international expert team and recommendations for an action plan, 2006
https://www-pub.iaea.org/MTCD/publications/PDF/Pub1230_web.pdf

[IAEA2006b] International Atomic Energy Agency, Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience, Report of the Chernobyl Forum Expert Group 'Environment', 2006
http://www-pub.iaea.org/MTCD/publications/PDF/Pub1239_web.pdf

[IAEA2010] International Atomic Energy Agency, Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments, Technical Reports Series No. 472, 2010
https://www-pub.iaea.org/MTCD/Publications/PDF/trs472_web.pdf

[ICRP2007] International Commission on Radiological Protection, The 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, Ann. ICRP 37 (2-4), 2007
http://www.icrp.org/publication.asp?id=ICRP%20Publication%20103

[ICRP2009] International Commission on Radiological Protection, Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas after a Nuclear Accident or a Radiation Emergency, ICRP Publication 111, Ann. ICRP 39 (3), 2009
http://www.icrp.org/publication.asp?id=ICRP%20Publication%20111

[ICRP2012] International Commission on Radiological Protection, Compendium of Dose Coefficients based on ICRP Publication 60, ICRP Publication 119, Ann. ICRP 41 (Suppl.), 2012
http://www.icrp.org/publication.asp?id=ICRP%20Publication%20119

[ICRP2018] International Commission on Radiological Protection, Dose Coefficients for External Exposures to Environmental Sources, Draft Report for Consultation, 2018
http://www.icrp.org/page.asp?id=389

[ICRP2019] International Commission on Radiological Protection, Radiological protection of people and the environment in the event of a large nuclear accident: update of ICRP Publications 109 and 111. Draft report for public consultation. ICRP Publication 1XX. Ann. ICRP 4X(X).
http://www.icrp.org/docs/TG93%20Draft%20Report%20for%20Public%20Consultation%202019-06-17.pdf

[IRSN2019] Institut de Radioprotection et de Sûreté Nucléaire, La radioprotection des travailleurs - Exposition professionnelle aux rayonnements ionisants en France : bilan 2018, September 2019
https://www.irsn.fr/FR/Actualites_presse/Communiques_et_dossiers_de_presse/Pages/20190912_Bilan-2018-exposition-professionnelle-rayonnements-ionisants-France.aspx

[MIG2015] Maritime Institute in Gdansk, Restoration of Inland Waterway E40 Dnieper – Vistula: from Strategy to Planning, Final Feasibility Study Report, December 2015
http://czech.mfa.gov.by/docs/e40restoration_feasibility_study_en.pdf

[PHE2019] J Wellings, P Bedwell, S M Haywood, T W Charnock, Public Health England, Estimation of radiation doses from inhalation of resuspended materials in emergency situations, April 2019
https://www.gov.uk/government/publications/radiation-doses-from-inhalation-of-resuspended-materials

[PNL1994] O. V. Voitsekhovitch, M. J. Zheleznyak and Y. Onishi, Pacific Northwest Laboratory, Chernobyl Nuclear Accident Hydrologic Analysis and Emergency Evaluation of Radionuclide Distributions in the Dnieper River, Ukraine, During the 1993 Summer Flood, Prepared for the U.S. Department of Energy, June 1994
https://www.osti.gov/servlets/purl/10168428

[SSEChNPP2019] State Specialized Enterprise Chernobyl NPP (SSE ChNPP), Current Decommissioning Projects, accessed in August 2019
https://chnpp.gov.ua/en/activity/chnpp-decommissioning/ongoing-projects

[TEPCO2019] Tokyo Electric Power Company Holdings, Fukushima Daiichi D&D d Engineering Company, Evaluation of the exposure dose of workers engaged in radiation work at the Fukushima Daiichi Nuclear Power Station, 31 October 2019
https://www7.tepco.co.jp/wp-content/uploads/handouts_191031_01-e.pdf

[UNECE2012] United Nations Economic Commission for Europe, Map of the European Inland Waterway Network, 2012
https://www.unece.org/fileadmin/DAM/trans/main/sc3/European_inland_waterways_-_2012.pdf

[UNECE2017] United Nations Economic Commission for Europe, Inventory of main standards and parameters of the E waterway network - "blue book", Third Revised Edition, 2017
http://www.unece.org/fileadmin/DAM/trans/doc/2017/sc3wp3/ECE-TRANS-SC3-144-Rev.3e.pdf

[UNSCEAR2000] United Nations Scientific Committee on the Effects of Atomic Radiation, Maps of radionuclide deposition, UNSCEAR 2000 Report
http://www.unscear.org/docs/JfigVI.pdf

Scientific publications:

[Beresford2016] N.A. Beresford, S. Fesenko, A. Konoplev, L. Skuterud, J.T. Smith, and G. Voigt, Thirty years after the Chernobyl accident: What lessons have we learnt?, Journal of Environmental Radioactivity 157 (2016) 77
http://dx.doi.org/10.1016/j.jenvrad.2016.02.003

[Eggleton2004] Jacqueline Eggleton and Kevin V Thomas, A review of factors affecting the release and bioavailability of contaminants during sediment disturbance events, Environment International 30 (2004) 973
https://doi.org/10.1016/j.envint.2004.03.001

[Golubev2011] A. Golubev, V. Sikorski and O. Stoliar, Ionizing radiation long-term impact on biota in water bodies with different levels radioactive contamination in Belarusian sector of Chernobyl nuclear accident zone, Radioprotection 46 (2011) S393
https://doi.org/10.1051/radiopro/20116502s

[Hatano2003] Y. Hatano and N. Hatano, Formula for the resuspension factor and estimation of the date of surface contamination, Atmospheric Environment 37 (2003) 3475
https://doi.org/10.1016/S1352-2310(03)00410-2

