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Potential consequences of hypothetical nuclear power plant accidents in Finland

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KEYWORDS: Nuclear power plant accident, protective actions, emergency preparedness, SILAM, emergency planning zones, operational intervention levels, dose criteria

Abstract

An assessment of the environmental consequences of radioactive releases from severe reactor accidents was performed for Finnish nuclear power plants (NPP) in operation (Loviisa 1 and 2, and Olkiluoto 1 and 2), in commissioning (Olkiluoto 3) and in the preparatory phase (Hanhikivi 1). Three hypothetical radioactive releases (Basic, Large and Very Large cases) with different magnitudes were considered. Basic case represents a release corresponding to the limit set in requirements for severe reactor accidents, and thus, the other two represent extremely unlikely situations where severe accident management has failed. The magnitude of Very Large case is similar to the Fukushima NPP accident and roughly one order of magnitude smaller than the Chernobyl NPP accident, while the magnitude of Large case is roughly one order of magnitude smaller. The environmental assessment on the consequences of the releases was performed using a probabilistic approach. The aim is to estimate radiation doses to the population around the NPP and land contamination resulting from the release of radioactive material. The results of the assessment were compared to the protective action criteria for radioactive release from an NPP, and further used to evaluate the sufficiency of the Precautionary Action Zone (PAZ) and Emergency Planning Zone (EPZ) given in Finnish regulation. The probability of exceeding different operational intervention levels (OIL) and dose criteria set for external dose rate, effective dose, thyroid dose, deposition of strong gamma emitters, deposition of cesium, and concentration of gamma emitters in the air were estimated for distances up to 300 km from each site.

Dispersion and deposition of releases were modelled with the dispersion model SILAM of the Finnish Meteorological Institute. The modelling applied historical weather forecast data from the years 2012–2015 retrieved with operative weather forecast models AROME and HARMONIE. Dose rates and doses were determined from the radionuclide air concentrations and depositions with the threat

assessment tool TIUKU. The assessment was preformed using 2920 dispersion realizations for each reactor type and release scenario. For the assessment, the 95th percentile of the modelled dispersion, deposition and dose data was selected.

The assessment showed that it is unlikely that any OILs or dose criteria would be exceeded outside PAZ and EPZ in a Basic case. In a Large case, the OILs may be exceeded up to about 110 km from the NPP sites, while it could be up to 170 km for dose criteria for the recommendation to limit being outside and iodine prophylaxis for children and pregnant females. The assessment indicated that it is unlikely that sheltering indoors or evacuation are needed outside the PAZ and EPZ during the early phase of the emergency due to the release in a Large case. In a Very Large case, extensive protective actions including permanent or temporary relocation are needed outside EPZ and less restrictive protective actions (i.e., recommendation to limit being outside and iodine prophylaxis for children and pregnant females) are needed beyond the area considered in this study (> 300 km). It was shown, however, that the protective actions outside the PAZ and EPZ are strongly dependent on prevailing weather conditions.

It was observed that the dose criteria for an adult's effective and thyroid dose were exceeded in larger areas than suggested by the criteria based on the external dose rate. Furthermore, dose criteria for a child's thyroid dose were exceeded in larger areas than the dose criteria for the recommendation to limit being outside, even though the iodine prophylaxis for children and pregnant females is set as a complementary protective action for the recommendation to limit being outside. The observation demonstrates that the content of the radioactive release must be carefully considered in a severe NPP accident as the amount of released iodine isotopes affect the thyroid dose, while other nuclides make only a small contribution to it. It was also observed that precipitation may cause the deposition of radioactive substances such that in large areas the criteria for protective action based on deposition may be exceeded, even when protective actions would not be warranted according to dose criteria for effective doses. In Large and Very Large cases, the deposition may lead to the need for decontamination of large areas, and temporary or even permanent relocation of people. These findings demonstrate the importance of primarily using dose criteria in decision making if dose calculations can be performed reliably during the actual nuclear or radiological emergency. The OILs shall be used only if measures with dose criteria cannot be determined reliably e.g., due to a lack of information. Based on the results, it was concluded that further study is needed to set an Extended Planning Distance (EPD) and Ingestion and Commodities Planning Distance (ICPD). In such a study, a level 2 Probabilistic Risk Assessments (PRA) considering the probability of atmospheric releases should be better linked with environmental consequence assessment. The International Atomic Energy Agency (IAEA) recommends the EPD and ICPD to facilitate preparedness planning and the execution of protective actions beyond the PAZ and EPZ. The existence of an EPD and ICPD could also improve the effective co-operation of different authorities and emergency workers in a nuclear emergency.

In Large and Very Large cases, the seasonal variations between summer and winter were found to be significant especially when considering deposition of cesium and strong gamma emitters. It was observed that precipitation during the winter season causes more wet deposition than in the summer. In a Very Large case, the seasonal variations were also significant in other measures.

AVAINSANAT: Ydinvoimalaitosonnettomuudet, suojelutoimenpiteet, valmius, varautuminen, SILAM, varautumisalueet, operatiiviset toimenpiderajat, annosrajat

Tiivistelmä

Ydinvoiman käyttöön liittyy hyvin pieni riski vakavasta onnettomuudesta, jonka seurauksena radioaktiivisia aineita voi vapautua myös laitoksen ympäristöön. Tässä työssä arvioitiin vakavien ydinvoimalaitosonnettomuuksien radioaktiivisten päästöjen vaikutuksia laitoksen ulkopuolella käytössä olevilla (Loviisa 1 ja 2, Olkiluoto 1 ja 2), koekäytössä olevalta (Olkiluoto 3) ja suunnitteilla olevalla (Hanhikivi 1) suomalaisilla ydinvoimalaitoksilla. Työssä tarkasteltiin kolmea eri suuruisen hypoteettisen päästön (perustapaus, vakava ja erittäin vakava) vaikutuksia. Perustapaus vastaa päästöä, joka on asetettu rajaksi vakavalle reaktorionnettomuudelle, minkä vuoksi kaksi muuta tapausta vastaavat erittäin epätodennäköisiä tilanteita, joissa vakavien onnettomuuksien hallintatoimet ovat epäonnistuneet. Kokonaisuudessaan erittäin vakava päästö on samaa suuruusluokkaa kuin Fukushiman ydinvoimalaonnettomuuden aiheuttama päästö, ja noin kertaluokkaa pienempi kuin Tšernobylin ydinvoimalaonnettomuuden aiheuttama päästö. Vastaavasti vakava päästö on suuruusluokaltaan kertaluokkaa pienempi kuin erittäin vakava päästö. Päästöjen seurausarviot tehtiin hyödyntäen todennäköisyyspohjaisia menetelmiä, joilla arvioitiin väestölle päästöstä aiheutuvia säteilyannoksia ja maan kontaminoitumisen laajuutta voimalaitosten ympäristössä. Päästön aiheuttavan onnettomuuden todennäköisyyksien arviointi rajattiin tarkastelun ulkopuolelle. Tulostenperusteella arvioitiin tarvittavia suojelutoimia annos- ja toimenpiderajojen perusteella suhteessa suomalaisen säännöstön velvoittamiin suojavyöhykkeeseen ja varautumisalueeseen. Työssä tarkasteltiin ulkoiselle annosnopeudelle, efektiiviselle annokselle, kilpirauhasannokselle, voimakkaiden gamma säteilijöiden laskeumalle, cesiumin isotooppien laskeumalle ja voimakkaiden gamma säteilijöiden ilmakonsentraatiolle asetettujen annos- ja toimenpiderajojen ylittymistä 300 kilometrin säteellä ydinvoimalaitospaikoista.

Päästöjen leviäminen ilmakehässä ja laskeuma mallinnettiin käyttäen Ilmatieteen laitoksen SILAM leviämismallia. Leviämismallinnuksessa hyödynnettiin AROME ja HARMONIE säämalleilla tuotettua Ilmatieteen laitoksen operatiivista sääennustedataa vuosilta 2012–2015. Annosnopeudet, efektiiviset annokset ja kilpirauhasannokset määritettiin SILAM-leviämisdatasta käyttäen Säteilyturvakeskuksen Tilanne- ja uhkakuvajärjestelmää (TIUKU). Analyyseissä hyödynnettiin 2920 eri sääennustetta jokaiselle reaktorityypille ja päästölle. Esitetyt tulokset edustavat 95. persentiiliä leviämis-, laskeuma ja annosdatasta, toisin sanottuna kussakin tarkastelupisteessä seuraamukset ovat vähäisempiä 95 %:n ja vakavampia 5 %:n todennäköisyydellä.

Perustapauksessa on erittäin epätodennäköistä, että yksikään annos- tai toimenpiderajoista ylittyisi päästön seurauksena suojavyöhykkeen tai varautumisalueen ulkopuolella. Vakavan päästön seurauksesta ulkona olon rajoittamisen annos- ja toimenpiderajat voivat ylittyä jopa 110 km:n etäisyydellä voimalaitoksista sekä lasten ja raskaana olevien joditablettisuositus jopa 170 km:n etäisyydellä. On epätodennäköistä, että sisälle suojautumiselle ja evakuoinnille asetetut annos- tai toimipiderajat ylittyisivät varhaisvaiheessa vakavan päästön seurauksena suojavyöhykkeen tai varautumisalueen ulkopuolella. Erittäin vakavan päästön seurauksena voidaan joutua sijoittamaan väestöä tilapäisesti tai jopa pysyvästi myös varautumisalueen ulkopuolella. Vähemmän rajoittavia suojelutoimia (ulkona olon rajoittaminen sekä lasten ja raskaana olevien jodi tabletit) voidaan tarvita jopa tarkastelu alueen ulkopuolella (> 300 km). Tulokset osoittivat kuitenkin, että suojelutoimien tarve suojavyöhykkeen ja varautumisalueen ulkopuolella riippuvat voimakkaasti vallitsevasta säätilasta.

Efektiiviselle annokselle ja kilpirauhasannokselle asetetut annosrajat ylittyvät laajemmilla alueilla kuin annosnopeuden mukaisen toimenpiderajan mukaan arvioituna. Lasten ja raskaana olevien naisten joditablettien ottamiselle annettu annosrajat ylittyvät laajemmilla alueilla kuin ulkona olon rajoittamiselle asetettu annosraja, vaikka lasten ja raskaana olevien naisten joditabletit ovat tarkoitettu ulkona olon rajoittamista täydentäväksi toimenpiteiksi. Tämä havainto korostaa kuinka tärkeää on tarkastella radioaktiivisen päästön koostumusta, sillä jodi-isotooppien määrä vaikuttaa voimakkaasti kilpirauhasannokseen. Sadanta voi aiheuttaa voimakkaan radionuklidien laskeuman, joka puolestaan aiheuttaa toimenpiderajojen ylittymisen laajemmilla alueilla kuin varhaisvaiheessa efektiiviselle annokselle asetettujen annosrajojen ylittymisen perusteella voisi olettaa. Vakavassa ja erittäin vakavassa tapauksessa radioaktiivisten aineiden laskeuma voi aiheuttaa laajoilla alueilla väliaikaisen tai pysyvän väestön uudelleensijoittamis tarpeen, mikäli alueita ei pystytä dekontaminoimaan riittävän hyvin. Tehdyt havainnot korostavat annosrajojen tärkeyttä ensisijaisena kriteerinä päätöksenteossa, mikäli annoksia kyetään arvioimaan luotettavasti tilanteen aikana. Toimenpiderajoja tulee käyttää päätöksenteossa, jos annoksia ei pystytä arvioimaan luotettavasti esim. tiedonpuutteen vuoksi. Työn tulosten perusteella todettiin tarpeelliseksi lisätutkimukset, joilla määritetään mahdollinen jatkettu suunnitteluetäisyys (Extended Planning Distance, EPD) ja elintarvikkeiden suojausetäisyys (Ingestion and Commodities Planning Distance, ICPD). Lisätutkimukset tulee suorittaa hyödyntäen tason 2 todennäköisyysperusteista riskianalyysiä, joka ottaa huomioon sekä mahdollisten päästöjen todennäköisyydet. IAEA on suositellut EPD:tä ja ICPD:tä käytettäväksi valmiussuunnittelussa, jotta mahdollisessa hätätilanteessa tarpeelliset suojelutoimet saataisiin suorettua tehokkaasti myös suojavyöhykkeen ja varautumisalueen ulkopuolella. EPD:n ja ICPD:n olemassaolo voisi lisäksi parantaa viranomaisten ja pelastushenkilökunnan yhteistyötä hätätilanteen aikana ja kykyä reagoida riittävän aikaisessa vaiheessa.

Vakavan ja erittäin vakavan päästön tapauksessa vuodenaikojen (kesä ja talvi) välisen vaihtelun todettiin olevan merkittävää. Ero korostui erityisesti tarkasteltaessa cesiumin ja voimakkaiden gamma emittereiden laskeumaa. Tämän todettiin johtuvan talven kesää voimakkaammasta sadannasta, joka puolestaan aiheuttaa voimamman märkälaskeuman. Erittäin vakavassa tapauksessa kesä ja talven välisten erojen todettiin olevan merkittäviä myös annoksia ja muiden toimenpiderajojen suureita tarkasteltaessa.

NYCKELORD: Kärnkraftverksolyckor, skyddsåtgärder, beredskap, förhandsberedskap, SILAM, beredskapszoner, operativa åtgärdsgränser, dosgränser

Sammanfattning

Användningen av kärnkraft är förknippad med en mycket liten risk för allvarliga olyckor till följd av vilka radioaktiva ämnen kan frigöras till området utanför anläggningen. I detta arbete bedömdes effekterna av radioaktiva utsläpp utanför anläggningen vid en allvarlig olycka vid en kärnanläggning på finländska kärnkraftverk som är i drift (Lovisa 1 och 2, Olkiluoto 1 och 2), som ska tas i drift (Olkiluoto 3) och som är under planering (Hanhikivi 1). I arbetet undersöktes hypotetiska utsläpp i tre storleksklasser (basfallet, allvarlig och mycket allvarlig). Basfallet motsvarar ett utsläpp som satts som gräns för en allvarlig reaktorolycka, varför de två andra fallen motsvarar högst osannolika situationer där åtgärder för att hantera svåra olyckor har misslyckats. Sammantaget är de mycket allvarliga utsläppen av samma storleksordning som de som orsakades av kärnkraftsolyckan i Fukushima, och ungefär en storleksordning lägre än de som orsakades av kärnkraftsolyckan i Tjernobyl. På motsvarande sätt är ett allvarligt utsläpp en storleksordning mindre än ett mycket allvarligt utsläpp. Utsläpps konsekvensbedömningar genomfördes med probabilistiska metoder för att bedöma stråldoserna till befolkningen och markföroreningar i närheten av kraftverk. Bedömningen av sannolikheten för en olycka som orsakar utsläpp lämnades utanför studien. På grundval av resultaten bedömdes de nödvändiga skyddsåtgärderna baserat på dos- och åtgärdsgränserna i förhållande till den skyddszon och beredskapszon som krävs enligt den finska lagstiftningen. I arbetet undersöktes överskridandet av de dos- och åtgärdsgränser som fastställts för den externa dosraten, effektiva dosen, sköldkörteldosen, nedfallet av starka gammastrålare, nedfallet av cesiumisotoper och koncentrationen av starka gammastrålare i luften inom 300 km:s radie från kärnkraftsanläggningarnas förläggningsplatser.

Spridningen av utsläppen i atmosfären och nedfallet av utsläppen modellerades med hjälp av Meteorologiska institutets spridningsmodell SILAM. I spridningsmodelleringen användes väderprognosdata för åren 2012–2015 som

Meteorologiska institutet tagit fram med hjälp av vädermodellerna AROME och HARMONIE. Dosraterna, de effektiva doserna och sköldkörteldoserna bestämdes utifrån spridningsdata från SILAM-modellen med hjälp av Strålsäkerhetsmyndighetens system för läges- och hotbilder (TIUKU). I analyserna utnyttjades 2 920 olika väderprognoser för respektive reaktortyp och utsläpp. Resultaten som visas representerar 95:e percentilen av spridnings-, nedfalls- och dosdata. Med andra ord är sannolikheten för mindre allvarliga konsekvenser 95 procent och för allvarligare konsekvenser fem procent vid varje observationspunkt.

Vid mindre utsläpp är det mycket osannolikt att någon dos- eller åtgärdsgräns skulle överskridas utanför skydds- eller beredskapszonen till följd av utsläpp. Till följd av allvarliga utsläpp kan dos- och åtgärdsgränserna för begränsning av utevistelse överskridas på upp till 110 km:s avstånd från anläggningen och för jodtablettrekommendationen för barn och gravida kvinnor på upp till 170 km:s avstånd. Det är osannolikt att de dos- eller åtgärdsgränser som fastställts för skydd inomhus och evakuering skulle överskridas i ett tidigt skede till följd av ett allvarligt utsläpp utanför skydds- eller beredskapszonen. Till följd av mycket allvarliga utsläpp kan det bli nödvändigt att tillfälligt eller till och med permanent flytta befolkningen utanför beredskapszonen. Mindre restriktiva skyddsåtgärder (begränsing av utevistelse och jodtabletter för barn och gravida kvinnor) kan behövas till och med utanför granskningsområdet (> 300 km). Resultaten visade dock att behovet av skyddsåtgärder utanför skydds- och beredskapszonen är starkt beroende av de rådande väderförhållandena.

Dosgränserna för effektiv dos och sköldkörteldos överskrids i större områden än vad som beräknats utifrån åtgärdsgränsen enligt dosraten. Dosgränserna för intag av jodtabletter hos barn och gravida kvinnor överskrids i större områden än dosgränsen för begränsning av utevistelse, även om jodtabletter för barn och gravida kvinnor är avsedda som kompletterande åtgärder för begränsning av utevistelse. Denna iakttagelse understryker vikten av att titta på sammansättningen av de radioaktiva utsläppen, eftersom mängden jodisotoper starkt påverkar sköldkörteldosen. Nederbörd kan orsaka kraftigt nedfall av radionuklider, vilket i sin tur leder till överskridande av åtgärdsgränserna i större områden än vad som kan förväntas baserat på de dosgränser för en effektiv dos som fastställts i ett tidigt skede. I en allvarlig och mycket allvarlig situation kan nedfallet av radioaktiva ämnen göra det nödvändigt att tillfälligt eller permanent omlokalisera befolkningen i stora områden, om områdena inte kan dekontamineras tillräckligt väl. De gjorda iakttagelserna understryker vikten av dosgränser som det primära kriteriet i beslutsfattandet, om doserna kan beräknas på ett tillförlitligt sätt under den pågående situationen. Åtgärdsgränser ska användas i beslutsfattandet om doserna inte kan beräknas på ett tillförlitligt sätt till exempel på grund av bristfällig information. På grundval av resultaten från arbetet ansågs det nödvändigt att genomföra ytterligare undersökningar för att fastställa det eventuella utökade planeringsavståndet (EPD) samt planeringsavståndet för skydd av livsmedelskedjan och dricksvattentäkter samt för skydd av andra varor (ICPD). De ytterligare undersökningarna ska utföras med hjälp av en sannolikhetsbaserad riskanalys på nivå 2 som beaktar sannolikheten av potentiella utsläpp. IAEA har rekommenderat att EPD och ICPD används i beredskapsplaneringen för att säkerställa ett effektivt genomförande av de nödvändiga skyddsåtgärderna även utanför skydds- och beredskapszonen i händelse av en nödsituation. EPD och ICPD kan dessutom bidra till ett bättre samarbete mellan myndigheter och räddningspersonal under en nödsituation och till ökad förmåga att reagera tillräckligt tidigt.

Det konstaterades att det i fråga om allvarliga och mycket allvarliga utsläpp fanns betydande variationer mellan årstiderna (sommar och vinter). Skillnaden var särskilt uttalad i granskningen av nedfallet av cesium och starka gammastrålare. Detta konstaterades i sin tur bero på att nederbörden är större på vintern jämfört med sommaren, vilket i sin tur ger större mängder vått nedfall. Ytterligare fastslogs att i en mycket allvarlig situation är även i granskningen av storheterna för doser och andra åtgärdsgränser skillnaderna mellan sommar och vinter betydande.

1 Introduction

Based on the Radiation Act, the use of radiation and practices are considered acceptable when the following requirements are fulfilled (Radiation Act):

1. The benefits derived from the practice should exceed the detriment it causes.
2. The practice should be arranged so that the resulting exposure to radiation hazardous to health is kept as low as is reasonably achievable.
3. No person should be exposed to radiation exceeding the maximum values prescribed by the Decree.

Furthermore, the Nuclear Energy Act defines provisions on the general principles for the use of nuclear energy (Nuclear Energy Act):

1. The use of nuclear energy, taking into account its various effects, shall be in line with the overall good of society.
2. The use of nuclear energy must be safe, and it shall not cause harm to people or damage to the environment or property.