[Onishi2007] Chernobyl – What Have We Learned? - The Successes and Failures to Mitigate Water Contamination over 20 Years, Edited by Yasuo Onishi, Oleg V. Voitsekhovich and Mark J. Zheleznyak, Springer 2007
https://doi.org/10.1007/1-4020-5349-5

[Polikarpov2015] G.G. Polikarpov, G.E. Lazorenko, N.N. Tereshchenko, and N.Yu. Mirzoyeva, The Northern-Crimean Canal as a Model Object for Radioecological Study of the Chernobyl Radionuclides Transport to the Black Sea, Physical Oceanography 3 (2015) 25
https://doi.org/10.22449/1573-160X-2015-3-25-34

[Saito2012] Kimiaki Saito, Nobuhito Ishigure, Nina Petoussi-Henss, and Helmut Schlattl, Effective dose conversion coefficients for radionuclides exponentially distributed in the ground, Radiation and Environmental Biophysics 51 (2012) 411
https://doi.org/10.1007/s00411-012-0432-y

[Sandalls1993] F.J. Sandalls, M.G. Segal, and N. Victorova, Hot particles from Chernobyl: A review, Journal of Environmental Radioactivity 18 (1993) 5
https://doi.org/10.1016/0265-931X(93)90063-D

[Sehmel1980] G. A. Sehmel, Particle Resuspension: a Review, Environment International 4 (1980) 107
https://doi.org/10.1016/0160-4120(80)90005-7

Annex: Contamination maps

Belorussian maps

Contamination maps are from meteorological agency of Belarus. For all maps, the upper scale is in kBq/m^2 and the lower scale in Ci/km^2. English names were added by us.

2009 contamination maps of the Chernobyl exclusion zone

Cesium-137:

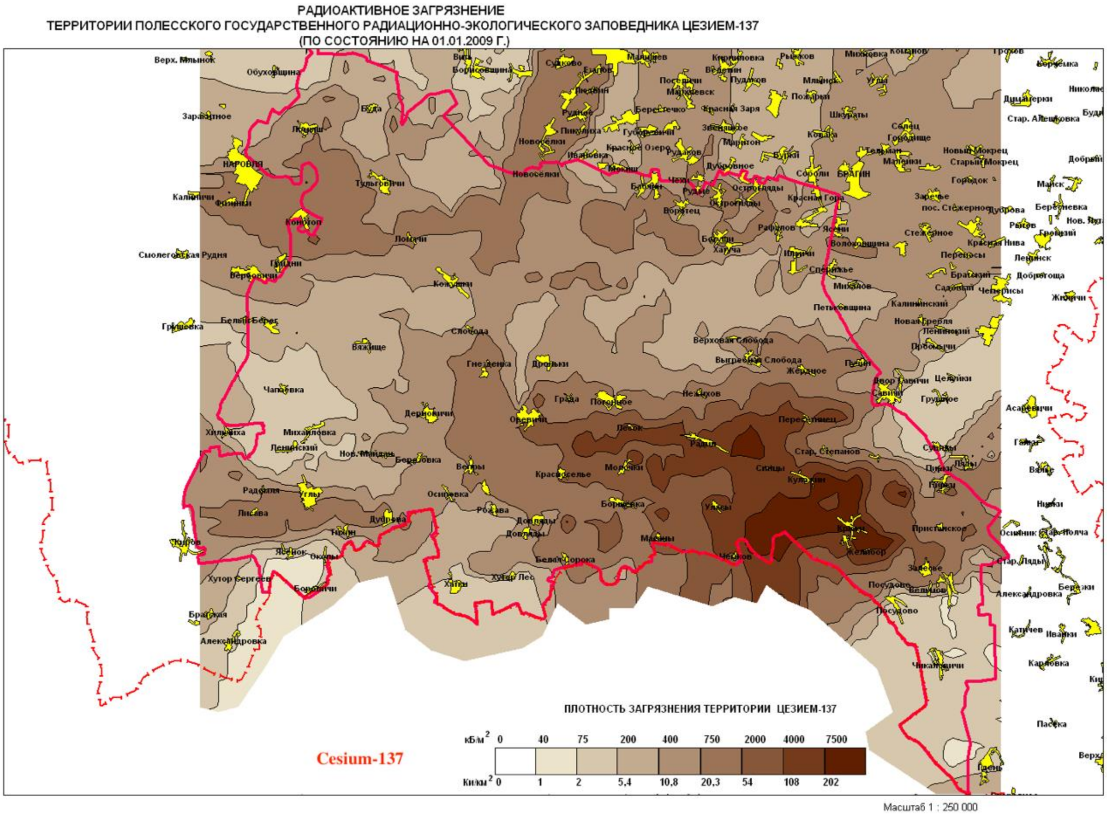

__Figure A1:__ 2009 map of the surface ground deposition of cesium-137 in the Belarussian part of the Chernobyl exclusion zone. The upper scale is in kBq/m^2 and the lower scale in Ci/km^2.

Strontium-90:

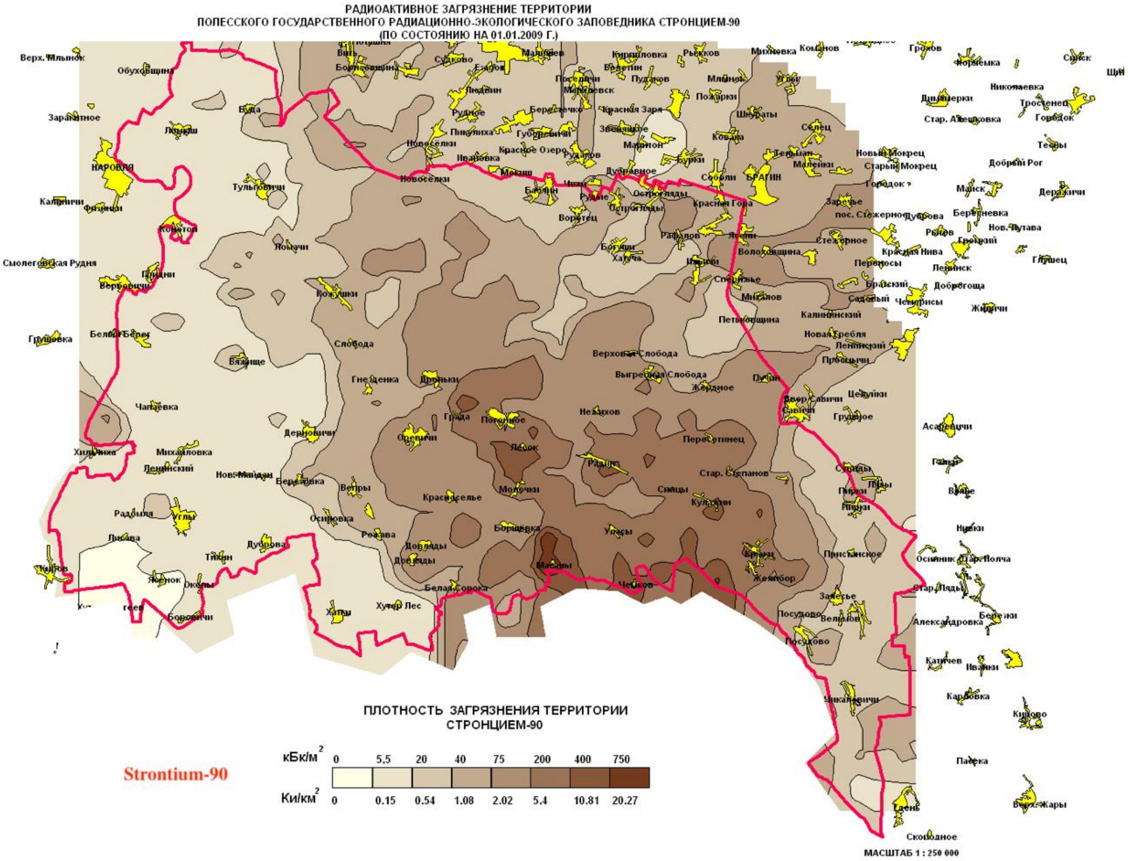

Figure A2: 2009 map of the surface ground deposition of strontium-90 in the Belarussian part of the Chernobyl exclusion zone. The upper scale is in kBq/m^2 and the lower scale in Ci/km^2.

Plutonium-238,239,240:

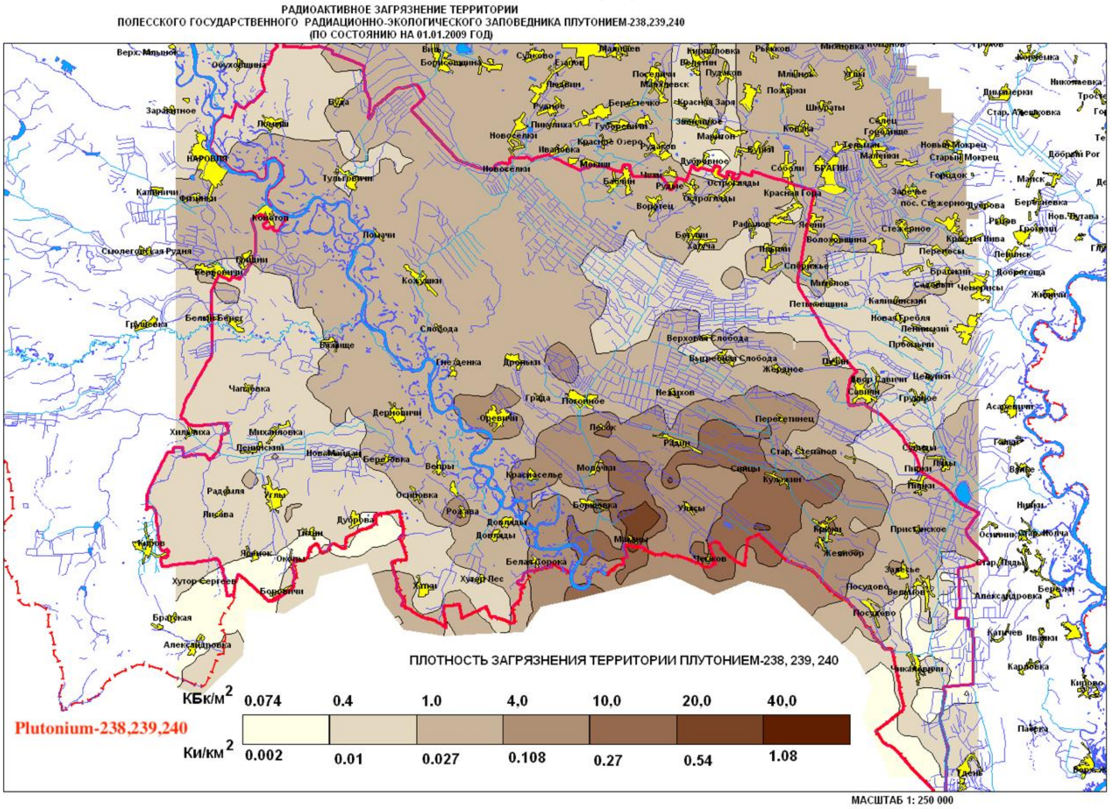

Figure A3: *2009 map of the surface ground deposition of plutonium-238,239,240 in the Belarussian part of the Chernobyl exclusion zone. The upper scale is in kBq/m*^{2} *and the lower scale in Ci/km*^{2}*.*

Plutonium-241:

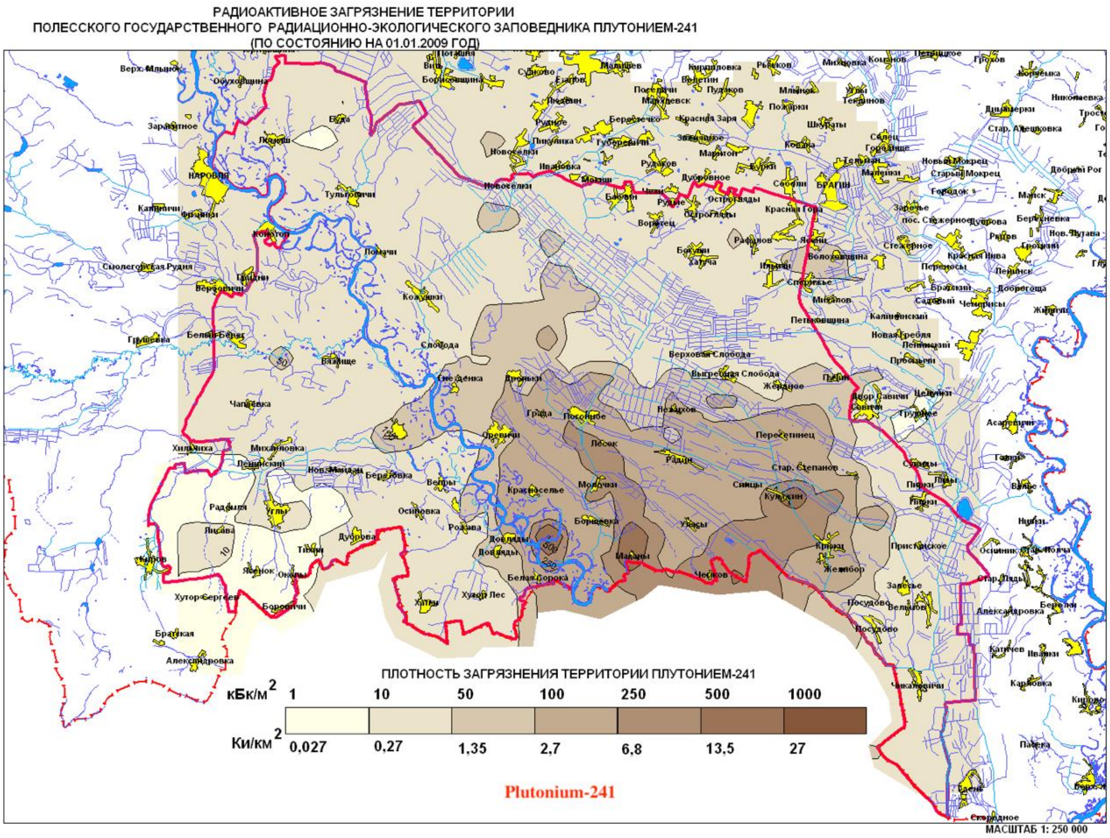

Figure A4: *2009 map of the surface ground deposition of plutonium-241 in the Belarussian part of the Chernobyl exclusion zone. The upper scale is in kBq/m^2 and the lower scale in Ci/km^2.*

Americium-241:

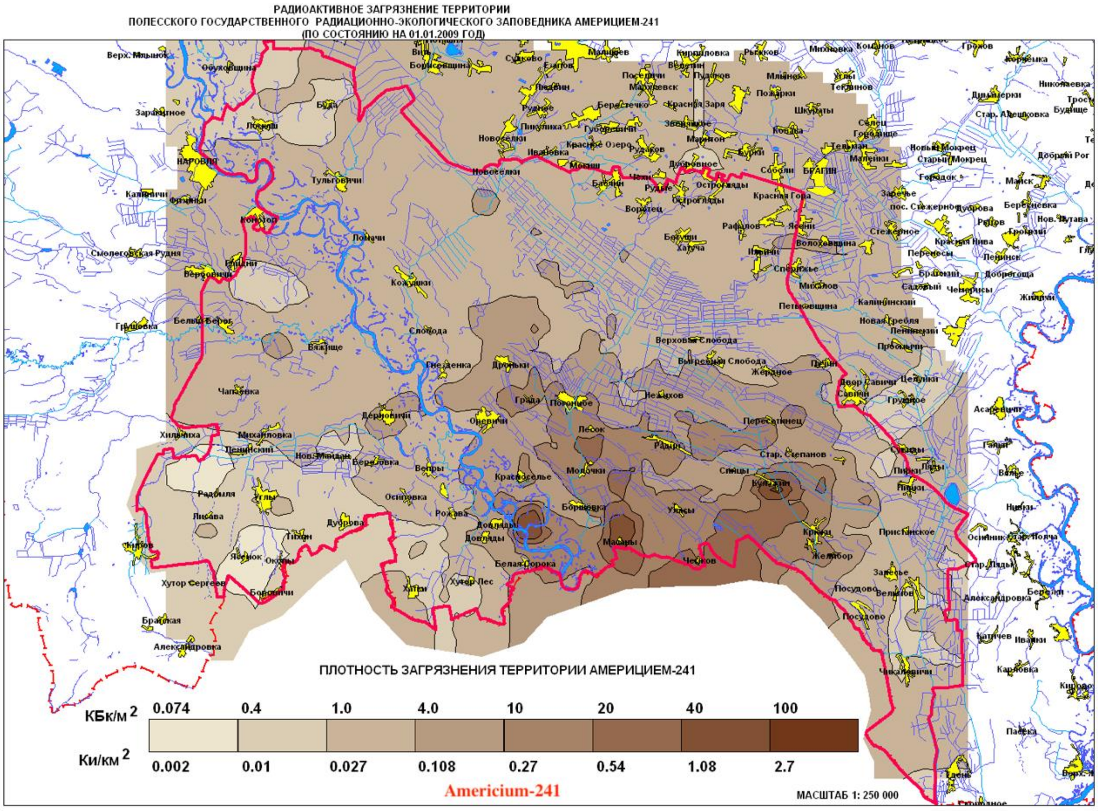

Figure A5: *2009 map of the surface ground deposition of americium-241 in the Belarussian part of the Chernobyl exclusion zone. The upper scale is in kBq/m^2 and the lower scale in Ci/km^2.*