The Nuclear Energy Decree specifies at a more detailed level that in anticipated operational occurrences the effective dose of people shall not exceed 0.1 mSv. It also specifies that in the case of a nuclear accident, the effective dose of people shall not exceed 1 mSv in a level 1 postulated accident, 5 mSv in a level 2 postulated accident, and 20 mSv in design extension conditions. A release of radioactive substances due to a severe nuclear accident shall not cause extensive protective actions of people or long-term use restrictions for large areas. Furthermore, it is specified that to decrease the long-term consequences of a nuclear accident, the probability of an accidental release that exceeds 100 TBq of Cs-137 must be extremely low. (Nuclear Energy Decree)

These Acts and Decree form the top-level acceptance criteria for the safe operation of Nuclear Power Plants (NPP). However, the operation always includes a very small risk of an accident leading to a release of radioactive substances into the environment. Hence, the probabilities of possible consequences of accidental releases must be carefully evaluated so that the legally binding requirements are met. To define necessary protective actions and to prepare for emergency situations, authorities need information on the potential consequences of NPP accidents.

Due to the high potential consequences for the population, environment, and society in general, production of nuclear power is highly regulated. The International Atomic Energy Agency (IAEA) supports member states in achieving governmental, regulatory and safety frameworks for nuclear power production by compiling The IAEA Safety Standards comprising Safety Fundamentals, Safety Requirements and Safety Guides. For example, the IAEA recommends that NPPs have specified off-site Emergency Planning Zones (EPZ) and Emergency Planning Distances (EPD) for which possible protective actions should be planned (IAEA 2015a). These EPZs and EPDs should include: 1. Precautionary Action Zone (PAZ) where urgent protective actions should be planned and taken before any significant radioactive release in order to avoid or to minimize severe deterministic effects, 2. Urgent Protective action planning Zone (UPZ) where protective actions should be initiated before radioactive release and taken based on the off-site monitoring and assessment of situation in order to reduce the risk of stochastic effects, 3. An Extended Planning Distance (EPD) where the situation should be monitored and assessed in order to identify areas where protective actions would decrease the risk of stochastic effects, and 4. An Ingestion and Commodities Planning Distance (ICPD) where response actions should be planned to protect the food chains, water supplies and other commodities from contamination as well as to protect the public from the ingestion of contaminated food, milk and drinking water and from the use of other contaminated commodities. Furthermore, there should be criteria for the initiation and adjusting of the protective actions.

Finnish legislation requires that the licensees provide a Probabilistic Risk Assessment (PRA) that forms the foundation for nuclear safety-related risk management. The PRAs are required for two levels: A Level 1 PRA estimates the probability of accidents leading to nuclear damage, and a Level 2 PRA estimates probability, magnitude, and duration of radioactive release. The environmental and health risks caused by the radioactive releases are estimated using a Level 3 PRA. Complete Level 3 PRA contains Levels 1 and 2 and effectiveness analyses and effectiveness of countermeasures and is not required but the environmental and health risks have to be estimated. In the Finnish legislation, about 5 km is used for the PAZ and 20 km for EPZ (equivalent of UPZ in terminology used by IAEA). In emergency situations, the owner of the NPP should be prepared for radiation monitoring in the PAZ, assessing the dispersion of radioactive release meteorological conditions, and assessing the possible radiation exposure of the public in the EPZ. The authorities must make an external rescue plan that covers the EPZ. In Finland, the competent authority on nuclear and radiological emergencies is the Radiation and Nuclear Safety Authority (STUK), which provides expertise and recommendations to rescue services and governmental authorities which have the decision-making power on protective actions concerning the population and society in general. The aim of this work is to estimate the possibility and probabilities of different actions in the EPZ and beyond, and the size of possibly contaminated areas in hypothetical release scenarios.

1.1 Previous research

In general, the consequences of the releases from NPP accidents are challenging to predict precisely. For example, modelling dispersion of the radioactive release using simplified weather forecast models, calculation of radiation doses using generalized effective dose rate coefficients, and limited information on the release time and duration increase the uncertainty of the predictions. In previous studies, the consequences of NPP accidents for the Finnish population in major cities near NPPs have been estimated using a scenario of severe reactor failure in unfavorable weather conditions. In a study published in 1993, the short-term radiological consequences of a hypothetical reactor accident in Leningrad NPP (Russia) for the populations in Helsinki and Kotka were evaluated (Lahtinen et al. 1993). The study concluded that the individual effective doses would not exceed 60 mSv and 40 mSv in Kotka and Helsinki, respectively. The study also found that in the early stage, inhalation would be the most dominant pathway for radiation exposure and that iodine is the main source of radiation dose. Later in 2011, the report was extended to cover the consequences of severe NPP accidents in NPPs operating in Finland in Loviisa and Olkiluoto and in foreign NPPs close to Finnish borders in Kola (Russia), Ignalina (Lithuania) and Forsmark (Sweden) (Toivonen et al. 2011). They reached the same conclusion as the earlier study regarding the dominant pathway for radiation exposure and the main source of radiation dose. Furthermore, they stated that accidents in foreign NPPs would not cause deterministic health effects in Finland. However, the land contamination may affect food production areas and necessitate restrictions. Accidents at domestic NPPs could require urgent countermeasures (evacuation, iodine prophylaxis, safeguarding in civil defense shelters) inside the EPZ while outside the EPZ, sheltering indoors and iodine prophylaxis would be sufficient.

To this date, only one probability-based study has been published focusing on the consequences of a predefined release due to NPP accidents for the Finnish population. In this study, the effects of a severe reactor accident in Leningrad NPP were studied using a trajectory-based approach to estimate radiation doses and their probabilities (Ilvonen et al. 1994). According to this study, an NPP accident in Leningrad NPP does not cause deterministic health effects in the Finnish population. However, they concluded that countermeasures (e.g., sheltering indoors and iodine prophylaxis) may be needed to decrease the probability of stochastic health effects. Previously, a similar study on the consequences of a severe NPP accident in Leningrad NPP for the Norwegian population was performed (Nalbandyan et al. 2012). The focus of the study was the long-term consequences of a hypothetical accident.

The Swedish Radiation Safety Authority (SSM) recently published a report where the consequences of NPP accidents for the Swedish population was studied using modern probability-based tools (Johansson et al. 2018). They studied three types of NPP accidents with different magnitudes for the NPPs at Forsmark, Oskarshamn and Ringhals. The aim of the study was to revise radii of EPZs according to a plan assigned by Swedish government. In the results, SSM proposed surrounding Swedish NPPs with a PAZ of 5 km and UPZ of 25 km. Furthermore, they proposed an EPD (up to 100 km) where protective actions (e.g., sheltering and iodine prophylaxis) would be taken based on measurements. Previously, a similar study was performed for German NPPs where the potential radiological consequences of a "Fukushima-like" accident were estimated (Walter et al. 2016). They reported that in the case of a severe NPP accident, the high radiation doses (> 1000 mSv) could be received at distances up to 3 km, evacuation could be needed at distances up to 18 km (adults) and 24 km (infants), sheltering could be needed at distances up to 80 km (adults) and 114 km (infants), and iodine prophylaxis could be needed up to 34 km (adults) and 161 km (infants and pregnant females). Based on the results of the study, the German Commission on Radiological Protection recommended new planning areas: a “central zone”, “middle zone” and “outer zone” that extend up to 5 km, 20 km, and 100 km, respectively, from the NPPs operating in Germany (Strahlenschutzkommission 2014). The recommended countermeasures inside the planning areas are similar to those of SSM for PAZ, UPZ and EPD.

1.2 Objective

The objective of this study is to update and supplement the previous reports focused on estimating the consequences of hypothetical NPP accidents in Finland. The aim is to estimate the potential radiation dose and land contamination in the accidents up to 300 km from the release point with up-to-date modelling and analysis tools using realistic weather scenarios. The assessment is performed with a probabilistic approach for Finnish NPPs in operation (Loviisa 1 and 2, and Olkiluoto 1 and 2), in commissioning (Olkiluoto 3) and in the preparatory phase (Hanhikivi 1). The approach is similar to a level 3 PRA, but the probabilities of applied releases (level 2 PRA) and effectiveness of countermeasures are not estimated. The aim is also to estimate more realistically the sufficiency of current PAZs and EPZs and the probability of protective actions outside the zones during an NPP accident in Finland. The assessment considers the actual weather conditions from the years 2012–2015 on each site and reveals possible bias in release and deposition patterns, e.g., due to dominant wind directions.

2 Nuclear power plants, hypothetical accidents, and potential releases to the environment

2.1 Hypothetical nuclear power plant accidents

NPP accidents can be caused by many initiating events. The significant releases that are studied in this work can occur only when the integrity of the nuclear fuel in the reactor core, reactor coolant system (RCS) and containment are compromised, and the safety systems are not working properly. In such cases, a part of fission and neutron activation products and their decay products may exit the fuel and RCS, leak into the containment, and be released to the environment through the damaged containment pressure boundary. The fission products and their decay products cause the largest risk in the NPP accidents.

Fuel damage can be caused by elevated temperature due to heat produced due to decay of the radioactive nuclides within the reactor core. Typically, the electrical power of NPP is about 35% of the thermal power (see Table 2.1.) for electrical and thermal powers of Finnish NPP units). Due to the decay heat of the fission products, the heat transfer from the fuel must be ensured for a long time after the reactor shut down, even though the fission chain reaction has been terminated. The rise of the temperature in fuel can be caused for example due to a loss-of-coolant accident (LOCA) (see e.g., STUK 2004). Such an event is one of the postulated accidents against which specific safety systems have been designed. These safety systems make sure that the reactor withstands the accident without sustaining severe fuel failure, even if some components of the safety systems do not work properly due to e.g., service or faults. If all these safety systems are not working properly, the core can be uncovered, the fuel temperature rises and causes damage and radioactive material could leak into the RCS.

In normal operation, the RCS acts as a release barrier and prevents the leak of radionuclides from the RCS into the containment. Typically, LOCA or other accidents leading to severe damage of reactor core require that the integrity of the RCS is compromised, and that coolant has leaked out from the RCS. At this point, the integrity of the containment becomes crucial. The integrity of the containment could be compromised due to the uncontrolled pressure rise caused by heat generated by damaged reactor core, a steam and hydrogen (generated by oxidation of molten reactor core) explosion inside the containment, or due to damage caused by the molten corium to the basemat of the containment. In the case of a severe accident, the containment also delays the release and decreases the magnitude of a possible release due to the radioactive decay of short living radionuclides. This also gives time for authorities to take precautionary and urgent protective actions and to minimize the potential radiation dose to people.

The scenarios studied are based on different integrity levels of the containment and on the capability of containment to delay the release of radioactive substances into the atmosphere once the integrity of the reactor core and the RCS has been lost. Initiating events or their probabilities are not determined, and the considered releases are rather selected to represent different magnitudes.

Criticality accidents caused by an uncontrolled chain reaction could cause more severe consequences. However, such accidents in light water reactors with low enriched uranium would be highly unlikely even when comparing to a complete meltdown of a reactor core and thus they are not considered in this work. In general, the probability of all accidents considered is extremely low. It is required that the design of a new NPP unit should be such that the frequency of reactor core damage is less than 10^{-5}/year (STUK 2019a). For older units these requirements are applied as far as reasonably practicable. Furthermore, it is required that the frequency for a release of radioactive substances from the plant during an accident involving a cesium-137 release (Cs-137) into the atmosphere in excess of 100 TBq is less than 5×10^{-7}/year, and that the accident sequences in which the containment function fails or is lost in the early phase of a severe accident make only a small contribution to the reactor core damage frequency. Even though the probability of an accident is small, possible consequences must be carefully assessed.

2.2 Radioactive substances released in NPP accidents and their significance for radioprotection

Uranium, containing mainly U-238 and U-235, is used as fuel in NPPs. Numerous radioactive isotopes are generated in the reactors as a side product of energy production. These radioactive isotopes include fission products and neutron activation products in the fuel, neutron activation products in coolant and structural materials, and decay products of all generated radioactive isotopes that may also be radioactive. Most of the radioactive nuclides are within the fuel that forms the major potential for releases of radioactive substances. During operation, the amounts of different radionuclides change due to fission, neutron activation and radioactive decay, and the amounts are dependent on the reactor type and design.

In the case of a reactor accident, volatile radionuclides may be released into the containment atmosphere in significant amounts. In the temperature ranges encountered in the core during power production, radioactive iodine, cesium, strontium, and tellurium isotopes are in solid or gaseous form and are trapped inside the fuel rods in the reactor core. If cooling of the reactor is compromised and the temperature of the fuel rises, the reactor core may be damaged, solid forms of radionuclides may be vaporized and gaseous radionuclides released from the fuel. If the containment has lost its integrity, these radionuclides may be released into the environment. The vaporized radionuclides form aerosols in the containment atmosphere. Furthermore, radioactive noble gases, such as krypton and xenon, are released very easily in an NPP accident and they do not form aerosols due to their chemical inertness. Inert noble gasses are difficult to remove from the containment atmosphere and they do not attach onto surfaces of the containment as other radionuclides do. Hence, the majority of noble gases are released into the atmosphere in severe reactor accidents.

For radiation protection purposes, I-131, Cs-134, and Cs-137 have special significance due to their radioactive properties. I-131 decays through beta decay also emitting gamma quanta and accumulates in the thyroid in a human body (STUK 2003). The accumulated radioactive iodine causes a local radiation dose for the thyroid. With a physical half-life of 8 days, I-131 is not relevant for long term dose accumulation. Cs-134 and Cs-137 (+Ba-137m) are strong gamma emitters through beta-decay. Cs-134 and Cs-137 have relatively long half-lives of 2.1 y and 30.1 y, respectively. Hence, their deposition after an NPP accident is meaningful for protective action planning. During the early and intermediate phases of an NPP accident, Cs-134, and Cs-137 cause external radiation dose from the radioactive cloud and deposited material and internal dose via inhalation. Due to deposition and possible accumulation of radioactive iodine, cesium, and strontium (Sr-89 and Sr-90) in food, some of radioactive substances may enter the human body via ingestion. Hence, protective actions and restrictions on consumption may be ordered for food production, drinking water and animal feed. When entering the human blood circulation, cesium accumulates mainly into muscles and strontium into bones. Sr-89 and Sr-90 are β-emitting radionuclides (half-lives 50.5 d and 28.9 y, respectively) that do not have considerable gamma emissions. Hence, they do not cause significant external dose due to atmospheric release of radioactive substances.

In a reactor accident, the release fraction of radioactive noble gasses is often much higher than for non-gaseous fission products. Noble gasses do not deposit nor accumulate in the human body in significant amounts. Hence, radioactive noble gasses cause mainly external radiation dose from the radioactive cloud during the early phase of an NPP accident.

2.3 Dispersion and deposition of radioactive materials

Dispersion of radioactive substances depends roughly on three factors: weather conditions, the height of the release, and the content of the release. The weather conditions such as the direction and speed of wind, vertical temperature profile, and precipitation strongly affect the dispersion. Wind affects the horizontal dispersion while pressure gradients caused by vertical temperature differences affect the vertical dispersion. These weather conditions vary as a function of altitude and thus the height of the release is an important factor affecting the dispersion. Furthermore, the precipitation affects the deposition of the radioactive substances.

As explained in the previous section, the distribution of radionuclides in a release may vary. Radioactive decay, in turn, changes the composition of the release through time. Furthermore, the radioactive substances can be released in gaseous form or as particles (aerosols) (STUK 2003).

The airborne radioactive substances can fall-out on the ground via wet and dry deposition. In the atmosphere, the released gases and aerosols mix with suspended water. They are washed out through precipitation and cause radioactive wet deposition. The dry deposition is caused by the movement of particles near the ground and impaction on it. Dry deposition can also be caused by gravitation which has a larger effect on heavier particles than on lighter ones. The heavy particles are thus likely deposited relatively fast and within short distances from the release source.

2.4 Nuclear power plants in Finland

Finland has four operational nuclear reactors. Two units are in Loviisa and two in Olkiluoto. Furthermore, there is one reactor in commissioning in Olkiluoto and one reactor is planned for Hanhikivi (the construction license has not been approved). The releases from light water reactors examined in this work include the operational Loviisa 1 and 2 VVER-440 type Pressurized Water Reactors (PWR) and Olkiluoto 1 and 2 Boiling Water Reactors (BWR), Olkiluoto 3 European Pressurized water Reactor (EPR) in commissioning, and the planned Hanhikivi 1 VVER-1200 type PWR. The basic information on these reactors is shown in Table 2.1.

TABLE 2.1. Reactor type, thermal power, and electrical power of Finnish NPP units in operation (Loviisa 1 & 2 and Olkiluoto 1 & 2), in commissioning (Olkiluoto 3) and in the planning phase (Hanhikivi 1).

NPP unit	Reactor type	Thermal power (MW)	Electrical power (MW)
Loviisa 1&2	PWR	1500	507
Olkiluoto 1&2	BWR	2500	890
Olkiluoto 3	EPR	4300	1600
Hanhikivi 1	PWR	3200	1200

Fuel inventories used for estimating the hypothetical releases from Loviisa 1 and 2, and Olkiluoto 1, 2 and 3 reactors were retrieved from STUK's database containing the information of current (operational NPPs) or estimated (NPP in commissioning) reactor inventory. The inventory estimate of Hanhikivi 1 was not available and it was estimated roughly by scaling the inventories of operational reactors using the nominal thermal power.

2.5 Accident scenarios and source terms

In this work, three different accident scenarios for three NPP sites and four light water reactor types located at Loviisa, Olkiluoto and Hanhikivi are studied. The accident scenarios include a small release (Basic case), a large release (Large case), and a very large release (Very Large case). The release scenarios are based on a certain source term with fixed parameters. It is assumed in all scenarios that the reactor is shut down after the initiating event and fission chain reaction is not ongoing when release occurs. The parameters are scaled according to the estimated inventory and nominal power of each reactor type (see Table 2.1). The radionuclides considered in this study were selected based on their significant contribution to effective dose, thyroid dose, and land contamination (Johansson et al. 2018).

The idea behind the analysis of various cases with different magnitudes is to create estimates for the need and extent of the protective actions. Hence, the source terms are only rough estimates of the potential releases. For example, precise inventories, release pathways and initial circumstances leading to the accident are unique, depend strongly on factors such as reactor type and burnup, and are impossible to predict in advance. Furthermore, the probabilities of the release cases are not studied here, and the probabilities may not be same for all NPP sites or reactor types. It should be noted that the considered cases represent situations where containment has lost its integrity due to failure of the severe accident management or closing of the containment during an accident has failed. Intact containment means that the containment may have very small leakages, which are defined in the design requirements of the NPP [STUK 2019e].
If integrity of the containment is maintained, the releases, even in severe accidents, will be much less than 100 TBq of Cs-137, and the consequences, if any, in the environment and to the people will be minor.

In the Basic case, the tightness of containment has been compromised. The leakage is about 10%/day that is over 10 times of that with the intact containment. The containment pressurization is only slightly affected. The release to environment occurs 6 hours after the termination of the fission chain reaction.

The release of Cs-137 from all sites has been fixed to 100 TBq and releases of Cs-134, I-131, Sr-89, Sr-90, and Te-127m are scaled using the inventory of the reactor. The release of these nuclides continues for 3 hours. Furthermore, 2% of the total inventory of noble gasses (Kr-87, Kr-88, Xe-133 and Xe-135) are released during the first 12 hours. The exact activities of the release considered in the Basic case are shown in Table 2.2.

In the Large case, the containment is damaged. The leakage is about 100%/day that is over 100 times of that with the intact containment. The leakage clearly affects the pressurization of the containment. The release occurs shortly (1 h) after the termination of fission chain reaction. In the release, 1% of Cs-137, Cs-134 and I-131 inventories, 0.4% of Te-127m inventory, and 0.004% of Sr-89 and Sr-90 inventories are released during first 3 hours. Furthermore, 20% of the total inventory of noble gasses (Kr-87, Kr-88, Xe-133 and Xe-135) are released during the first 12 hours. The exact activities of the release considered in the Large case are shown in Table 2.2.

In the Very Large case, a maintenance shutdown with large openings through the containment pressure boundary and significant pathways to the environment. The leakage is about 1000%/day, which is over 1000 times of that with the intact containment. The containment will not pressurize. The release occurs 48 h after the start of maintenance and termination of the fission chain reaction. The release is roughly one order of magnitude larger than in the Large case and in the release 10% of Cs-137, Cs-134 and I-131 inventories, 4% of Te-127m inventory, and 0.04% of Sr-89 and Sr-90 inventories are released during the first 3 hours. Furthermore, the inventories of noble gasses (Kr-87, Kr-88, Xe-133 and Xe-135) are released completely during the first 12 hours. The exact activities of the release considered in the Very Large case are shown in Table 2.2. The total release of the Very Large case is similar to the Fukushima NPP accident and roughly one order of magnitude smaller than the Chernobyl NPP accident. It has been estimated that in the Fukushima accident 100–400 PBq of I-131 and 7–20 PBq of Cs-137 were released, while release in the Chernobyl accident was about 1800 PBq of I-131 and 85 PBq of Cs-137 [IAEA 2015b, IAEA 2006].