2016 cesium-contamination maps of the South part of Belarus

Gomel oblast:

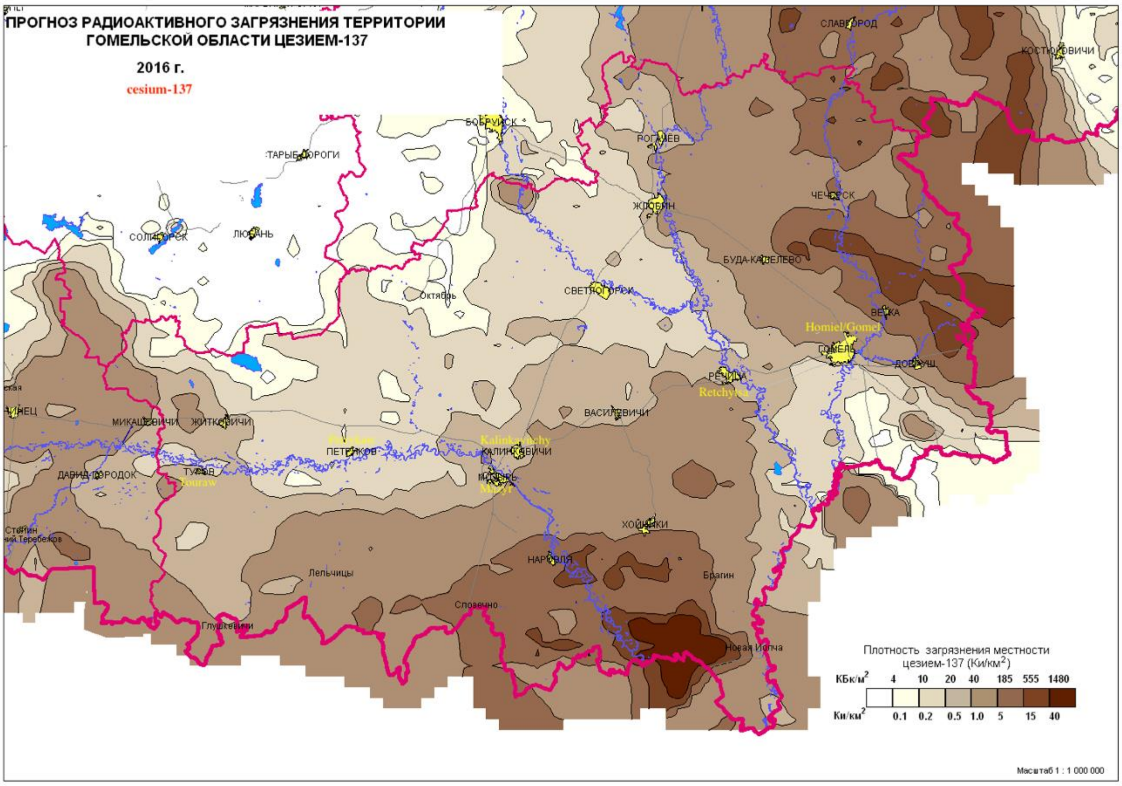

Figure A6: *2016 map of the surface ground deposition of cesium-137 in the Gomel oblast. The upper scale is in kBq/m^2 and the lower scale in Ci/km^2.*

Brest oblast:

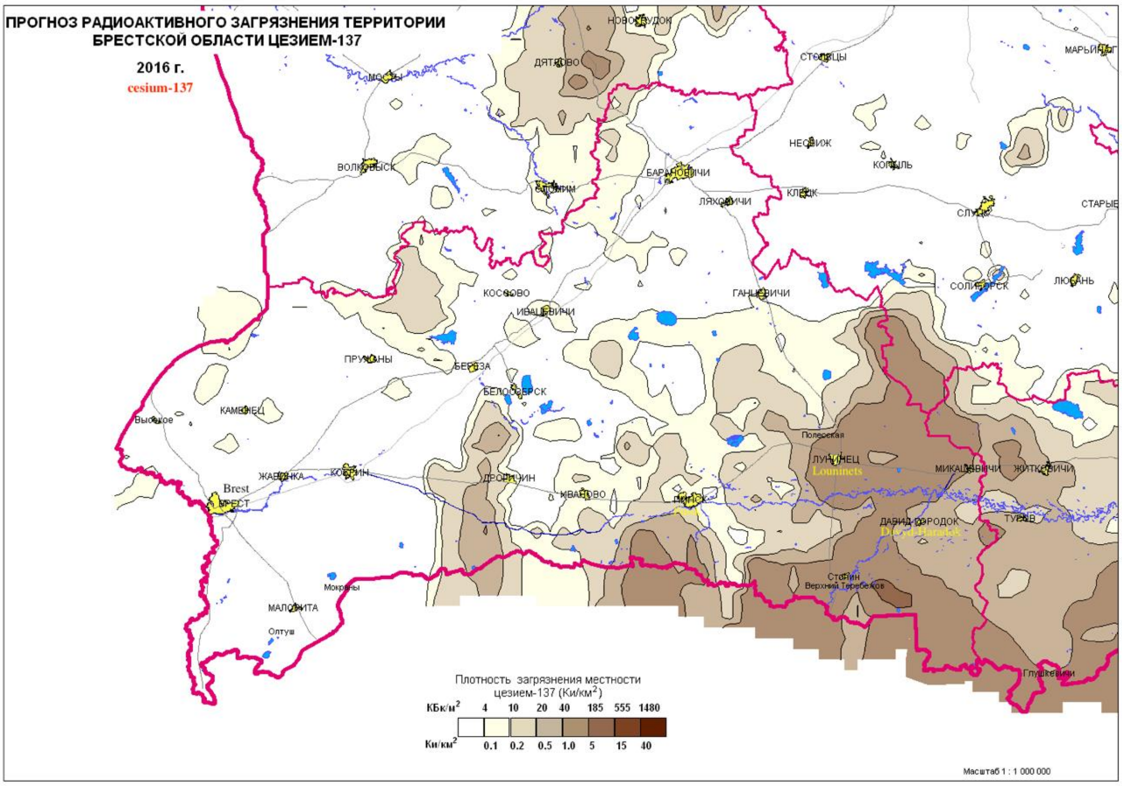

Figure A7: *2016 map of the surface ground deposition of cesium-137 in the Brest oblast. The upper scale is in kBq/m² and the lower scale in Ci/km².*