TABLE 2.2. The potential source terms examined for Basic, Large and Very Large release cases from operational reactors in Loviisa and Olkiluoto 1 & 2, the reactor under commissioning in Olkiluoto 3, and the planned reactor in Hanhikivi.

Case	Radio-nuclide	Loviisa [TBq]	Olkiluoto 1&2 [TBq]	Olkiluoto 3 [TBq]	Hanhikivi [TBq]
Basic	Cs-137	100	100	100	100
	Cs-134	150	110	140	150
	I-131	880	1×10^3	670	880
	Sr-89	3.2	4.4	2.7	3.2
	Sr-90	0.3	0.3	0.3	0.3
	Te-127m	53	5.6	3.9	53
	Kr-87	19	40	60	49
	Kr-88	1×10^3	2×10^3	3.2×10^3	2.5×10^3
	Xe-133	5.8×10^4	1.0×10^5	1.7×10^5	1.5×10^5
	Xe-135	2.2×10^4	4.2×10^4	7.4×10^4	5.5×10^4
Large	Cs-137	1.6×10^3	2.4×10^3	6.1×10^3	4.1×10^3
	Cs-134	2.4×10^3	2.6×10^3	8.3×10^3	6.0×10^3
	I-131	1.5×10^4	2.5×10^4	4.2×10^4	3.7×10^4
	Sr-89	52	110	160	130
	Sr-90	4.7	7.2	18	12
	Te-127m	850	130	240	2.1×10^3
	Kr-87	3.0×10^3	6.0×10^3	9.3×10^3	7.5×10^3
	Kr-88	3.4×10^4	7.0×10^4	1.1×10^5	8.6×10^4
	Xe-133	5.8×10^5	1.0×10^6	1.7×10^6	1.5×10^6
	Xe-135	2.3×10^5	4.5×10^5	8.0×10^5	5.7×10^5
Very Large	Cs-137	1.6×10^4	2.4×10^4	6.1×10^4	4.1×10^4
	Cs-134	2.4×10^4	2.6×10^4	8.3×10^4	6.0×10^4
	I-131	1.5×10^5	2.5×10^5	4.2×10^5	3.7×10^5
	Sr-89	520	1 × 103	1.6×10^3	1.3×10^3
	Sr-90	47	72	180	120
	Te-127m	8.5×10^3	1.3×10^3	2.4×10^3	2.1×10^4
	Kr-87	2.6×10^4	5.2×10^4	8.0×10^4	6.4×10^4
	Kr-88	2.2×10^5	4.5×10^5	6.9×10^5	5.5×10^5
	Xe-133	2.9×10^6	5.2×10^6	8.7×10^6	7.4×10^6
	Xe-135	1.1×10^6	2.3×10^6	4.0×10^6	2.8×10^6

3 Preparedness for nuclear emergency and protective actions

3.3 Nuclear emergency

The guidelines for the Finnish emergency preparedness and protective actions in a nuclear or radiological emergency are described in detail in the Ministry of the Interior’s Guide for Radiation Hazards and in the recently updated Preparedness Guide (Sisäministeriö 2016, STUK 2020). The radiation hazard situation, in general, can be divided into early, intermediate and recovery phases. These phases are preceded by a constant preparedness phase where the emergency preparedness is constantly developed and the ability to react to the emergencies are exercised. The early phase of a nuclear or radiological emergency contains the actual event, incidents that lead to the release of radioactive substances, and the dispersion of radioactive substances into the environment. The early phase ends when the radiation levels are not increasing significantly and there is no threat of rerelease of the substances.

In the intermediate phase, the radiation levels are not increasing, and the rerelease of radioactive substances are not expected. During the intermediate phase, it is estimated if some of the protective actions implemented in the early phase can be lifted or changed. In this phase, new protective actions can also be activated to decrease radiation doses and the amount of radioactive substances in the environment. The intermediate phase is followed by a recovery phase if the radiation situation leads to long-term effects. Typical actions that reduce the radiation dose in the recovery phase are based on the recommendations given by the authorities. In the recovery phase, decontamination of the environment and handling of contaminated materials may continue if needed. Also, long-term restrictions may be given for highly contaminated areas. In this report, we concentrate on the consequences and protective actions during early and intermediate phases in NPP accidents.

3.2 Emergency planning zones

Finnish legislation sets a requirement that NPPs must have a PAZ and EPZ. With existing plants, the radii are 5 km and about 20 km, respectively. In the Finnish legislation, the term EPZ is used instead of the IAEA's term UPZ (IAEA 2015a). Furthermore, in the Finnish preparedness plan, the PAZ is also part of the EPZ, while in terminology used by IAEA, the PAZ and UPZ do not overlap. From here onwards, the abbreviation EPZ is used for the approximately 20 km Emergency Planning Zone around Finnish NPPs. Finnish regulation does not include an EPD or ICPD; instead, the current preparedness plan states that in a severe NPP accident sheltering indoors, the recommendation to limit being outside and the protection of primary production of foodstuff could be needed as protective actions up to 100 km, 200 km, and 1,000 km, respectively (STUK 2020).

In Fig. 3.1 the range of PAZs and EPZs around NPP sites at Loviisa, Olkiluoto and Hanhikivi are illustrated. 100 km zones around the sites are shown in the Figure to illustrate distances between the sites and the closest cities. The same 100 km zones are also used when illustrating the results of the analyses. It must be noted that in practice, the zones are defined with respect to municipality and city borders, not with exact circles.

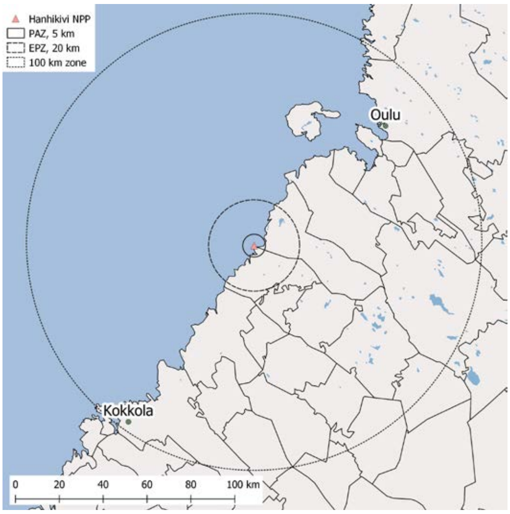

FIGURE 3.1. Precautionary Action Zone (PAZ), Emergency Planning Zone (EPZ) and 100 km zone around Finnish NPP sites at Loviisa, Olkiluoto and Hanhikivi. Note that in Olkiluoto, the EPZ follows the borders of municipalities, and the circular EPZ shown here is used only for congruence of all the sites.

The PAZ has limitations in land use. For example, a PAZ should not contain facilities inhabited or visited by a considerable number of people, or with socially significant functions that could affected by an accident at an NPP. Furthermore, the number of both permanent and temporary inhabitants should be limited inside the PAZ to enable effective evacuation. The land use in the EPZ is not as strict but the authorities are to draw up a detailed external rescue plan for the protection of the public inside the EPZ. (STUK 2019b)

3.3 Protective actions and operational intervention levels

Protective actions can be ordered to ensure the safety of the population and emergency workers, the functioning of the society, and the continuation of business activities. Predefined dose criteria and operational intervention levels (OIL) are set to help decision making during a nuclear or radiological emergency. The protective actions, dose criteria and OILs are described in detail in the Preparedness Guide (STUK 2020). The dose criteria are to be primarily used in decision making if dose calculations can be performed reliably during the emergency. The OILs are to be used if effective or thyroid doses cannot be determined reliably e.g., due to lack of information. Protective actions in a nuclear emergency include sheltering indoors, the recommendation to limit being outside, iodine prophylaxis, evacuation, access control and evacuation. These protective actions and related dose criteria and OILs are the focus of the study. Furthermore, there are protective actions related to foodstuff production (i.e., protecting primary foodstuff production and protecting foodstuff production facilities) and restricting land usage (i.e., restricting use of public and natural recreational areas). The summary of protective actions and related dose criteria and OILs for the early phase of an emergency are given in Table 3.1 and for the intermediate phase in Table 3.2. These dose criteria and OILs are used later in the analysis to determine the areas where protective actions might be warranted. The dose criteria and OILs for protection of foodstuff production and restricting use of recreational areas are given here only for completeness.

In addition to the protective actions related to dose criteria and OILs, there are preplanned protective actions that are performed inside the PAZ and EPZ. These protective actions include (STUK 2020): 1. Evacuation and iodine prophylaxis inside the PAZ if a threat of considerable radioactive release exists. 2. Sheltering indoors and iodine prophylaxis on areas inside the EPZ where the radioactive release is expected to disperse. These protective actions are warranted regardless of exceeding dose criteria or OILs. Furthermore, evacuation is warranted only if it can be performed safely before the release.

TABLE 3.1. Protective actions in the early phase of a nuclear emergency, and the dose criteria and operational intervention levels (OIL) related to the actions. (STUK 2020)

Protective action	Dose criteria / OIL
Sheltering indoors	Dose is predicted to be > 10 mSv in 2 days*
	External dose rate is or is predicted to be > 100 μSv/h
	α-emitter concentration is or is predicted to be > 1 Bq/m^3 (Pu-239, Am-241)
	β-emitter concentration is or is predicted to be > 1 kBq/m^3 (Sr-90)
	Strong γ-emitter concentration is or is predicted to be > 10 kBq/m^3 (Cs-137, I-131, etc.)
Recommendation to limit being outside	Dose is predicted to be 1–10 mSv in 2 days*
	External dose rate is or is predicted to be > 10 μSv/h
	α-emitter concentration is or is predicted to be > 0.1 Bq/m^3 (Pu-239, Am-241)
	β-emitter concentration is or is predicted to be > 100 Bq/m^3 (Sr-90)
	Strong γ-emitter concentration is or is predicted to be > 1 kBq/m^3 (Cs-137, I-131, etc.)
Iodine prophylaxis (adults)	Thyroid dose is predicted to be > 100 mGy
	External dose rate is or is predicted to be > 100 μSv/h
	Air concentration of radioactive iodine for 48 hours is or is predicted to be > 10 kBq/m^3
Iodine prophylaxis (children and pregnant females)	Thyroid dose is predicted to be > 10 mGy
	External dose rate is or is predicted to be > 10 μSv/h
	Air concentration of radioactive iodine for 48 hours is or is predicted to be > 1 kBq/m^3
Evacuation	People from PAZ are evacuated if threat of significant radioactive release exists
	People from EPZ are evacuated if situation allows and dose is decreased considerably compared to sheltering indoors**
	It is likely that the need of sheltering indoors is more than 2 days
Access control	Areas where sheltering or evacuation is ordered
Protecting primary production of foodstuff	External dose rate is or is predicted to be > 1 μSv/h
	α-emitter concentration is or is predicted to be > 0,1 Bq/m^3 (Pu-239, Am-241)
	β-emitter concentration is or is predicted to be > 10 Bq/m^3 (Sr-90)
	Strong γ-emitter concentration is or is predicted to be > 100 Bq/m^3 (Cs-137, I-131, etc.)
Protecting production facilities of foodstuff	External dose rate is or is predicted to be > 10 μSv/h
	α-emitter concentration is or is predicted to be > 0,1 Bq/m^3 (Pu-239, Am-241)
	β-emitter concentration is or is predicted to be > 100 Bq/m^3 (Sr-90)
	Strong γ-emitter concentration is or is predicted to be > 1 kBq/m^3 (Cs-137, I-131, etc.)

* For unprotected people

** Please see further details from Preparedness Guide (STUK 2020)

TABLE 3.2. Protective actions in the intermediate phase of a nuclear emergency, and the dose criteria and operational intervention levels (OIL) related to the actions. (STUK 2020)

Protective action	Dose criterion / OIL
Sheltering indoors	Dose is predicted to be > 10 mSv in 2 days*
	External dose rate is > 100 μSv/h
	Strong γ- and β-emitter deposition in total > 10 MBq/m^2 (Cs-137, I-131, Sr-90 etc.)
	α-emitter deposition is > 100 kBq/m^2 (Pu-239, Am-241)**
Recommendation to limit being outside	Dose is predicted to be > 10 mSv in 1 month but < 10 mSv in 2 days*
	External dose rate is > 10 μSv/h but < 100 μSv/h
	Strong γ- and β-emitter deposition in total is 1–10 MBq/m^2 (Cs-137, I-131, Sr-90 etc.)
	α-emitter deposition is 10–100 kBq/m^2 (Pu-239, Am-241)**
Evacuation	Dose in first week after the accident is predicted to be > 20 mSv*
	External dose rate is > 100 μSv/h for over 2 days
	Strong γ- and β-emitter deposition in total > 10 MBq/m^2 (Cs-137, I-131, Sr-90 etc.) for over 2 days
	α-emitter deposition is > 100 kBq/m^2 (Pu-239, Am-241) for over 2 days**
Temporary relocation	Monthly dose is predicted to be > 10 mSv after a month from the accident*
	External dose rate is > 10 μSv/h regardless of decontamination
	Strong γ- and β-emitter deposition in total > 1 MBq/m^2 (Cs-137, I-131, Sr-90 etc.) regardless of decontamination
	α-emitter deposition is > 10 kBq/m^2 (Pu-239, Am-241) regardless of decontamination**
Permanent relocation	Annual dose is predicted to be > 50 mSv after a year from the accident*
Access control	Areas where sheltering or evacuation is ordered
Restricting use of public recreation areas	External dose rate is > 1 μSv/h
	Strong γ- and β-emitter deposition in total > 100 kBq/m^2 (Cs-137, I-131, Sr-90 etc.) regardless of decontamination
	α-emitter deposition is > 1 kBq/m^2 (Pu-239, Am-241)**
Restricting use of natural recreation areas	External dose rate is > 10 μSv/h
	Strong γ- and β-emitter deposition in total > 1 MBq/m^2 (Cs-137, I-131, Sr-90 etc.)
	α-emitter deposition is > 10 kBq/m^2 (Pu-239, Am-241)**

* For unprotected people

** Assuming that resuspension of radionuclides is possible

Sheltering indoors reduces the exposure to airborne radioactive substances and decreases the dose from external radiation. When sheltering indoors, ventilation should be turned off and incoming airways (e.g., doors, windows, vents, and chimneys) should be sealed. Ideally, sheltering indoors should be initiated well before the radioactive cloud arrives to the area and it should continue while the cloud passes the area. Sheltering indoors should not last more than 48 hours as other disadvantages related to isolation increase quickly and contamination of the interior is inevitable. The dose criteria and OILs for sheltering indoors are given in Tables 3.1 and 3.2 for the early and intermediate phases, respectively.

The recommendation to limit being outside is given in situations when there are radioactive substances in the air and/or in the environment but not to the extent that sheltering indoors would be necessary. Ventilation should still be turned off to avoid unnecessary contamination of indoors. The dose criteria and OILs for the recommendation to limit being outside are given in Tables 3.1 and 3.2 for the early and intermediate phases, respectively. For the recommendation to limit being outside, the same measures are followed as for sheltering indoors but their numerical values are slightly lower.

As explained in Section 2.2, radioactive iodine can be released in NPP accidents. Intake of iodine can take occur via inhalation, food, water, and milk, or by absorption through the skin when handling contaminated surfaces. Radioactive iodine accumulates in the thyroid and causes radiation dose to the organ. Iodine prophylaxis can prevent the accumulation and dose to the thyroid. It does not, however, decrease the dose to other organs. Iodine prophylaxis is very important for children and pregnant females as thyroids of children and fetuses are more sensitive to the effects of radiation. Iodine prophylaxis is always a complementary action to sheltering indoors. The dose criteria and OILs for thyroid prophylaxis are given in Table 3.1 for the early phase. Once the cloud of radioactive iodine has passed the area, the most effective ways to prevent thyroid dose are to prevent the intake of iodine through food and water. This could require restrictions on the consumption of produce from contaminated areas, monitoring of foodstuff, milk and water and monitoring and restrictions on the use of animal feed.

If there is a threat of a severe NPP accident, the PAZ is evacuated (if this can be performed in a timely manner before the release) and iodine prophylaxis is ordered. Otherwise, evacuation should be considered if the need of sheltering indoors is predicted to last over 2 days. If radiation doses are predicted to remain at a high level for an extended period, temporary or permanent relocation of people might be warranted. Relocation is not used in the early phase as the consequences of the NPP accident may not be fully known. The evacuated people, however, may be relocated later if quick return is not possible due to contamination. Access control needs to be set to evacuated areas and to areas where sheltering indoors is ordered. The dose criteria and OILs for evacuation, temporary and permanent relocation, and access control are given in Tables 3.1 and 3.2 for the early and intermediate phases, respectively.

Contamination level is a key factor in deciding on the need for temporary or permanent relocation. The contamination levels can be determined by measuring the dose rates and activities in contaminated areas. Dispersion modelling can help to target measuring activities and complete the deposition maps. The contamination levels are also used for targeting protective actions related to decontamination, primary production, protection of emergency workers, and setting other restrictions. Related protective actions and their dose criteria and OILs are described in more detail in the Preparedness Guide (STUK 2020). In this study, the focus is on the consequences to people and contamination of the environment. Contamination levels with related dose rates and activities of deposited radioactive substances used in assessing contamination levels are given in Table 3.3.

TABLE 3.3. Contamination levels describe the magnitude of deposited radioactive substances. The contamination level can be estimated from external dose rate, deposited activity of gamma- and beta-emitter in total, and deposited activity of alfa-emitters. (STUK 2020)

Contamination level	External dose rate	Combined γ- and β-emitter deposition	α-emitter deposition*
Extremely contaminated	> 100 μSv/h	> 10 MBq/m^2	> 100 kBq/m^2
Highly contaminated	10–100 μSv/h	1–10 MBq/m^2	10–100 kBq/m^2
Contaminated	1–10 μSv/h	100–1000 kBq/m^2	1–10 kBq/m^2
Slightly contaminated	< 1 μSv/h	< 100 kBq/m^2	< 1 kBq/m^2
Non-contaminated	Dose rate in the level of normal background radiation	no deposition or very low deposition	no deposition or very low deposition

* Assuming that resuspension of radionuclides is possible

In this study, the focus is on consequences to people and contamination of the environment. The following measures were studied against their dose criteria and OILs: External dose rates, effective and thyroid doses of adults and children, deposition of cesium and strong gamma emitters, and activity concentration of strong gamma emitters in the air. In the assessment, the cesium isotopes include Cs-134 and Cs-137, and strong gamma emitters include I-131, Cs-134 and Cs-137.

4 Modelling dispersion of radioactive release and effective doses to population

4.1 Weather data

The weather data used in the dispersion modelling was collected from operative weather forecasts by the Finnish Meteorological Institute (FMI) between 2012–2015. The data includes forecasts by AROME model for the years 2012–2013 and HARMONIE model for the years 2014–2015. A grid with a radius of about 300 km from each NPP was selected from the weather data for dispersion modelling. The HARMONIE model has replaced the AROME model in operative weather prediction and thus different models are used for the beginning and end of the analysis period. HARMONIE covers the whole modelling area while AROME covers only the area of Finland causing discrepancies when analyzing dispersion outside Finland.

The representativeness of weather (precipitation, temperature, and wind roses) during the period studied was estimated by climatic comparison to years 1981–2010. In Olkiluoto and Loviisa, NPPs have their own weather stations while weather data for Hanhikivi was taken from Ulkokalla weather station (about 50 km southwest from Hanhikivi). The comparison showed that the temperature was exceptionally high during the summer of 2013, and the winter of 2014 and 2015. In 2012, the precipitation was 50–70% higher than on average. Otherwise, the temperature and precipitation well represented the average values of climatic comparison period. The wind conditions were within the average during the whole period. The wind roses determined from weather observations at stations closest to Finnish NPP sites are shown in Fig. 4.1. The wind roses show that the wind directions from the open sea dominate with all wind strengths.

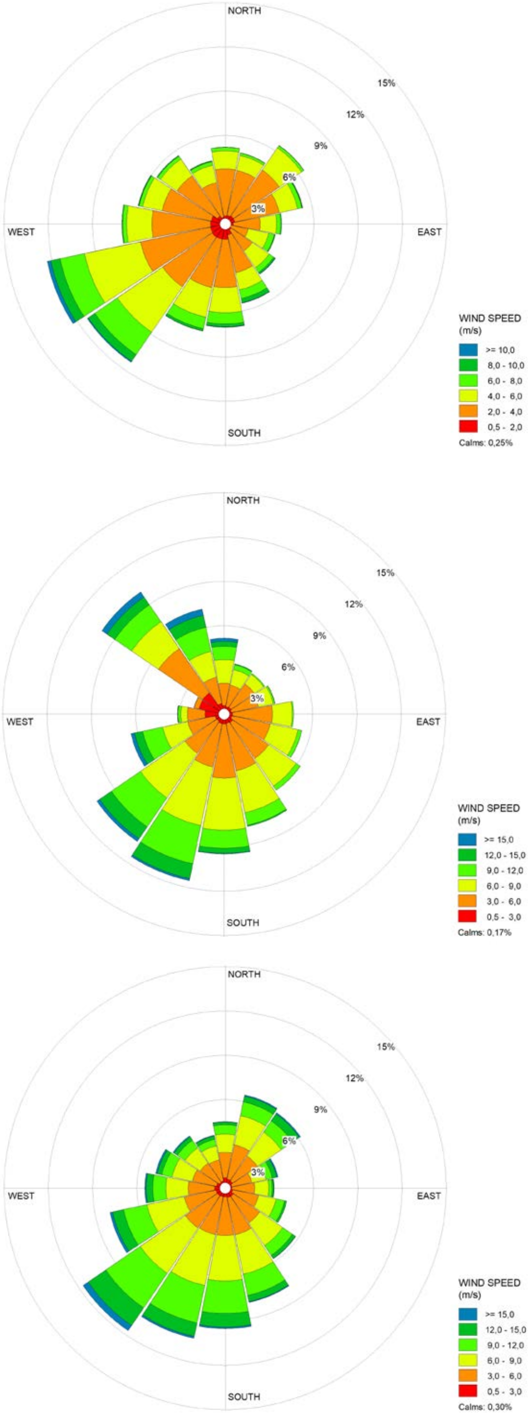

FIGURE 4.1. The wind roses for weather stations closest to Finnish NPP sites at Loviisa, Olkiluoto and Hanhikivi (Ulkokalla).

4.2 Modelling dispersion and deposition

The dispersion and deposition modelling of radioactive release were done using the “System for Integrated modeLling of Atmospheric coMposition” (SILAM) model. SILAM is a global to meso scale dispersion model that has been developed for atmospheric composition, air quality, and emergency decision support applications, as well as for inverse dispersion problem solutions (Finnish Meteorological Institute 2020). SILAM version 5.4 was used in this study. It also contains modules for handling radioactive decay and decay chains that cause ingrowth of daughter nuclides for released nuclei from the air and deposition. The model determines the decay at every time step for each grid point. The simulations consider the daughter nuclei from the following decay chains:

Kr-87 → Rb-87
Xe-135 → Cs-135
Sr-90 → Y-90
Cs-137 → Ba-137m
Kr-88 → Rb-88
I-131 → Xe-131m
Te-127m → Te-127

The decay of other modelled nuclei is considered but the decay products are neglected.

The SILAM model contains both Eulerian and Lagrangian methods for dispersion modelling. In this work, however, only the Eulerian method was used (Sofiev et al. 2015). This method uses a finite-volume approach to solve the time-dependent tracer transport equation, which describes the three-dimensional advective and diffusive transport, transformation and removal of released radioactive gases and particles.

The dispersion modelling was performed over an area with a radius of 300 km from the NPP sites. The Eulerian method allows the use of weather prediction grids from AROME and HARMONIE directly in the dispersion modelling. However, as the grids of AROME and HARMONIE were slightly different, a linear interpolation was performed to get dispersion data from the same coordinates from both forecast models. The final dispersion data had a grid with a resolution of about 2.5 km × 2.5 km (0.02° × 0.02°) in longitude-latitude projection.

Vertically the dispersion modelling was performed up to 10 km using 16 layers with varying thickness. For the lowest layer 40 m thickness was used and for the following layers between 1–4 km, 4–6 km, and 6–10 km thicknesses of 500 m, 1,000 m, and 2,000 m, respectively, were used. The lowest layer was 40 m thick, between 1–4 km 500 m, between 4–6 km 1,000m, and 6–10 km 2,000 m.

The releases were modelled as point releases at an altitude of 90–110 m. Two sets of releases with durations of 3 h and 12 h were modelled for all three NPP sites. To get variation caused by daily and seasonal weather conditions, the releases were set to start daily at 00 UTC and 12 UTC during the years 2012–2015. A time step of 2 minutes and duration 48 hours were used, and the hourly data was saved for later analysis in each modelling case. Dispersion of 8,760 release cases were modelled from Loviisa, Olkiluoto and Hanhikivi in total. Each release case was modelled using 10 radionuclides given in Section 2.5.

Each release consisted of gaseous release of the noble gases (Kr-87, Kr-88, Xe-133 and Xe-135), gaseous and aerosol release of I-131, and aerosol release of the other nuclei (Sr-89, Sr-90, Te-127m, Cs-134 and Cs-137). The aerosols were assumed to have an average particle size of 0.6 µm.

In the SILAM model both dry and wet deposition are considered. The dry deposition flux, F_{dry} [$Bqm^{-2}s^{-1}$], can be expressed with dry deposition velocity, v_d, [ms^{-1}], as (Kouznetsov and Sofiev 2012):

$$F_{dry} = -v_d C\,(z_{ref}) \tag{4.1}$$

where $C(z_{ref})$ is the activity concentration on the lowest modelling layer above the ground. The deposition velocity for aerosols was modeled using the method described in (Kouznetsov and Sofiev 2012), in which the main parameters affecting the deposition velocity are the particle size, the local friction velocity u* and surface roughness z_0, and a scale parameter (collection scale) representing the effect of vegetation. In SILAM, the collection scale has a constant value over land areas, and the friction velocity and surface roughness are obtained from the meteorological data. The deposition velocity of gaseous iodine was modeled using the method by Wesely (1989).

Wet deposition was modelled using a first order washout coefficient as (Jylhä 1991)

$$F_{wet} = -\int \Lambda(z)\;\; C(z)\, dz \tag{4.2}$$

where F_{wet} [$Bqm^{-2}s^{-1}$] is the wet deposition flux, $\beta\Lambda(z)$ [s^{-1}] and $C(z)$ are the washout coefficient and activity concentration at height z. The integration is over the vertical levels. The washout coefficient describes the removal rate of gases or aerosol particles from the atmosphere as a function of precipitation intensity. The three-dimensional distribution of the washout coefficient is determined from total precipitation of HARMONIE and AROME weather data.

4.3 Effective dose calculations

Effective dose calculations were performed using the threat assessment tool TIUKU that has been developed by the Radiation and Nuclear Safety Authority (STUK) in Finland (Ammann 2013). With TIUKU it is possible to run SILAM and there is a post-processing script at STUK to calculate dose rates, effective doses, and thyroid doses etc. from deposition and airborne activity concentration near the ground level. Dose rate conversion factors are retrieved from the database of the JRODOS decision support system (Karlsruhe Institute of Technology 2020) that are calculated in according the recommendations of the ICRP-119 document (Eckerman et al. 2012). The dose conversion factors for inhaled radionuclides are given by ICPR (ICRP database) and the dose conversion factors from the radioactive cloud and deposition are given by Petoussi-Henss et al. 2012. The doses determined using these conversion factors are based on semi-infinite approximation of the concentration of the airborne radioactive substances and do not consider possible vertical variation in the concentration.

For dose calculations, the activity is divided into an even grid of point sources. The effective doses and thyroid doses were determined for adults and one-year-old children in this study. When determining the doses, exposure pathways via inhalation and external dose from the radioactive cloud and deposition were considered. Ingestion doses were not considered. Effective and thyroid dose calculations were performed using the first 7 days after release. In practice this was done by summing total dose from cloud exposure, dose from deposition using 7-day dose coefficient and inhalation dose calculated using lifetime dose coefficient. Due to this, the estimated effective and thyroid doses slightly overestimate the doses for 2 days that are used in dose criteria for sheltering indoors and the recommendation to limit being outside (see Tables 3.1 and 3.2), and the values can be used as conservative estimates. The lifetime dose coefficient for inhalation was used, as once inhaled the dose accumulation continues even when the contaminated area is left and doses leading to stochastic effects are the main interest.

4.4 Post-processing and selection of studied weather scenarios

The post-processing of the dispersion of radionuclides and dose calculation data were performed with Python and analysis packages. The output files of the SILAM model and TIUKU were in netCDF4 file format. The output files were processed with Python's netCDF4 library, computational post-processing was performed with NumPy-library for scientific computation, and the data was converted to a suitable format for map production with csv-library. The final dispersion, deposition and dose maps were generated with geographic information system software QGIS version 3.12. The dose criteria, operational intervention levels and contamination levels given in Tables 3.1–3.3 were considered when generating the maps to assist probability estimation of different protective actions.

In this work, the analysis was performed using the 95th percentile of the data in Guide YVL C.4 which states that "When determining compliance with dose constraints in accordance with the Nuclear Energy Decree (161/1988) and Guide YVL C.3 in various accidents, dose estimates representing the 95% fractile shall be used" [STUK 2019c]. This kind of analysis excludes some of the extreme cases such as storms. Technically the percentile means that if a certain value x_p of all possible values X corresponds to percentile p, there are p% of values in X that are equal to or smaller than x_p. Hence, in this study 5% of the most extreme cases (caused by e.g., storms, heavy precipitation, strong wind) were neglected. In other words, it is expected that in 95% of the cases the consequences would be milder than the analysis indicates.

Similar analyses were done also using numerical estimates for maximum and mean values doses, depositions, and durations when different operational intervention levels are exceeded inside the PAZ and EPZ. Maximum distances for exceeding different dose criteria, operational intervention and contamination levels were also estimated in different release scenarios. In this analysis, direction information was neglected. The purpose of the analyses is to demonstrate the probability of different protective actions needed inside the PAZ and EPZ and the maximum distances for them in different release scenarios. Furthermore, the seasonal variation of doses, deposition and air concentrations were studied during summer (June–August) and winter (December–February).

4.5 Potential sources of uncertainties

The largest effect on the magnitude of doses and contamination arises from the source terms applied in the release scenarios. The source term depends on the case, the accident type, and radionuclides that are released into the atmosphere. In an actual emergency, the duration of a release cannot be known accurately beforehand as it is not known how fast the situation can be brought under control. In this work, a relatively short temporal duration of releases was used to demonstrate the most severe local consequences and to save computational resources. Constant release rates were also assumed while real accidents could exhibit release rates with more complex time dependent variation. It should be also noted that the probabilities of actual emergencies are not studied, and theoretical accident frequencies may not be the same for all the NPP sites or reactor types (STUK 2019d).

Sources of uncertainties are linked to dose accumulation, weather, dispersion, and deposition models. The models are always a simplification of the real nature and focus on the dominant processes. For example, the activity of deposition decreases faster than the applied model estimates as it does not consider infiltration and diffusion into the soil. These uncertainties are, however, much smaller compared to the uncertainty of the source term.

The results are presented for the 95th percentile of the data as required in Finnish regulation [STUK 2019c]. The results would change drastically if a different percentile was used in the analyses. Simply put, 5 percent of the scenarios produce severer doses, depositions, and durations while in 95 percent of the scenarios the effects are milder. When making the conclusions from results of such analysis, one must keep in mind that the scenario that represents the 95th percentile of effective dose is not the same as that which represents the 95th percentile of deposition. In a nuclear or radiological emergency, there will be only one realization of all the possibilities. The results of this study can only be used to estimate the probability of different measures in the case of a particular release.

5 Results

5.1 Doses and dose rates

In NPP accidents, protective actions are taken to minimize potential radiation dose to the population, thus potential radiation doses and dose rates need to be estimated. Dose rate is a key factor when taking protective actions as it can be directly measured by fixed monitoring networks and simple hand-held instruments. The durations when the dose rate exceeds 1, 10 and 100 μSv/h were estimated for four NPP sites in Finland and for all three hypothetical release scenarios.

The durations when the dose rate exceeds 10 μSv/h in Large and Very Large cases, and 100 μSv/h in a Very Large case are shown in Figs 5.1–5.3. In general, the duration maps correlate well with wind roses (see Fig. 4.1). In Loviisa, winds from the south-west dominate while in Hanhikivi and Olkiluoto winds from the south and south-west dominate in the wind roses with most of the wind strengths.

Numerical results of the analysis for median durations for exceeding each dose rate, and maximum and median distances for exceeding durations of 1, 24 and 48 h are shown in Tables 5.1–5.3. In a Basic case, dose rates of 10 and 100 μSv/h are not exceeded in any of the NPP sites. However, slightly elevated dose rates (> 1 μSv/h) can be followed from the releases in all NPP sites. The median duration for exceeding a dose rate of 1 μSv/h varies from 3 to 4 h inside the PAZ and from 1 to 2 h inside the EPZ. Median distances where the dose rate of 1 μSv/h is exceeded remain below 20 km in all cases while the maximum distances may reach up to 33 km.

In a Large case, median duration when the dose rate exceeds 10 μSv/h varies from 47 to over 48 h in the PAZ and from 2 to 47 in the EPZ. The duration exceeds 24 and 48 h mainly inside the PAZ and EPZ. However, in Olkiluoto 3 and Hanhikivi the maximum distances where the dose rate of 10 μSv/h may be exceeded for over 24 h can reach over 35 km from NPP sites. The dose rate of 10 μSv/h may be exceeded for shorter periods of time (< 12 h) at distances up to 40–110 km from the

NPP sites. The dose rate of 100 μSv/h is exceeded for a short period of time (1–2 h) inside the PAZ and EPZ due to large releases from Olkiluoto 3 and Hanhikivi NPP sites. In Large cases, the dose rate of 100 μSv/h is not exceeded in Loviisa and Olkiluoto 1 and 2, or in Olkiluoto and Hanhikivi outside the EPZ. In a Large case, the slightly elevated dose rates (> 1 μSv/h) can be reached over 300 km from the NPP sites. In general, the duration when the dose rate exceeds 1 μSv/h is over 48 h inside the PAZ and EPZ.

In a Very Large case, median duration when the dose rate exceeds 100 μSv/h varies from 46 to over 48 h in the PAZ and from 2 to 47 in the EPZ. The duration exceeds 24 and 48 h mainly inside the PAZ and EPZ. The dose rate of 100 μSv/h may be exceeded for shorter periods of time (< 12 h) at distances up to 42–110 km from the NPP sites. The duration when the dose rate exceeds 10 μSv/h, in turn, is over 48 h in the PAZ and EPZ, and the duration may be considerable also outside the EPZ. For example, the duration when the dose rate exceeds 10 μSv/h may be over 24 h in Kemi and Oulu (release from Hanhikivi), Porvoo, Kotka and Kouvola (Loviisa), and Pori and Tampere (Olkiluoto 3). In a Very Large case, the slightly elevated dose rates (> 1 μSv/h) are reached far beyond the considered distance (> 300 km) from the NPP sites.

Variations between the seasons of summer and winter are significant in Very Large cases. During the winter season, the dispersion towards the north, northeast and east are the dominant directions of dispersion, and this can also be seen in the duration maps. During the summer season, the duration maps are more evenly distributed to all directions. However, the directions away from the continent are slightly less prominent than directions toward the continent and along the coast. In Large cases, the seasonal variations are also present but not as pronounced as in Very Large cases. The directional emphasis is similar to that of Very Large cases. In Basic cases, the seasonal variations are negligible in terms of the duration for exceeding the examined dose rates. Longer durations of elevated dose rates caused by releases from Hanhikivi and Olkiluoto 3 in Large and Very Large cases compared to Loviisa and Olkiluoto 1 and 2 arise from the larger radionuclide inventory. However, the probability of a severe accident is lower for modern NPPs than for older ones.

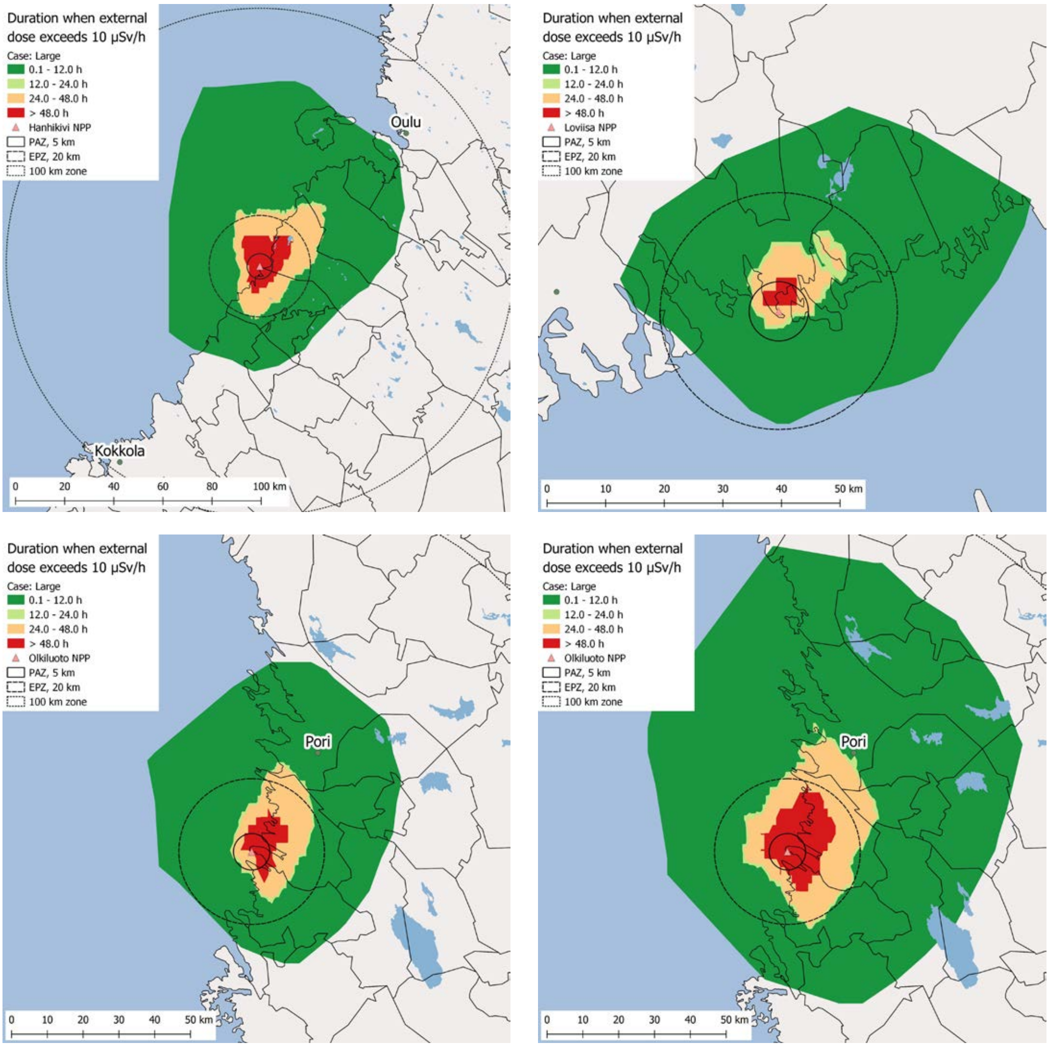

FIGURE 5.1. Duration when external dose rate of 10 µSv/h is exceeded in a Large case at Hanhikivi (upper left panel), Loviisa (upper right), Olkiluoto 1 & 2 (lower left) and Olkiluoto 3 (lower right). Note that the length scales vary.