Reconstruction of the cesium-contamination map along the Pripyat river (2016)

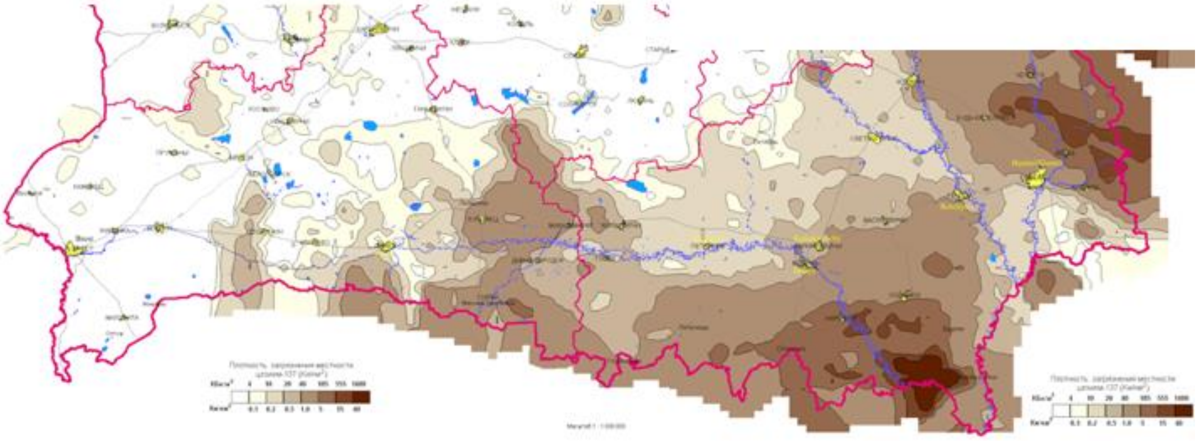

Figure A8: *Reconstruction map of the surface ground deposition of cesium-137 in the South part of Belarus by merging the two previous maps. The upper scale is in kBq/m² and the lower scale in Ci/km².*

Ukrainian maps

Maps are provided by the state agency of Ukraine on exclusion zone management[10]. English names were added by us.

Exclusion zone

Cesium-137 (May 2011)

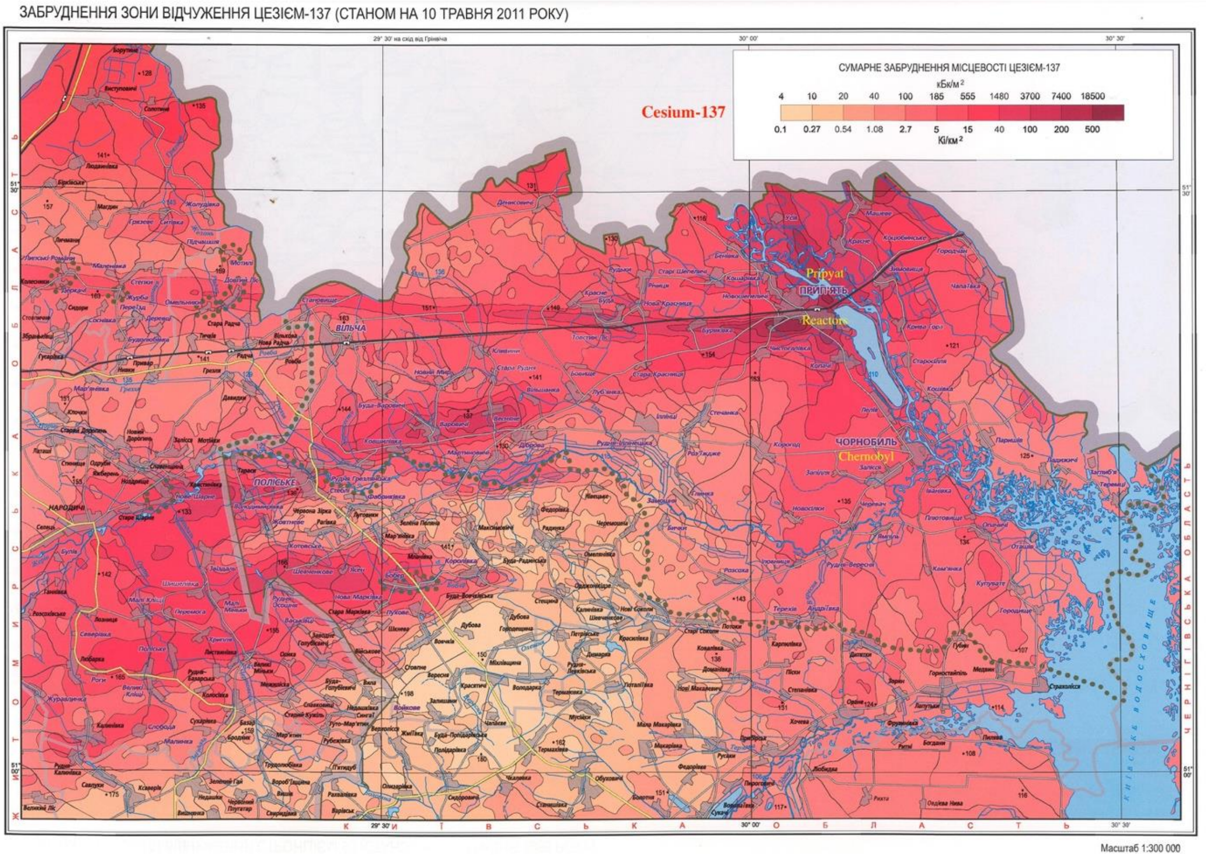

Figure A9: *2011 map of the surface ground deposition of cesium-137 in the Ukranian part of the Chernobyl exclusion zone. The upper scale is in kBq/m^2 and the lower scale in Ci/km^2.*