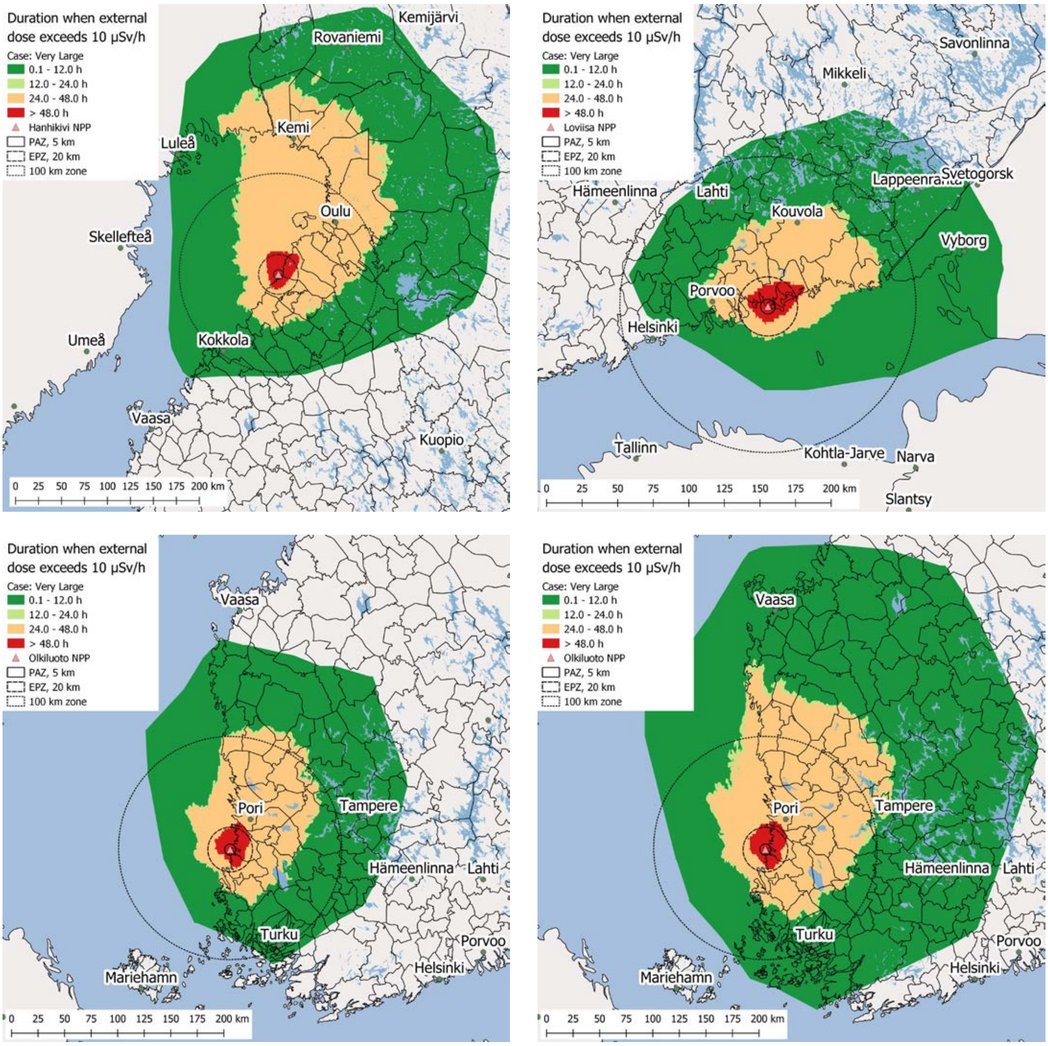

FIGURE 5.2. Duration when external dose rate of 10 µSv/h is exceeded in a Very Large case at Hanhikivi (upper left panel), Loviisa (upper right), Olkiluoto 1 & 2 (lower left) and Olkiluoto 3 (lower right). Note that the length scales vary.

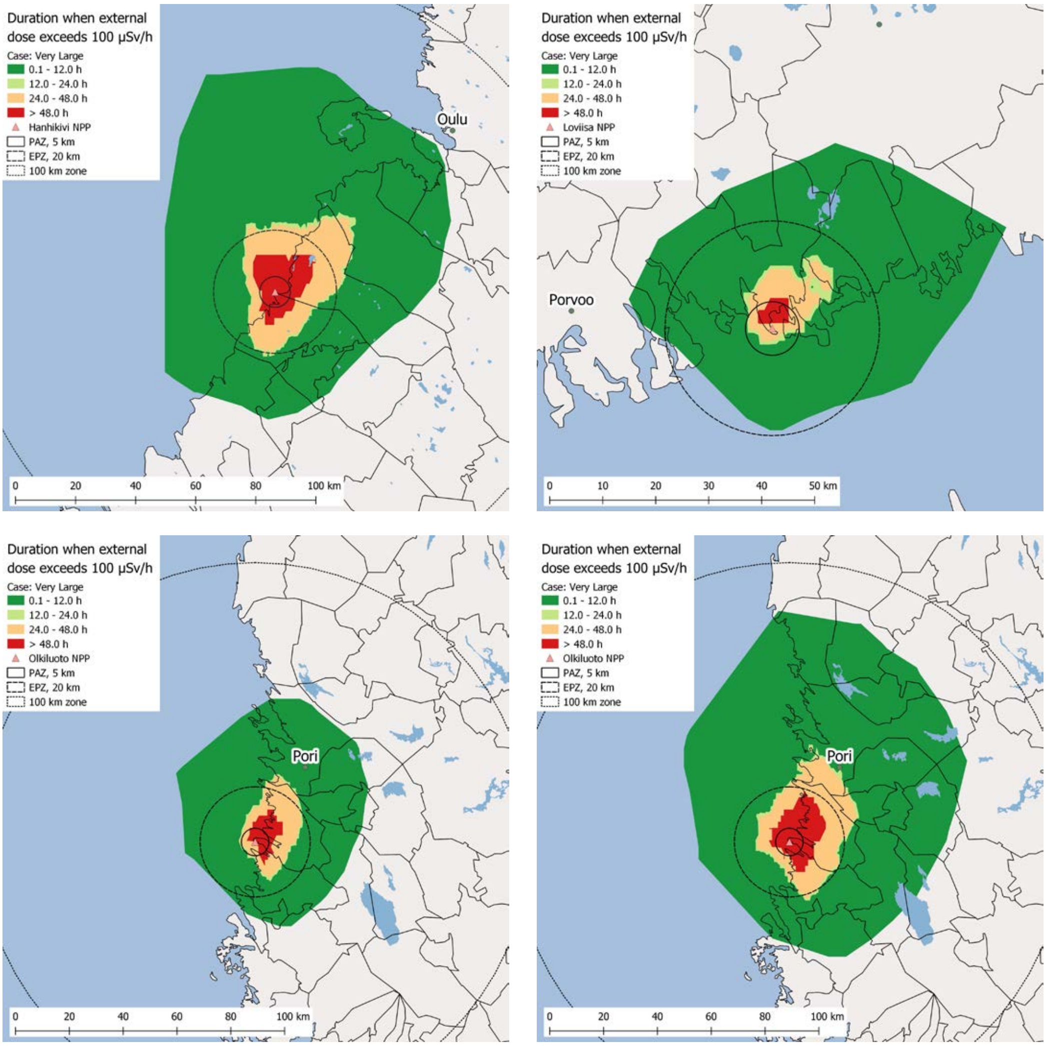

FIGURE 5.3. Duration when external dose rate of 100 µSv/h is exceeded in a Very Large case at Hanhikivi (upper left panel), Loviisa (upper right), Olkiluoto 1 & 2 (lower left) and Olkiluoto 3 (lower right). Note that the length scales vary.

TABLE 5.1. Median durations for dose rates exceeding 1 μSv/h inside PAZ (< 5 km) and EPZ (< 20 km), and maximum and median distances when exceeding dose rate for over 1, 24 and 48 h. The values analyzed for all year, summer and winter data using Basic, Large, and Very Large cases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median duration d < 5 km (h)	median duration d < 20 km (h)	maximum distance for 1 h (km)	median distance for 1 h (km)	maximum distance for 24 h (km)	median distance for 24 h (km)	maximum distance for 48 h (km)	median distance for 48 h (km)
Hanhikivi	Basic	all	4	2	27	14	3.9	2.4	-	-
		summer	4	2	29	15	8.5	4	1	0.51
		winter	3	2	33	15	6.5	3.4	3.3	1.7
	Large	all	48	48	270	130	200	90	28	13
		summer	48	48	220	110	110	51	23	11
		winter	48	48	>300	170	270	130	31	17
	Very Large	all	48	48	>300	220	>300	180	35	16
		summer	48	48	>300	220	>300	160	27	13
		winter	48	48	>300	210	>300	210	41	21
Loviisa	Basic	all	3	2	29	14	4.4	2.7	-	-
		summer	3	2	37	15	3.3	1.4	-	-
		winter	4	2	30	14	17	5.8	5.4	3.3
	Large	all	48	48	160	77	80	38	28	11
		summer	48	47	190	80	83	33	28	11
		winter	48	48	190	81	89	43	28	13
	Very Large	all	48	48	>300	190	>300	140	35	15
		summer	48	48	>300	180	250	120	33	14
		winter	48	48	>300	210	>300	170	38	17
Olkiluoto 1 & 2	Basic	all	3	2	28	13	5.4	2.8	-	-
		summer	4	2	26	15	3.5	1.9	-	-
		winter	3	2	29	14	10	5	-	-
	Large	all	48	48	190	94	120	50	26	12
		summer	48	48	170	88	99	44	24	12
		winter	48	48	>300	110	290	70	28	14
	Very Large	all	48	48	>300	200	>300	170	32	15
		summer	48	48	>300	200	>300	130	28	14
		winter	48	48	>300	210	>300	200	39	18
Olkiluoto 3	Basic	all	3	1	23	10	-	-	-	-
		summer	3	1	22	12	1.4	0.6	-	-
		winter	3	1	23	11	3.4	2.9	-	-
	Large	all	48	48	290	140	160	70	28	13
		summer	48	48	260	120	130	61	25	12
		winter	48	48	>300	180	>300	100	31	16
	Very Large	all	48	48	>300	210	>300	190	34	16
		summer	48	48	>300	210	>300	160	29	14
		winter	48	48	>300	210	>300	210	42	20

TABLE 5.2. Median durations for dose rates exceeding 10 μSv/h inside PAZ (< 5 km) and EPZ (< 20 km), and maximum and median distances when exceeding dose rate for over 1, 24 and 48 h. The values analyzed for all year, summer and winter data using Basic, Large, and Very Large cases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median duration d < 5 km (h)	median duration d < 20 km (h)	maximum distance for 1 h (km)	median distance for 1 h (km)	maximum distance for 24 h (km)	median distance for 24 h (km)	maximum distance for 48 h (km)	median distance for 48 h (km)
Hanhikivi	Basic	all	-	-	-	-	-	-	-	-
		summer	-	-	-	-	-	-	-	-
		winter	-	-	-	-	-	-	-	-
	Large	all	48	45	73	35	33	14	17	8
		summer	48	45	67	37	30	15	15	7.5
		winter	48	20	110	49	34	17	20	10
	Very Large	all	48	48	270	130	200	90	28	13
		summer	48	48	220	110	110	51	23	11
		winter	48	48	>300	170	270	130	31	17
Loviisa	Basic	all	-	-	-	-	-	-	-	-
		summer	-	-	-	-	-	-	-	-
		winter	-	-	-	-	-	-	-	-
	Large	all	46	2	45	20	15	6.3	6.2	3.3
		summer	46	2	56	21	15	5.7	10	4.1
		winter	47	3	42	21	24	11	12	5.4
	Very Large	all	48	48	160	77	80	38	28	11
		summer	48	47	190	80	83	33	28	11
		winter	48	48	190	81	89	43	28	13
Olkiluoto 1 & 2	Basic	all	-	-	-	-	-	-	-	-
		summer	-	-	-	-	-	-	-	-
		winter	-	-	-	-	-	-	-	-
	Large	all	48	3	53	26	24	11	12	6.4
		summer	48	3	50	27	22	10	11	6.3
		winter	47	4	59	29	27	12	15	7.8
	Very Large	all	48	48	190	94	120	50	26	12
		summer	48	48	170	88	99	44	24	12
		winter	48	48	>300	120	290	70	28	14
Olkiluoto 3	Basic	all	-	-	-	-	-	-	-	-
		summer	-	-	-	-	-	-	-	-
		winter	-	-	-	-	-	-	-	-
	Large	all	48	45	83	39	35	14	19	8.4
		summer	48	45	75	39	29	16	17	8.3
		winter	48	47	93	44	53	19	20	9.6
	Very Large	all	48	48	290	140	160	70	28	13
		summer	48	48	260	120	140	61	25	12
		winter	48	48	>300	180	>300	100	31	16

TABLE 5.3. Median durations for dose rates exceeding 100 µSv/h inside PAZ (< 5 km) and EPZ (< 20 km), and maximum and median distances when exceeding dose rate for over 1, 24 and 48 h. The values analyzed for all year, summer and winter data using Basic, Large, and Very Large cases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median duration d < 5 km (h)	median duration d < 20 km (h)	maximum distance for 1 h (km)	median distance for 1 h (km)	maximum distance for 24 h (km)	median distance for 24 h (km)	maximum distance for 48 h (km)	median distance for 48 h (km)
Hanhikivi	Basic	all	-	-	-	-	-	-	-	-
		summer	-	-	-	-	-	-	-	-
		winter	-	-	-	-	-	-	-	-
	Large	all	1	1	10	4.7	-	-	-	-
		summer	2	1	13	7.4	-	-	-	-
		winter	1	0.4	3.6	3.2	-	-	-	-
	Very Large	all	48	45	73	35	33	14	17	8
		summer	48	45	67	37	30	15	15	7.5
		winter	48	21	110	49	34	17	20	10
Loviisa	Basic	all	-	-	-	-	-	-	-	-
		summer	-	-	-	-	-	-	-	-
		winter	-	-	-	-	-	-	-	-
	Large	all	-	-	-	-	-	-	-	-
		summer	-	-	-	-	-	-	-	-
		winter	-	-	-	-	-	-	-	-
	Very Large	all	46	2	45	20	15	6.3	6.2	3.3
		summer	46	2	56	21	15	5.7	10	4.1
		winter	47	3	42	21	24	11	12	5.4
Olkiluoto 1 & 2	Basic	all	-	-	-	-	-	-	-	-
		summer	-	-	-	-	-	-	-	-
		winter	-	-	-	-	-	-	-	-
	Large	all	-	-	-	-	-	-	-	-
		summer	1	-	2.6	1.3	-	-	-	-
		winter	-	-	-	-	-	-	-	-
	Very Large	all	48	3	53	26	24	11	13	6.4
		summer	48	3	50	27	22	10	11	6.3
		winter	47	4	59	30	27	12	15	7.8
Olkiluoto 3	Basic	all	-	-	-	-	-	-	-	-
		summer	-	-	-	-	-	-	-	-
		winter	-	-	-	-	-	-	-	-
	Large	all	1	1	10	4.9	-	-	-	-
		summer	2	1	13	7.7	-	-	-	-
		winter	1	1	8.8	5.2	-	-	-	-
	Very Large	all	48	45	83	39	35	14	19	8.4
		summer	48	45	75	39	29	16	17	8.3
		winter	48	47	93	44	53	19	20	9.7

In an NPP accident, dose rates are components of the effective doses of an adult and a child. The effective dose includes radiation doses accumulating directly from the cloud and deposition of radioactive substances and via inhalation. The effective doses for the first 7 days after the release were estimated for four NPP sites in Finland and for three hypothetical release scenarios. The effective doses of an unprotected adult and a one-year-old child were considered. Note that the effective doses were determined using 7-day dose coefficients for external dose and of lifetime for dose via inhalation, while the dose criteria given in Tables 3.1 and 3.2 are given for 2 days after the accident. In practice, this means that the effective doses may slightly overestimate the effective dose for 2 days and can be used as conservative estimates when considering the probabilities of taking protective actions.

Areas where an adult's and child's effective doses of 1, 10, 20 and 100 mSv may be exceeded in Large and Very Large cases are shown in Figs. 5.4–5.11. In general, the effective dose maps correlate well with wind roses (see Fig. 4.1). In Loviisa, winds from the south-west dominate while in Hanhikivi and Olkiluoto winds from the south and south-west are dominant in the wind roses with most of the wind strengths.

Numerical results of the analysis for an adult's and child's median effective doses, and the maximum and median distances for exceeding effective doses of 1, 10, 20 and 100 mSv in Basic, Large and Very Large cases are shown in Tables 5.4–5.5. In Basic cases, the adult's effective dose does not exceed 1 mSv in any of the NPP sites. The adult's median effective doses vary from 0.35 mSv to 0.49 mSv inside the PAZ and from 0.18 mSv to 0.25 mSv inside the EPZ. In all the NPP sites, a child's effective dose may exceed 1 mSv inside the PAZ and in some sites also inside the EPZ. The child's median effective doses, in turn, vary from 0.65 mSv to 0.92 mSv inside the PAZ and from 0.33 mSv to 0.47 mSv inside the EPZ.

In Large cases, the adult's median effective doses vary from 6.6 mSv to 20 mSv inside the PAZ and from 4.3 mSv to 10 mSv inside the EPZ. In Hanhikivi and Olkiluoto 3, the adult's effective dose of 20 mSv may be exceeded inside the PAZ and EPZ. Furthermore, the adult's effective dose of 10 mSv may be exceeded also in Olkiluoto 1&2 and in some rare cases in Loviisa inside the PAZ and EPZ. In Hanhikivi and Olkiluoto 3, the adult's effective dose of 10 mSv may be exceeded also slightly beyond the EPZ. The maximum distances for exceeding effective dose of 1 mSv vary from 67 km to 98 km. The child's median effective doses, in turn, vary from 12 mSv to 39 mSv inside the PAZ and from 6.5 mSv to 20 mSv inside the EPZ in Large cases. The child's effective dose of 20 mSv may be exceeded in Hanhikivi, Olkiluoto 1&2 and Olkiluoto 3 inside the PAZ and EPZ. The maximum distances for exceeding the child's effective dose of 10 mSv vary from 17 km to 35 km while 1 mSv may be exceeded at distances up to 140 km.

In Very Large cases, the adult's median effective doses vary from 66 mSv to 200 mSv inside the PAZ and from 33 mSv to 100 mSv inside the EPZ. The adult's effective dose of 100 mSv may be exceeded inside the PAZ and EPZ in all NPP sites while in Hanhikivi, Olkiluoto 1&2 and Olkiluoto 3 it may be exceeded also slightly beyond the EPZ. The adult's effective dose of 20 mSv may be exceeded in all sites inside the PAZ and EPZ. Furthermore, in some cases 20 mSv may be exceeded up to distances of 66 km while the median distance for exceeding it varies from 17 km to 31 km. The adult's effective dose of 10 mSv, in turn, may be exceeded at distances varying from 67 km to 98 km while medium distances vary from 27 km to 46 km. The adult's effective dose of 1 mSv may be exceeded far beyond the EPZ and the maximum distances may even exceed the distances considered (> 300 km) from the NPP sites. For example, 1 mSv can be exceeded in Kokkola, Rovaniemi and Kemijärvi (release from Hanhikivi), Porvoo, Lahti and Lappeenranta (Loviisa), and Turku, Hämeenlinna and Vaasa (Olkiluoto 3). The child's median effective doses, in turn, vary from 120 mSv to 380 mSv inside the PAZ and from 65 mSv to 200 mSv inside the EPZ. In Very Large cases, the child's effective dose of 100 mSv may be exceeded inside the PAZ and EPZ in all NPP sites, and it may be exceeded slightly outside the EPZ (up to 35 km). The child's effective dose of 20 mSv may be exceeded in some cases up to distances of 93 km while the median distance for exceeding it varies from 26 km to 44 km. The child's effective dose of 10 mSv, in turn, may be exceeded at distances varying from 95 km to 140 km while medium distances for exceeding it vary from 39 km to 66 km. In Very Large cases, the child's effective dose of 1 mSv may be exceeded beyond the distance considered (> 300 km) from the NPP sites.

Seasonal variations between summer and winter are significant Very Large cases. During the winter season, the dispersion towards the north and north-east are the dominant directions of dispersion which can be seen in the effective dose maps. During the summer season, the dose maps are more evenly distributed in all directions. However, the directions away from the continent are slightly less prominent than directions toward the continent and along the coast. In Loviisa, directions toward the east are more prominent than during winter. In Large cases, the seasonal variations are present but not as pronounced as in Very Large cases.

Directional emphases are similar to those in Very Large case. In Basic cases, the seasonal variations are negligible in terms of the effective doses. In general, the effective doses caused by releases from Hanhikivi and Olkiluoto 3 in Large and Very Large cases are higher than in Loviisa and Olkiluoto 1 and 2, due to the larger radionuclide inventory. However, the probability of a severe accident is lower for modern NPPs than for older ones.