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[10] http://dazv.gov.ua/en/

Strontium-90 (May 2011)

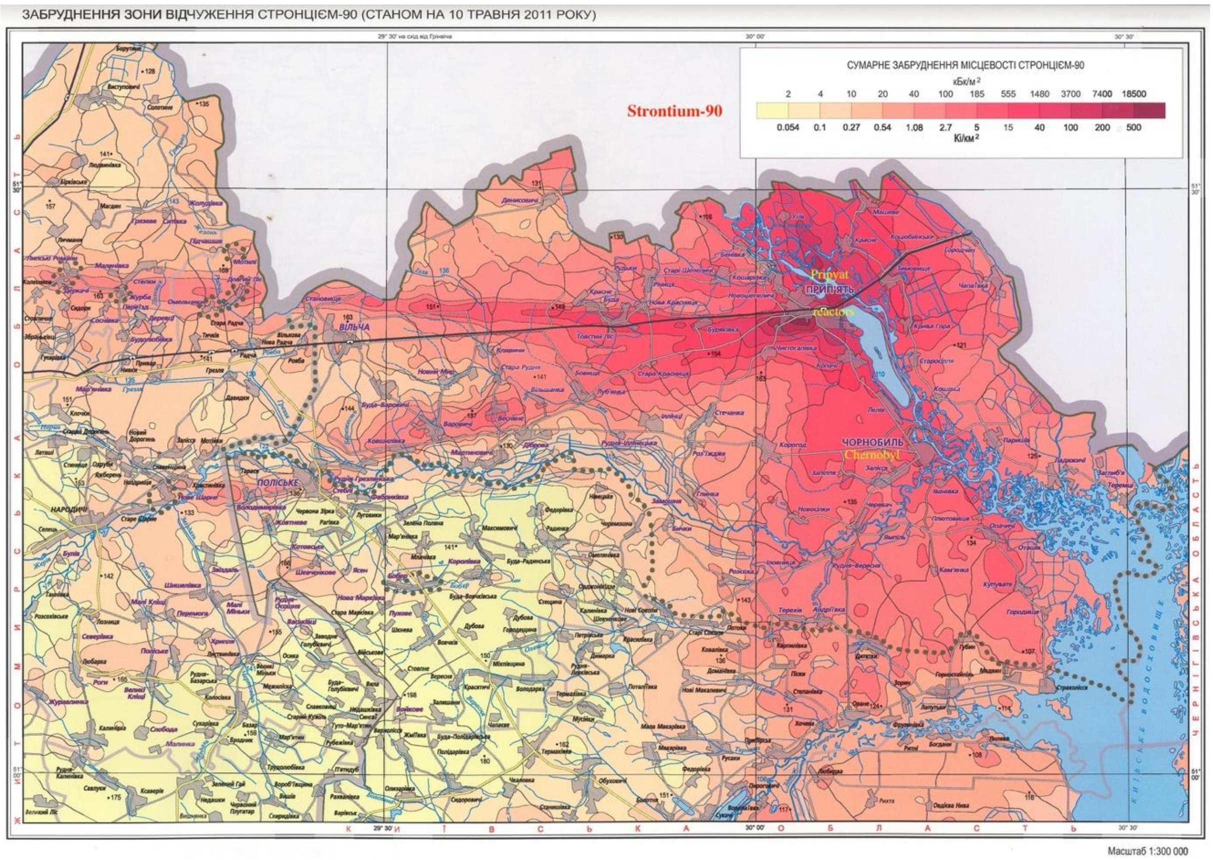

Figure A10: *2011 map of the surface ground deposition of strontium-90 in the Ukranian part of the Chernobyl exclusion zone. The upper scale is in kBq/m^2 and the lower scale in Ci/km^2.*