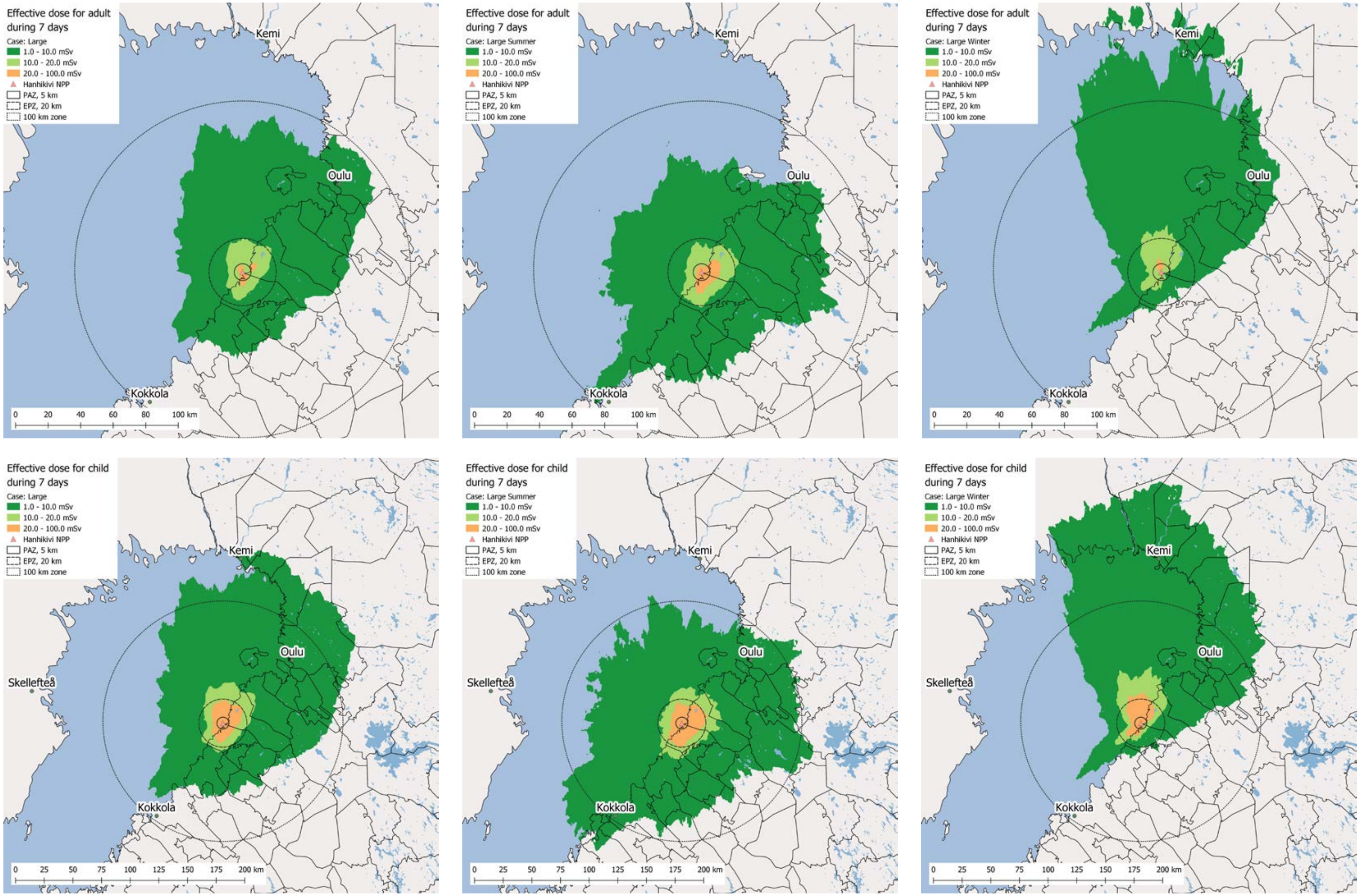

FIGURE 5.4. Adult's (upper panels) and child's (lower) effective dose in 7 days for a Large case at Hanhikivi using 95th percentile all year (left panels), summer (middle) and winter (right) data. Note different length scales.

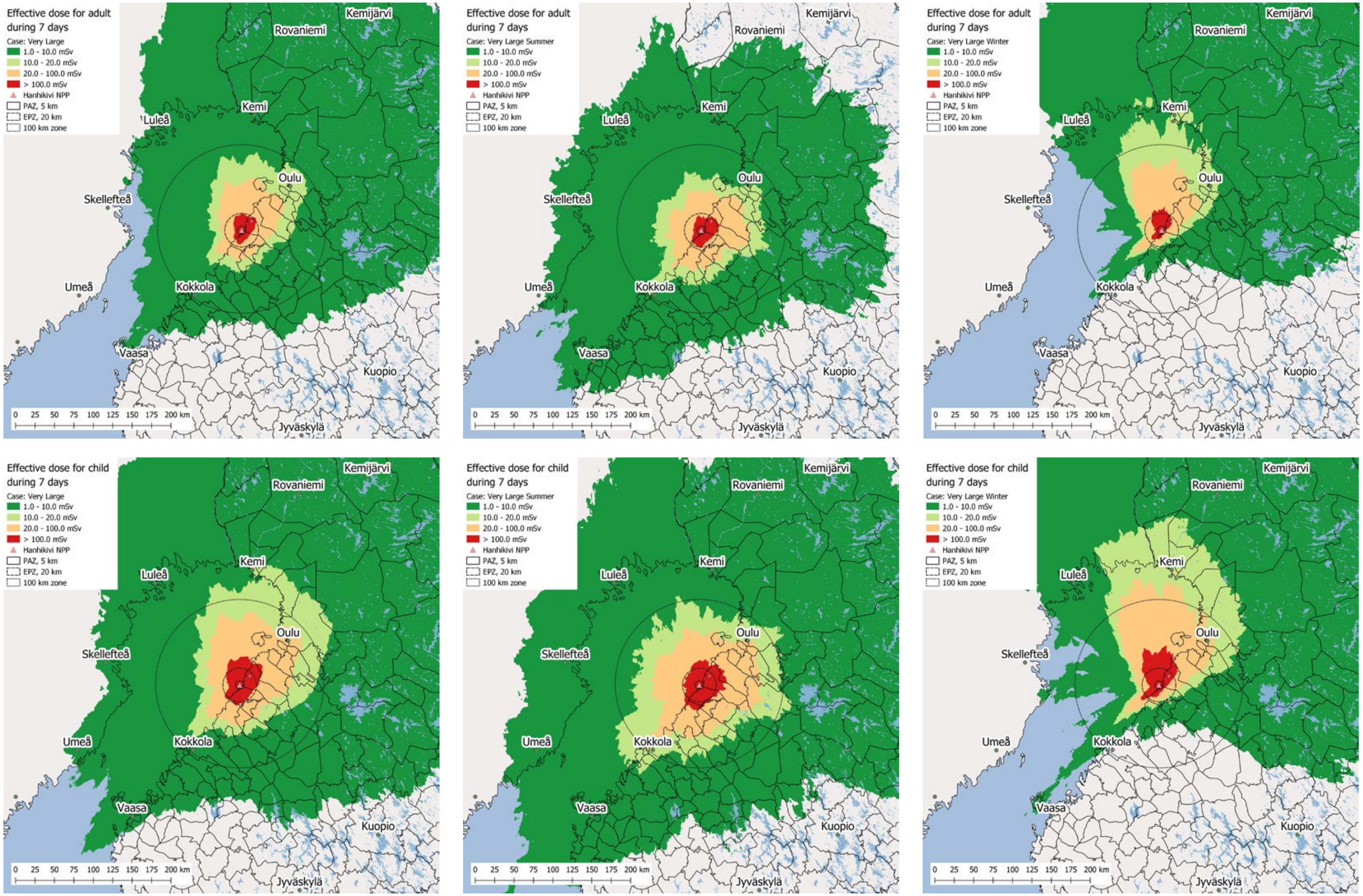

FIGURE 5.5. Adult's (upper panels) and child's (lower) effective dose in 7 days for a Very Large case at Hanhikivi using 95th percentile all year (left panels), summer (middle) and winter (right) data.

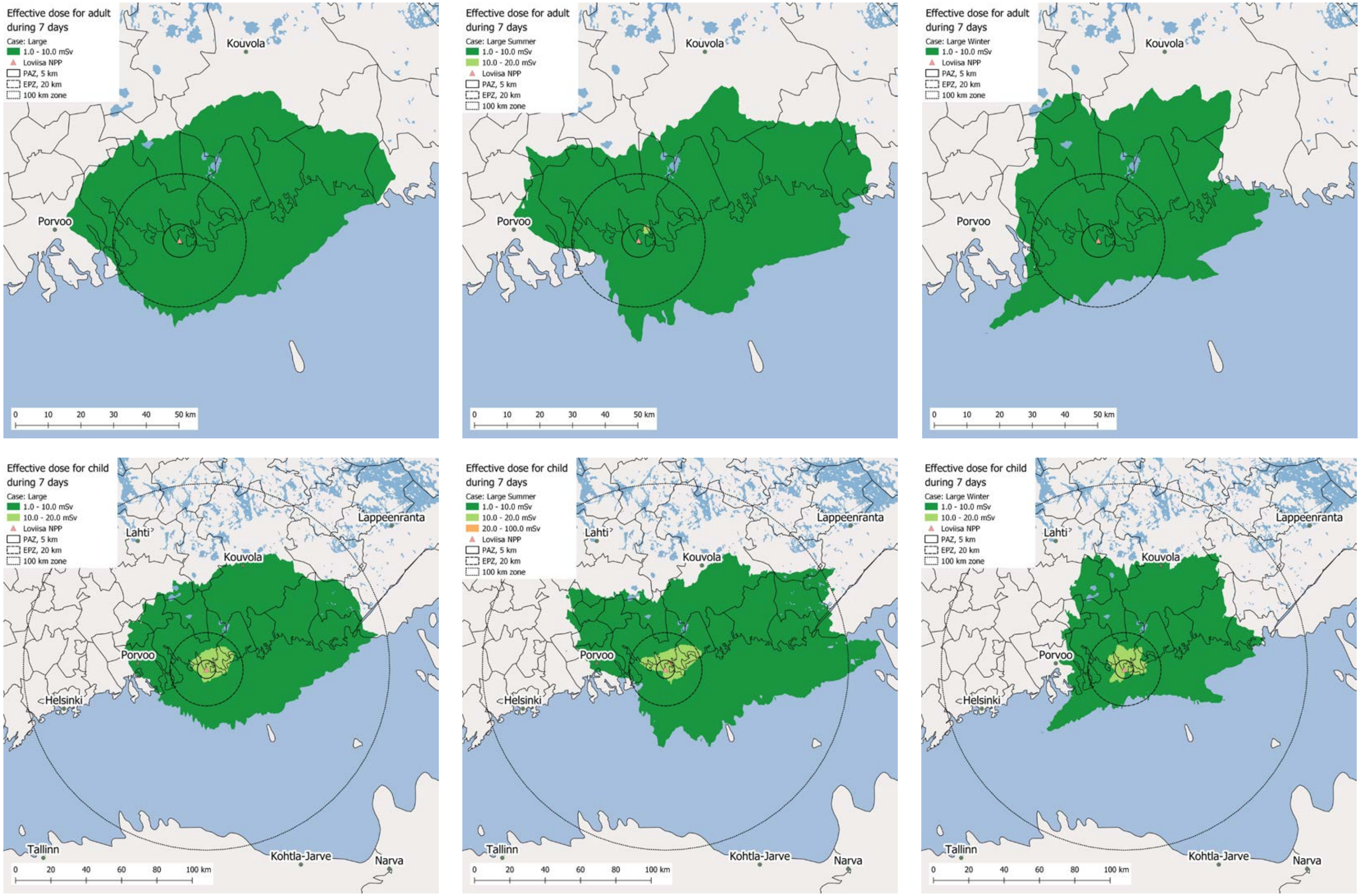

FIGURE 5.6. Adult's (upper panels) and child's (lower) effective dose in 7 days for a Large case at Loviisa using 95th percentile all year (left panels), summer (middle) and winter (right) data. Note different length scales.

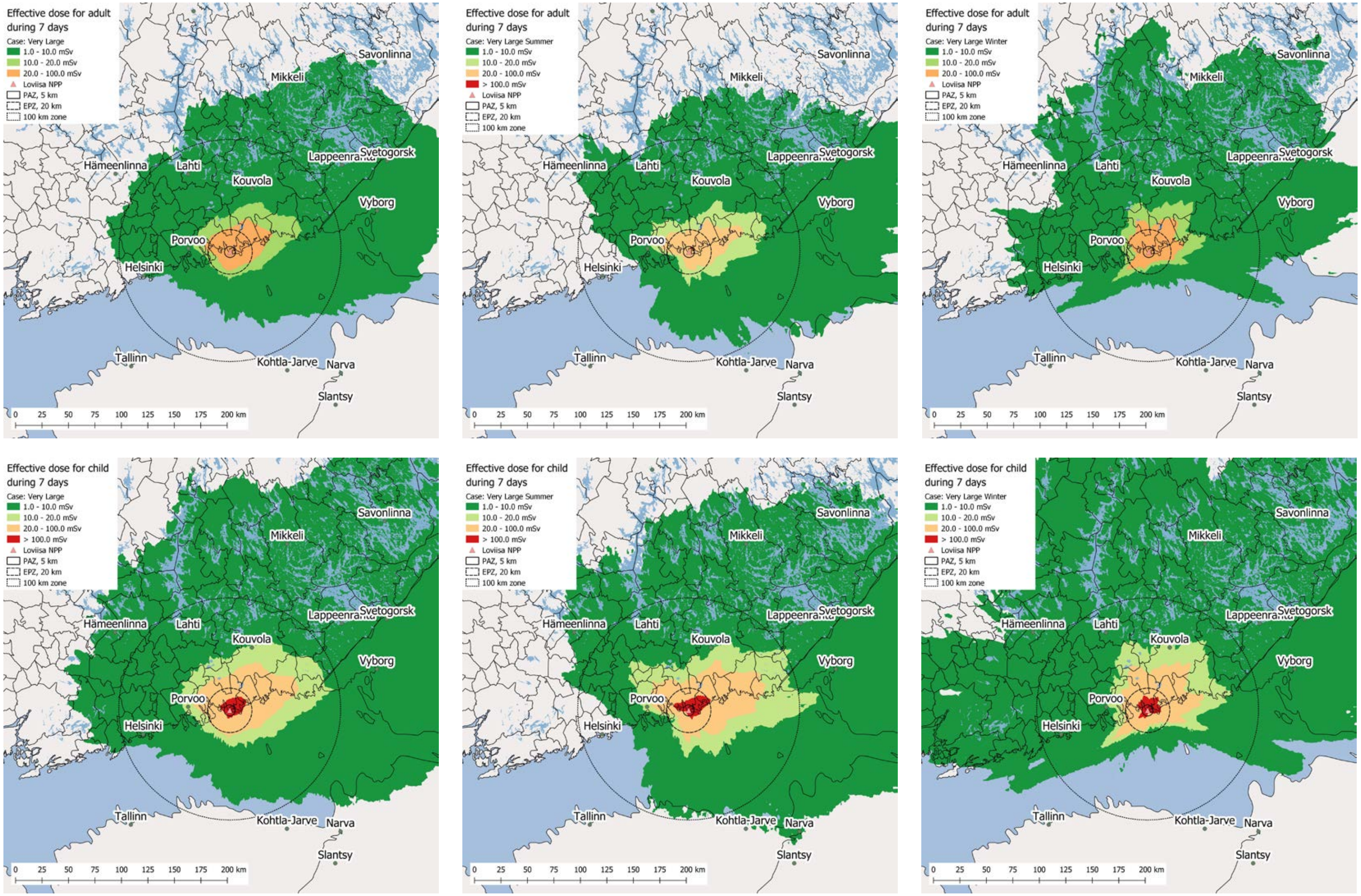

FIGURE 5.7. Adult's (upper panels) and child's (lower) effective dose in 7 days for a Very Large case at Loviisa using 95th percentile all year (left panels), summer (middle) and winter (right) data.

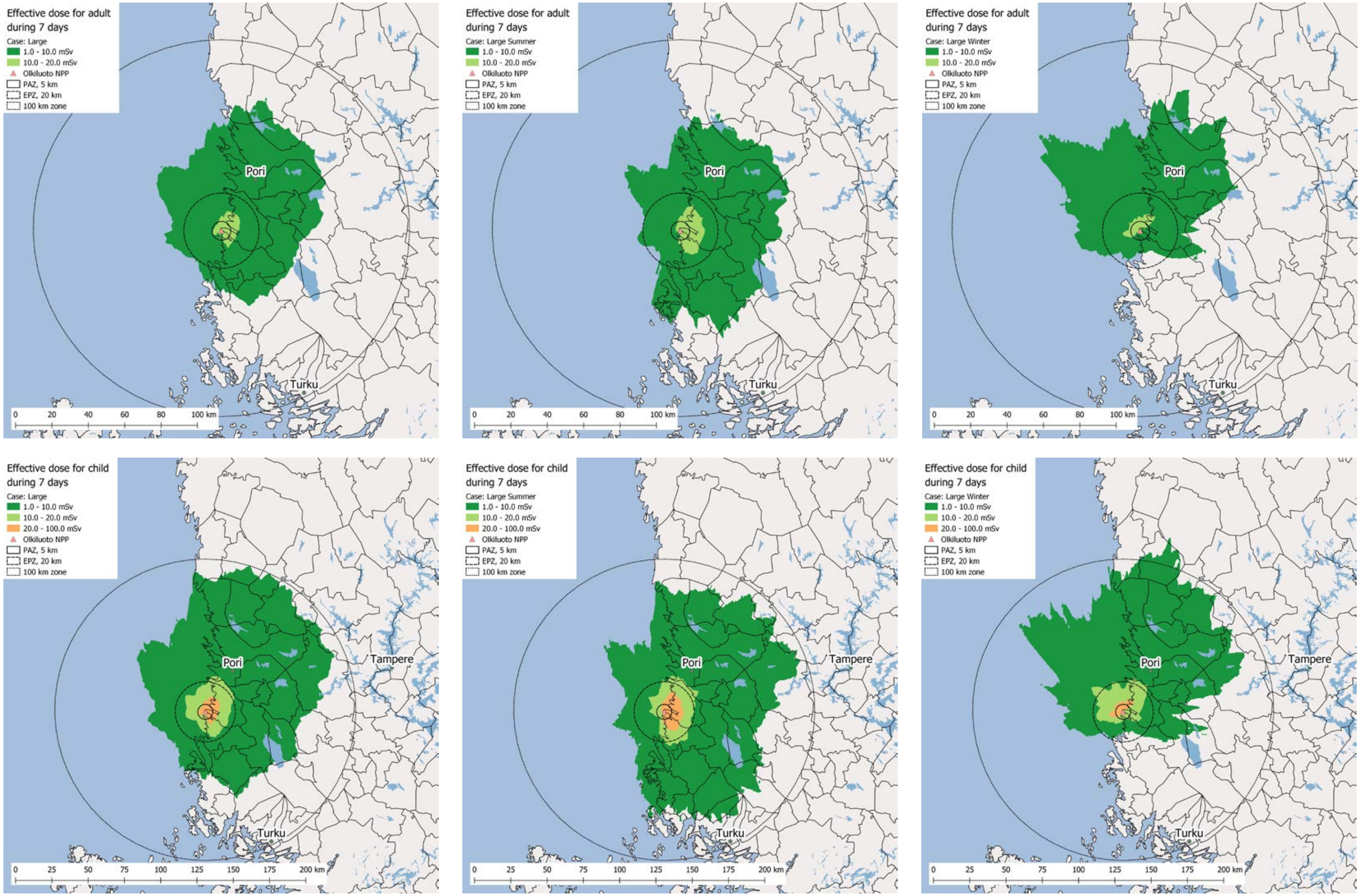

FIGURE 5.8. Adult's (upper panels) and child's (lower) effective dose in 7 days for a Large case at Olkiluoto 1 & 2 using 95th percentile all year (left panels), summer (middle) and winter (right) data. Note different length scale.

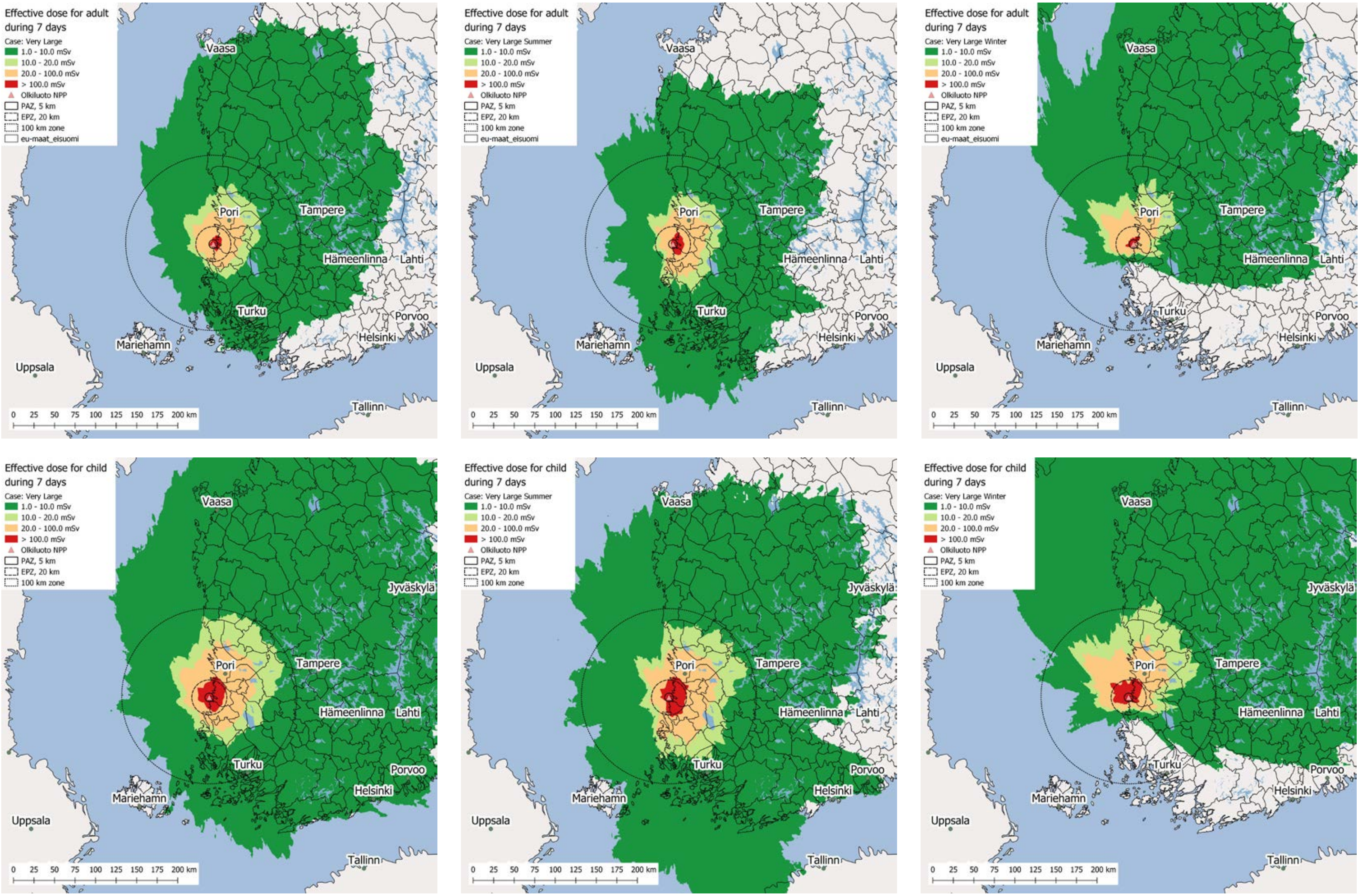

FIGURE 5.9. Adult's (upper panels) and child's (lower) effective dose in 7 days for a Very Large case at Olkiluoto 1 & 2 using 95th percentile all year (left panels), summer (middle) and winter (right) data.

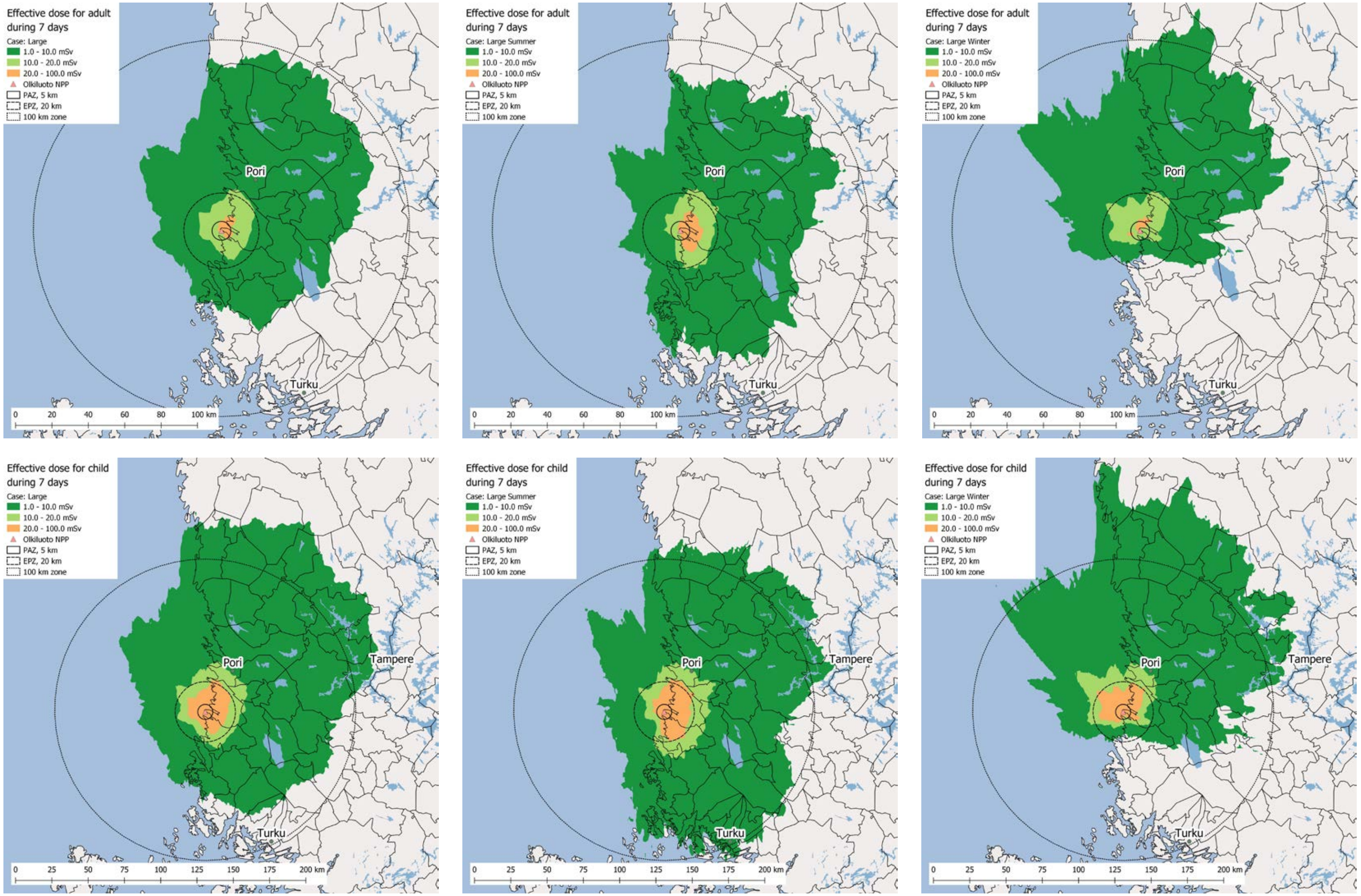

FIGURE 5.10. Adult's (upper panels) and child's (lower) effective dose in 7 days for a Large case at Olkiluoto 3 using 95th percentile all year (left panels), summer (middle) and winter (right) data. Note different length scales.summer (middle) and winter (right) data.

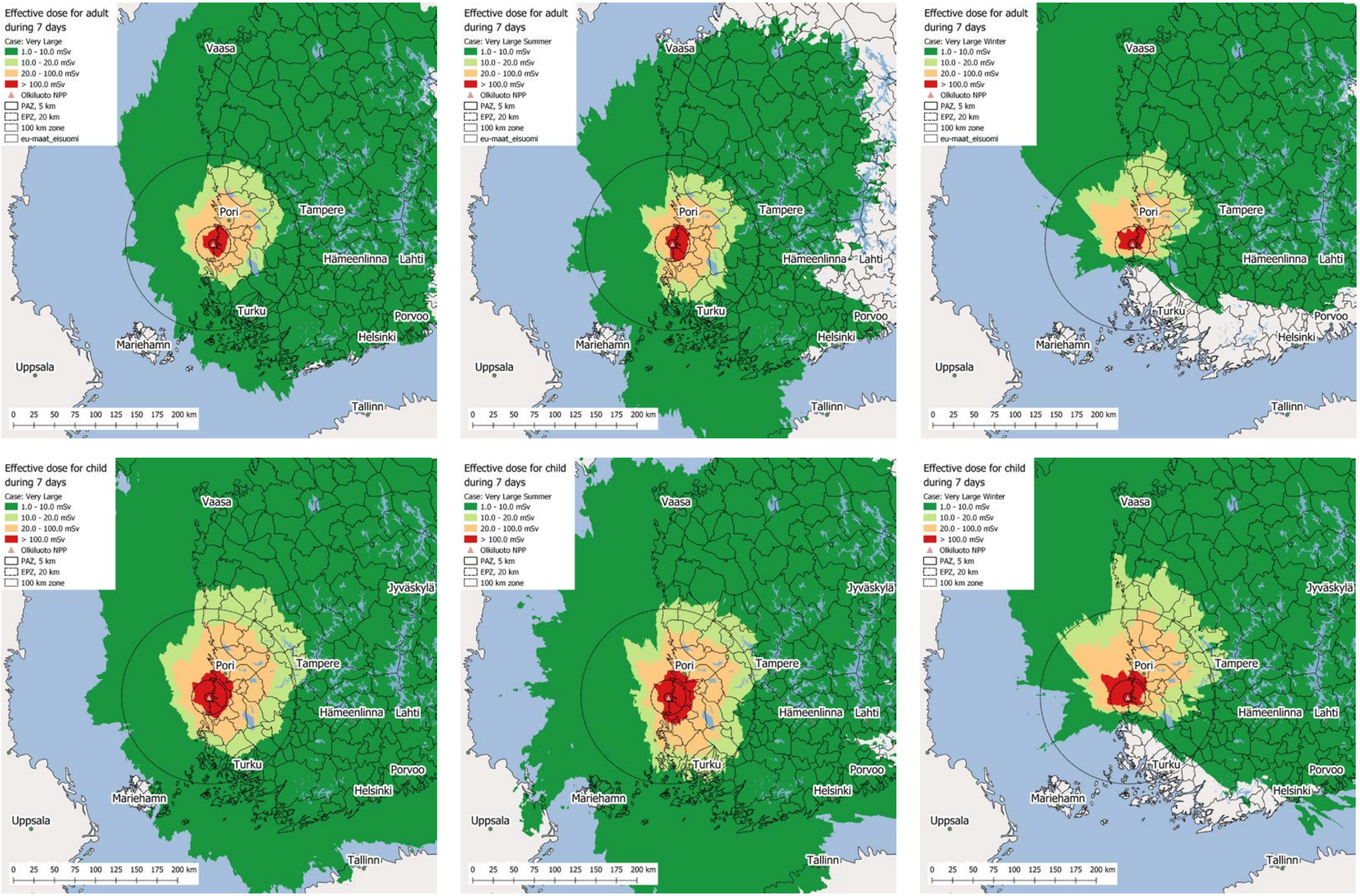

FIGURE 5.11. Adult's (upper panels) and child's (lower) effective dose in 7 days for a Very Large case at Olkiluoto 3 using 95th percentile all year (left panels), summer (middle) and winter (right) data.

TABLE 5.4. Adult's median effective dose in 7 days inside the PAZ (< 5 km) and EPZ (< 20 km), and maximum and median distances for exceeding the dose of 1, 10, 20 and 100 mSv. The values analyzed for all year, summer and winter data using Basic, Large, and Very Large releases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median dose d < 5 km (mSv)	median dose d < 20 km (mSv)	maximum distance for 1 mSv (km)	median distance for 1 mSv (km)	maximum distance for 10 mSv (km)	median distance for 10 mSv (km)	maximum distance for 20 mSv (km)	median distance for 20 mSv (km)	maximum distance for 100 mSv (km)	median distance for 100 mSv (km)
Hanhikivi	Basic	all	0.49	0.25	-	-	-	-	-	-	-	-
		summer	0.63	0.28	-	-	-	-	-	-	-	-
		winter	0.4	0.19	-	-	-	-	-	-	-	-
	Large	all	20	10	97	45	22	10	10	3.9	-	-
		summer	26	11	100	46	23	12	12	6.7	-	-
		winter	16	7.5	160	70	28	12	7.8	3.9	-	-
	Very Large	all	200	99	>300	170	97	44	64	30	22	10
		summer	260	110	260	140	100	45	60	32	23	12
		winter	160	74	>300	200	160	70	89	42	28	12
Loviisa	Basic	all	0.4	0.2	-	-	-	-	-	-	-	-
		summer	0.42	0.21	-	-	-	-	-	-	-	-
		winter	0.4	0.2	-	-	-	-	-	-	-	-
	Large	all	6.6	3.4	67	27	-	-	-	-	-	-
		summer	6.9	3.4	73	30	4.4	3.7	-	-	-	-
		winter	6.6	3.4	58	26	-	-	-	-	-	-
	Very Large	all	66	33	220	100	67	27	41	17	-	-
		summer	69	34	220	100	73	30	52	19	4.4	3.7
		winter	66	33	240	110	58	26	37	17	-	-
Olkiluoto 1 & 2	Basic	all	0.48	0.24	-	-	-	-	-	-	-	-
		summer	0.5	0.25	-	-	-	-	-	-	-	-
		winter	0.38	0.21	-	-	-	-	-	-	-	-
	Large	all	11	5.8	73	33	11	5.7	-	-	-	-
		summer	12	6.1	64	35	15	8.3	-	-	-	-
		winter	9.2	5.2	78	36	10	5.4	-	-	-	-
	Very Large	all	110	57	280	130	73	33	46	22	11	5.7
		summer	120	61	240	110	64	35	46	25	15	8.2
		winter	92	51	>300	170	78	36	53	24	10	5.5
Olkiluoto 3	Basic	all	0.35	0.18	-	-	-	-	-	-	-	-
		summer	0.37	0.19	-	-	-	-	-	-	-	-
		winter	0.29	0.16	-	-	-	-	-	-	-	-
	Large	all	20	10	98	47	23	11	8.8	4.1	-	-
		summer	22	11	94	48	24	13	12	7.5	-	-
		winter	17	9.1	120	54	23	12	8.8	5.1	-	-
	Very Large	all	200	100	>300	170	98	46	66	31	23	11
		summer	220	110	>300	150	94	48	60	33	24	13
		winter	170	91	>300	200	120	54	75	34	23	12

TABLE 5.5. Child's median effective dose in 7 days inside the PAZ (< 5 km) and EPZ (< 20 km), and maximum and median distances for exceeding the dose of 1, 10, 20 and 100 mSv. The values analyzed for all year, summer and winter data using Basic, Large and Very Large releases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median dose d < 5 km (mSv)	median dose d < 20 km (mSv)	maximum distance for 1 mSv (km)	median distance for 1 mSv (km)	maximum distance for 10 mSv (km)	median distance for 10 mSv (km)	maximum distance for 20 mSv (km)	median distance for 20 mSv (km)	maximum distance for 100 mSv (km)	median distance for 100 mSv (km)
Hanhikivi	Basic	all	0.92	0.47	8	4.4	-	-	-	-	-	-
		summer	1.1	0.54	12	6.5	-	-	-	-	-	-
		winter	0.74	0.35	5.9	3.9	-	-	-	-	-	-
	Large	all	37	19	140	65	35	17	21	10	-	-
		summer	44	22	130	64	34	18	21	12	-	-
		winter	30	14	190	99	47	22	28	12	-	-
	Very Large	all	370	190	>300	180	140	65	94	43	35	17
		summer	440	220	>300	180	130	64	99	44	34	18
		winter	300	140	>300	210	190	99	140	62	47	21
Loviisa	Basic	all	0.74	0.4	4.4	3.7	-	-	-	-	-	-
		summer	0.78	0.4	11	6.2	-	-	-	-	-	-
		winter	0.74	0.39	4.4	2.2	-	-	-	-	-	-
	Large	all	12	6.5	95	39	17	7.6	-	-	-	-
		summer	13	6.6	120	44	22	9.1	4.4	3.7	-	-
		winter	12	6.3	80	38	15	7.6	-	-	-	-
	Very Large	all	120	65	290	140	95	39	65	26	17	7.6
		summer	130	66	300	130	120	44	72	29	22	9.1
		winter	120	63	>300	170	80	38	56	25	14	7.6
Olkiluoto 1 & 2	Basic	all	0.92	0.48	6.4	3.4	-	-	-	-	-	-
		summer	0.96	0.51	12	7.4	-	-	-	-	-	-
		winter	0.75	0.43	6.9	5.1	-	-	-	-	-	-
	Large	all	22	12	99	48	24	12	11	5.7	-	-
		summer	23	12	96	50	25	14	15	8.3	-	-
		winter	18	10	120	54	27	12	10	5.6	-	-
	Very Large	all	220	120	>300	170	99	48	69	32	24	12
		summer	230	120	>300	150	96	50	63	35	25	14
		winter	180	100	>300	210	120	54	73	35	27	12
Olkiluoto 3	Basic	all	0.65	0.33	-	-	-	-	-	-	-	-
		summer	0.68	0.35	5.4	3.5	-	-	-	-	-	-
		winter	0.52	0.3	-	-	-	-	-	-	-	-
	Large	all	39	20	140	66	33	17	22	10	-	-
		summer	40	21	120	65	38	20	22	13	-	-
		winter	31	17	160	77	41	18	22	11	-	-
	Very Large	all	380	200	>300	190	140	66	93	44	33	17
		summer	400	210	>300	190	120	65	88	46	38	20
		winter	310	170	>300	210	160	77	100	49	41	18

These dose routes were considered to determine thyroid doses of an unprotected adult and one-year-old child. The thyroid doses for the first 7 days after the release were estimated for four NPP sites in Finland and for three hypothetical release scenarios. Note that the thyroid doses were determined using dose coefficients of 7 days for external dose and of lifetime for dose via inhalation, while dose criteria given in Tables 3.1 and 3.2 are given for 2 days after the accident. In practice, this means that the determined thyroid doses may slightly overestimate the thyroid dose for 2 days and can be used as conservative estimates when considering the probabilities of taking protective actions.

The areas where an adult's and child's thyroid doses of 1, 10, 20 and 100 mSv may be exceeded in Basic, Large and Very Large cases are shown in Figs 5.12–5.23. In general, the thyroid dose maps correlate well with wind roses (see Fig. 4.1). In Loviisa, winds from the south-west dominate while in Hanhikivi and Olkiluoto winds from south and south-west are dominant in the wind roses with most of the wind strengths. Numerical results of the analysis for the adult's and child's median thyroid doses, and the maximum and median distances for exceeding doses of thyroid doses of 1, 10, 20 and 100 mSv in Basic, Large and Very Large cases are shown in Tables 5.6–5.7. In Basic cases, the adult's thyroid dose of 1 mSv may be exceeded inside the PAZ and EPZ while it may be exceeded also at distances up to 62 km from the NPP sites. In some rare cases the adult's thyroid dose of 10 mSv may be exceeded inside the PAZ and EPZ. The adult's median thyroid doses vary from 4.6 mSv to 6.9 mSv inside the PAZ and from 2.4 mSv to 3.7 mSv inside the EPZ. In Basic cases, the child's median thyroid doses vary from 10mSv to 15 mSv inside the PAZ and from 5.3 mSv to 8.0 mSv inside the EPZ. In Basic cases, the child's thyroid dose of 1 mSv may be exceeded at distances up to 96 km while the median distance for exceeding it varies from 30 km to 39 km. In all NPP sites, the child's thyroid dose may exceed 10 mSv inside the PAZ and EPZ and in some rare cases it may exceed also 20 mSv.

In Large cases, the adult's median thyroid doses vary from 89 mSv to 290 mSv inside the PAZ and from 50 mSv to 150 mSv inside the EPZ. The adult's thyroid dose of 100 mSv may be exceeded in all NPP sites inside the PAZ and EPZ while in Hanhikivi and Olkiluoto 3 it may be exceeded also slightly beyond the EPZ. In Large cases, the maximum distance where the adult's thyroid dose of 20 mSv is exceeded varies from 55 km to 76 km while the medium distance is below 37 km. The adult's thyroid dose of 10 mSv may be exceeded up to distances of 110 km while the median distance for exceeding it varies from 33 km to 54 km. In Large cases, the adult's thyroid dose of 1 mSv may be exceeded beyond the distance considered (> 300 km) from the NPP sites. The child's median thyroid doses, in turn, vary from 190 mSv to 620 mSv inside the PAZ and from 110 mSv to 330 mSv inside the EPZ in Large cases. The child's thyroid dose of 100 mSv may be exceeded in all sites inside the PAZ and EPZ while maximum distance for exceeding it varies from 28 km to 47 km. In Large cases, the maximum distance for exceeding the child's thyroid dose of 20 mSv varies from 86 km to 120 km while the medium distance is below 57 km. The child's thyroid dose of 10 mSv may be exceeded up to distances of 180 km while the median distance for exceeding it varies from 53 km to 85 km. In Large cases, the child's thyroid dose of 1 mSv may be exceeded beyond the distance considered (> 300 km) from the NPP sites.

In Very Large cases, the adult's median thyroid doses vary from 900 mSv to 2900 mSv inside the PAZ and from 500 mSv to 1500 mSv inside the EPZ. The adult's thyroid dose of 100 mSv may be exceeded outside the EPZ at all NPP sites and the median distance for exceeding it varies from 33 km to 55 km while the maximum distance may reach up to 110 km. In Very Large cases, the maximum distance for exceeding the adult's thyroid dose of 20 mSv varies from 180 km to 290 km while the medium distance is below 140 km. The adult's thyroid dose of 10 mSv may be exceeded at distances beyond the distances considered (> 300 km) while the median distance for exceeding it is over 120 km. The child's median thyroid doses, in turn, vary from 2900 mSv to 6200 mSv inside the PAZ and from 1100 mSv to 3300 mSv inside the EPZ. In Very Large cases, the child's thyroid dose of 100 mSv may be exceeded far beyond the EPZ in all NPP sites and the median distance for exceeding it varies from 53 km to 85 km while the maximum distance may reach up to 180 km. The child's thyroid dose of 20 mSv may be exceeded beyond the distances considered (> 300 km) while the median distance for exceeding it is over 120 km. In Very Large cases, the adult's and child's thyroid dose of 1 mSv, and child's thyroid dose of 10 mSv may be exceeded beyond the distance considered (> 300 km) from the NPP sites.