Plutonium isotopes

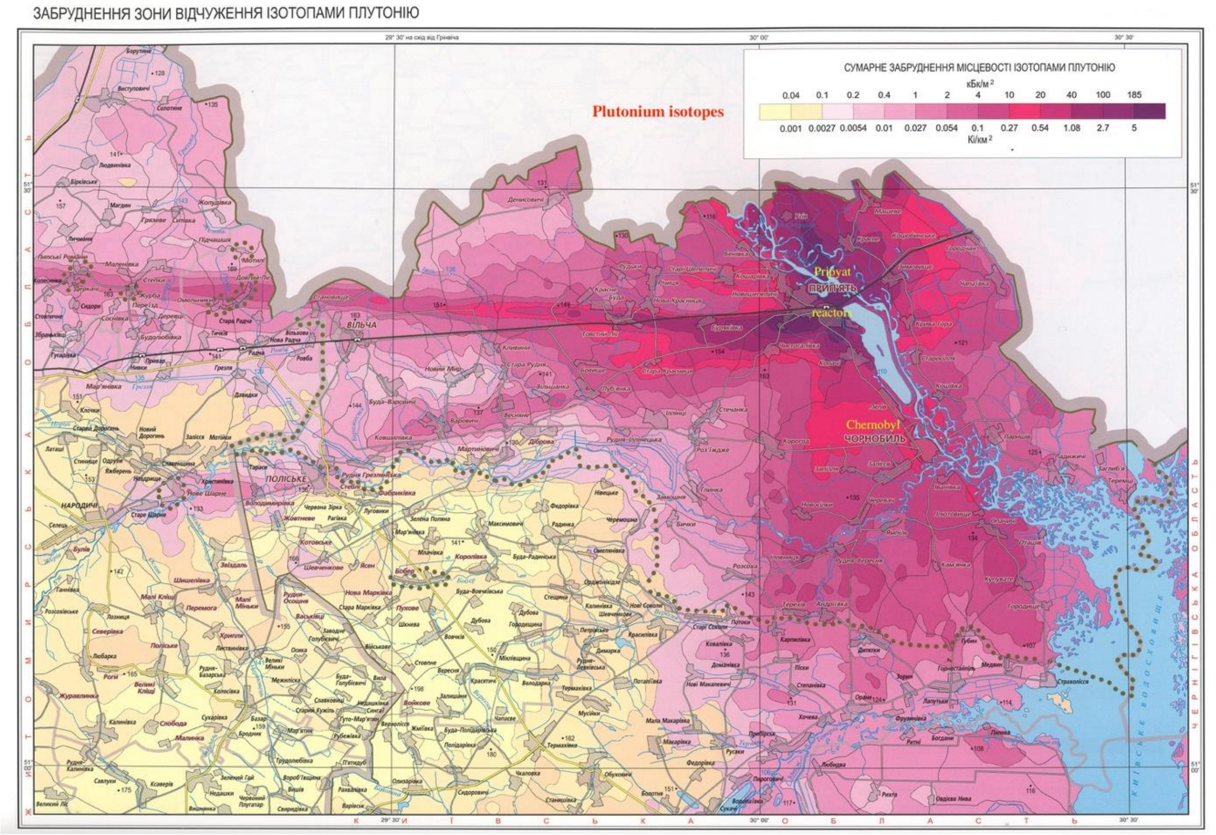

Figure A11: *2011 map of the surface ground deposition of plutonium isotopes in the Ukranian part of the Chernobyl exclusion zone. The upper scale is in kBq/m^2 and the lower scale in Ci/km^2.*

Americium-241

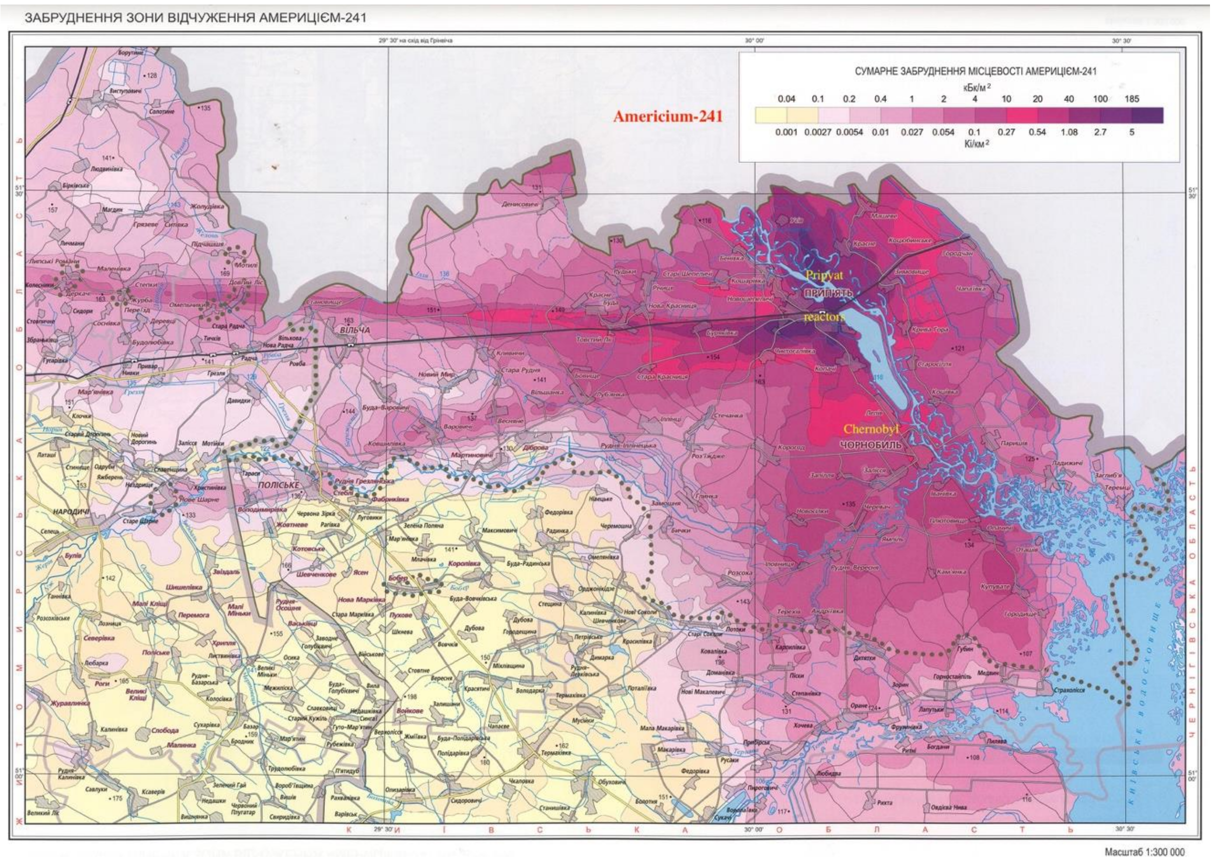

Figure A12: *2011 map of the surface ground deposition of americium-241 in the Ukranian part of the Chernobyl exclusion zone. The upper scale is in kBq/m^2 and the lower scale in Ci/km^2.*