Variations between the seasons of summer and winter are significant in Large and Very Large cases. During the winter season, the dispersion towards the north and north-east are the dominant directions of dispersion that can be seen in the thyroid dose maps. During the summer season, the dose maps are more evenly distributed to all directions. However, the directions away from the continent are slightly less prominent than directions toward the continent and along the coast. In Loviisa, directions toward the east are more prominent than during the winter season. In Large cases, the seasonal variations are not as large as in Very Large cases. In Basic cases, the seasonal variations are negligible in terms of the thyroid doses. In general, the thyroid doses caused by releases from Hanhikivi and Olkiluoto 3 in Large and Very Large cases are higher than in Loviisa and Olkiluoto 1 and 2 arise from larger radionuclide inventory. However, the probability of a severe accident is lower for modern NPPs than for older ones

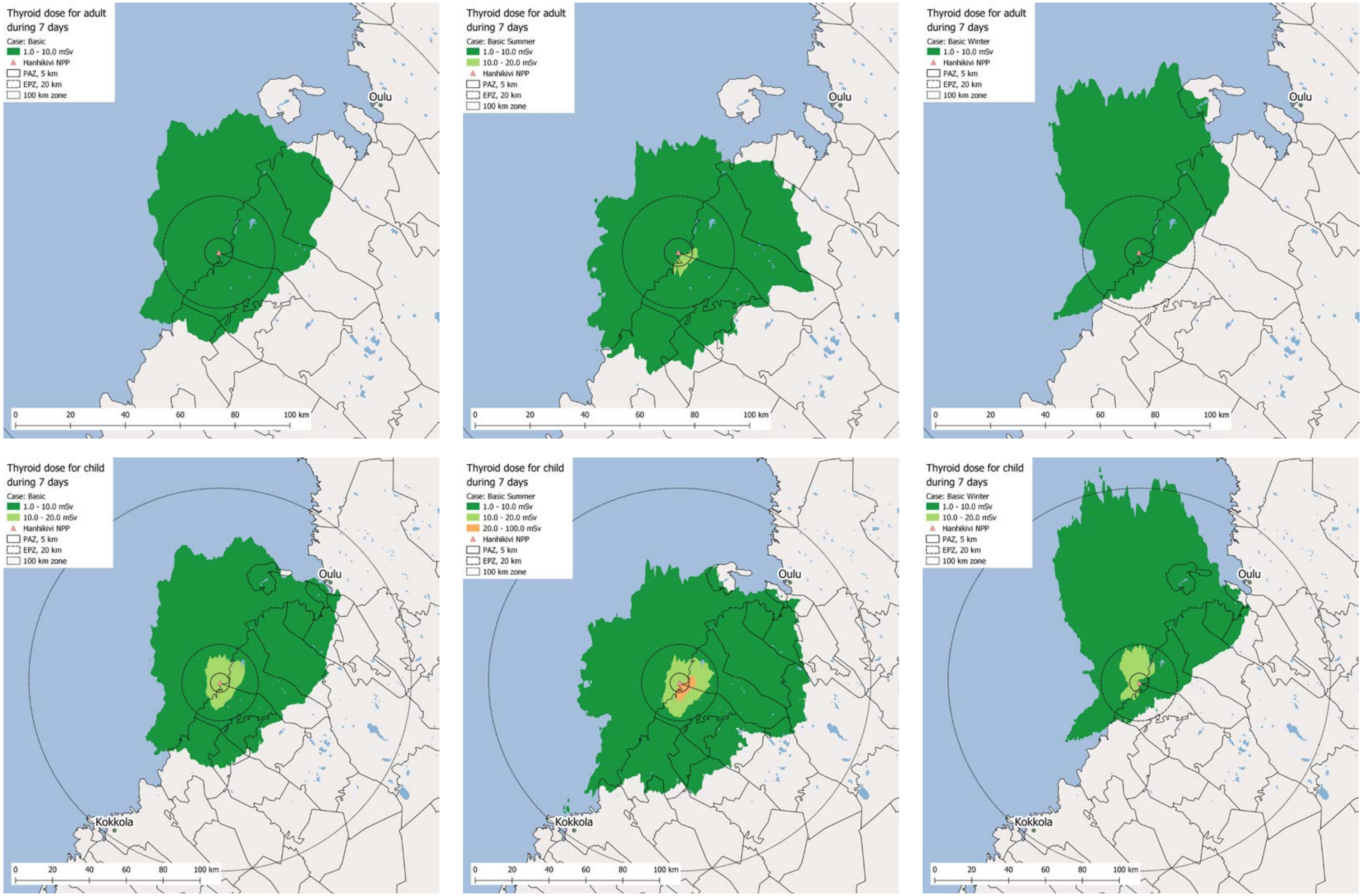

FIGURE 5.12 Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Basic case at Hanhikivi using 95th percentile all year (left panels), summer (middle) and winter (right) data. Note different length scales.

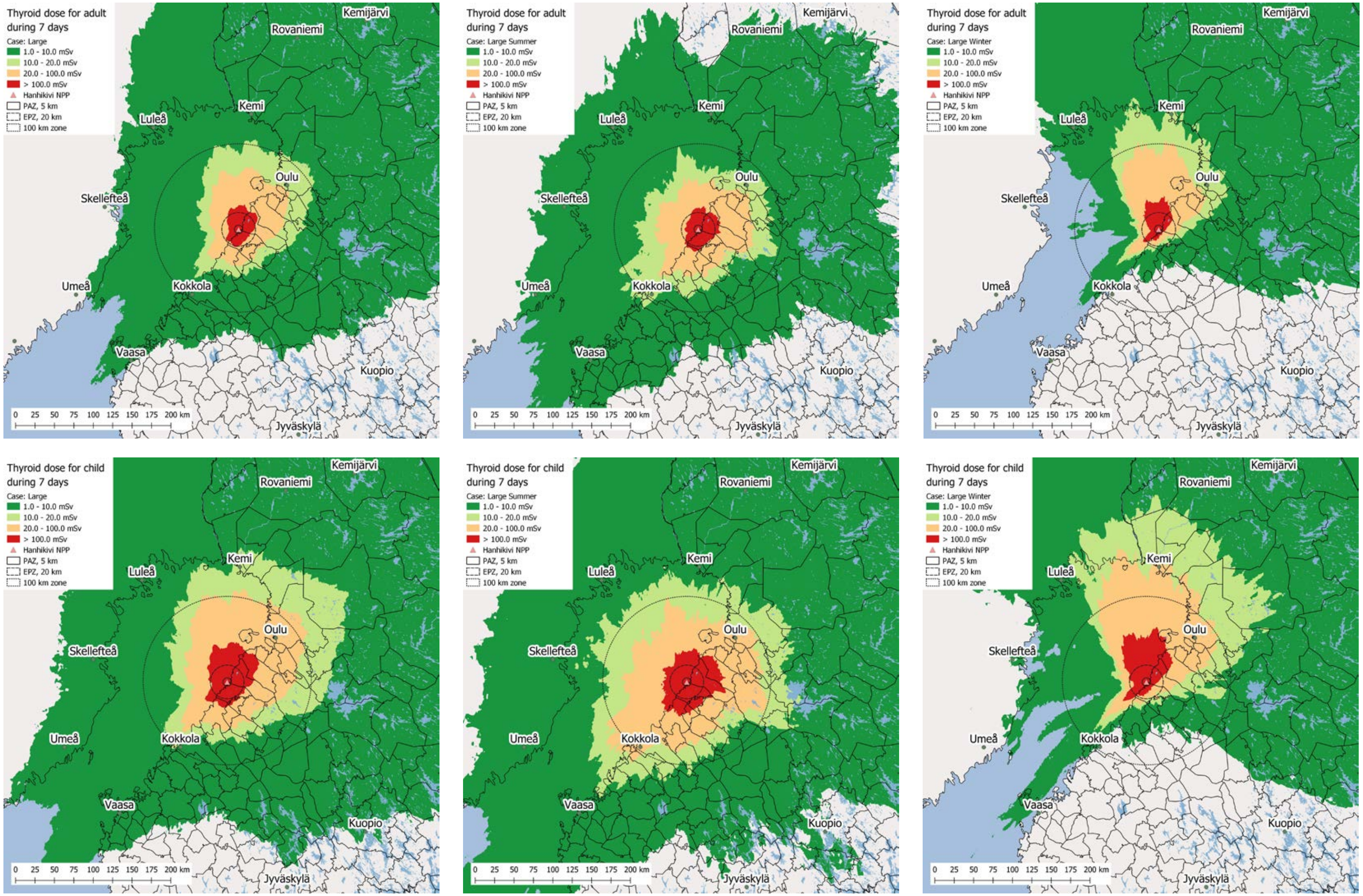

FIGURE 5.13. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Large case at Hanhikivi using 95th percentile all year (left panels), summer (middle) and winter (right) data.

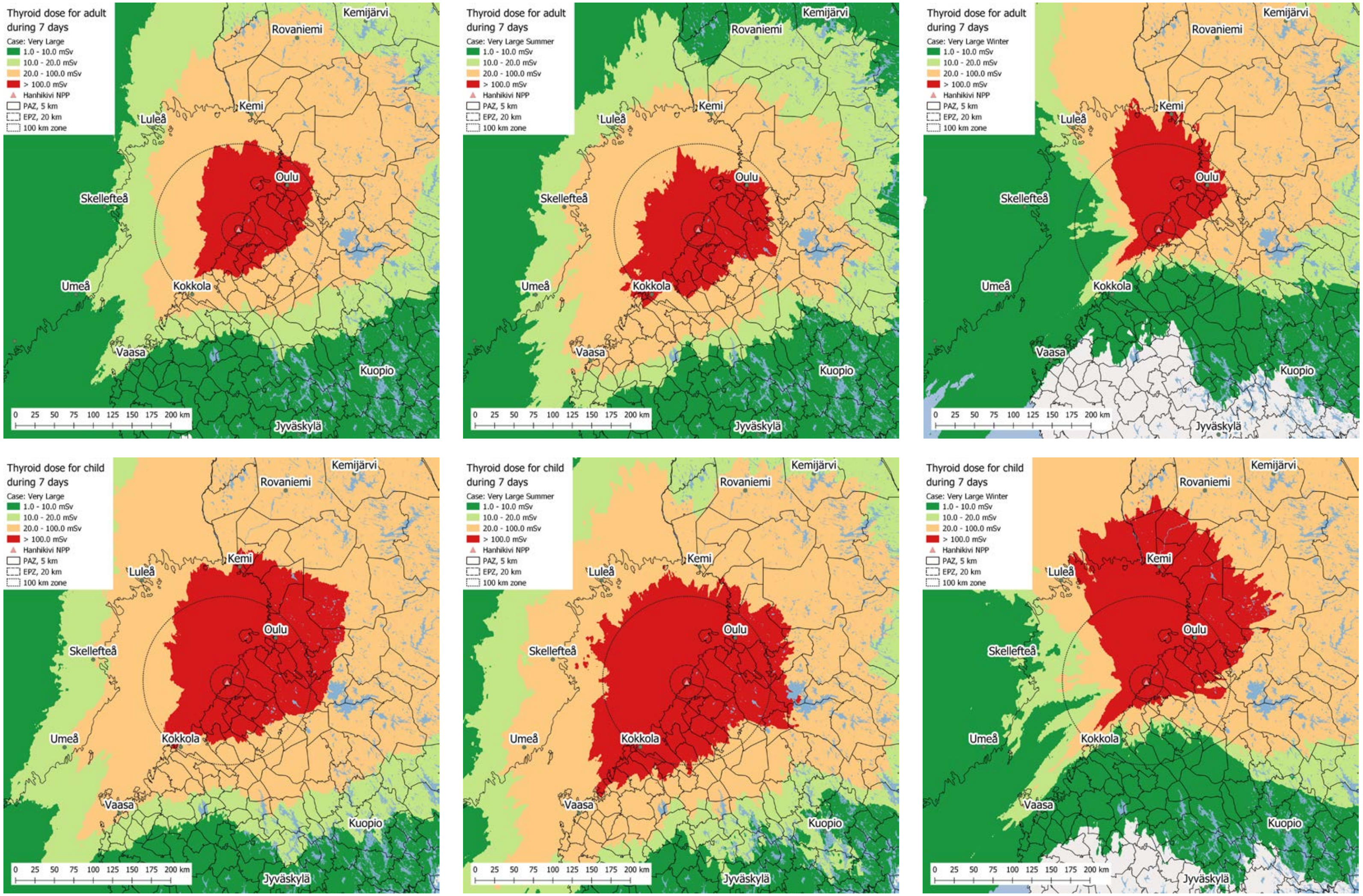

FIGURE 5.14. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Very Large case at Hanhikivi using 95th percentile all year (left panels), summer (middle) and winter (right) data.

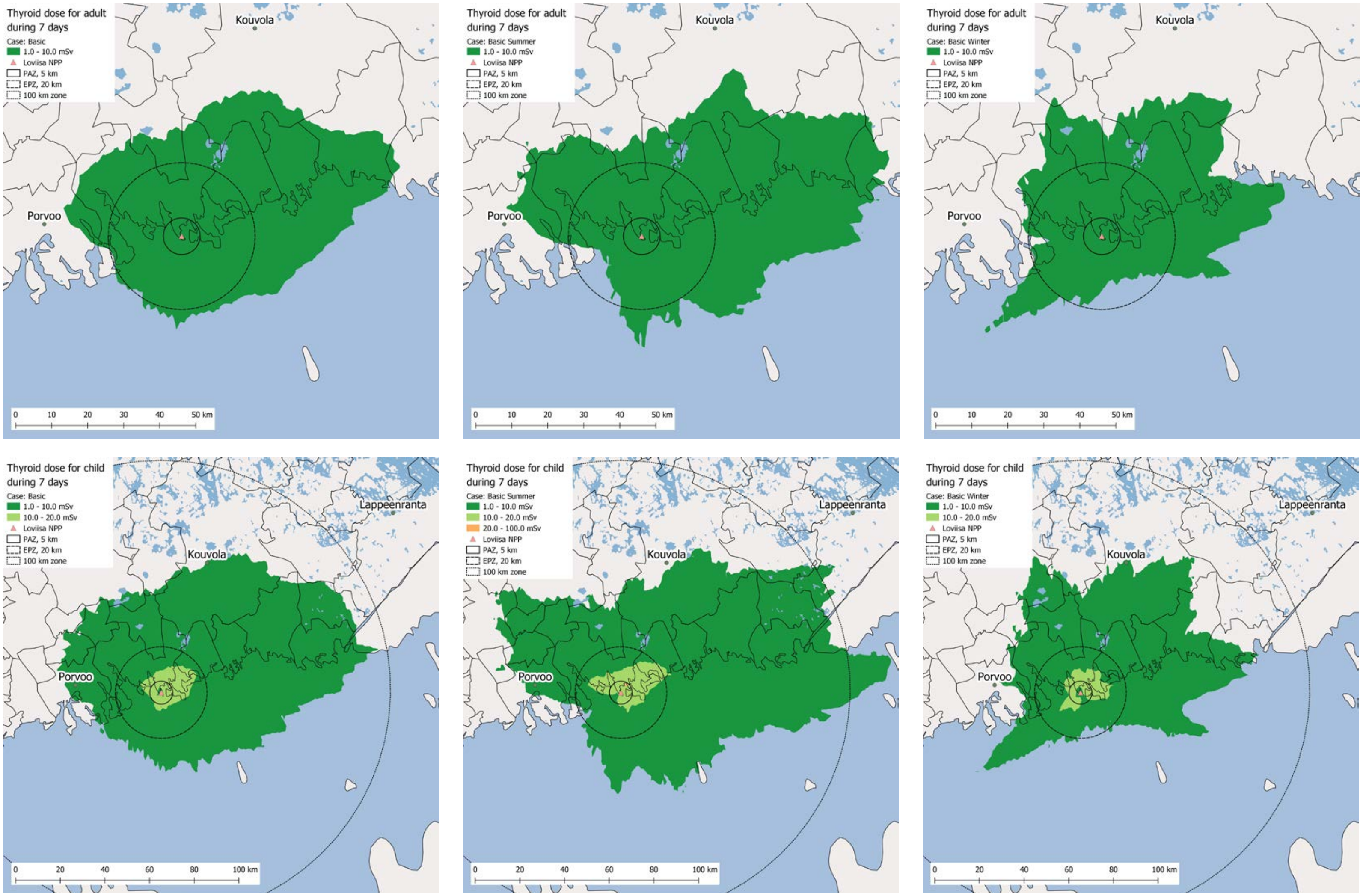

FIGURE 5.15. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Basic case at Loviisa using 95th percentile all year (left panels), summer (middle) and winter (right) data. Note different length scales.

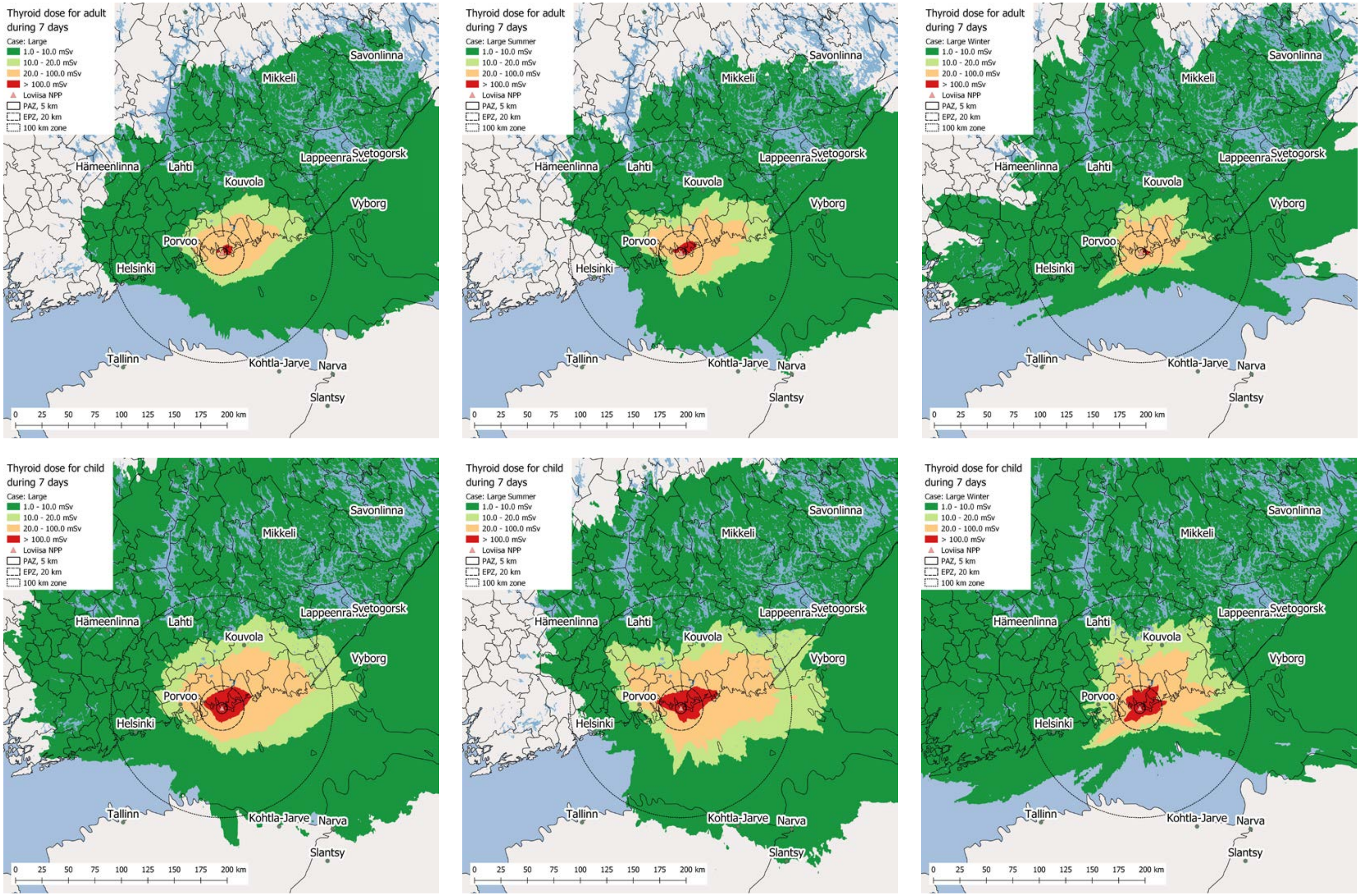

FIGURE 5.16. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Large case at Loviisa using 95th percentile all year (left panels), summer (middle) and winter (right) data.

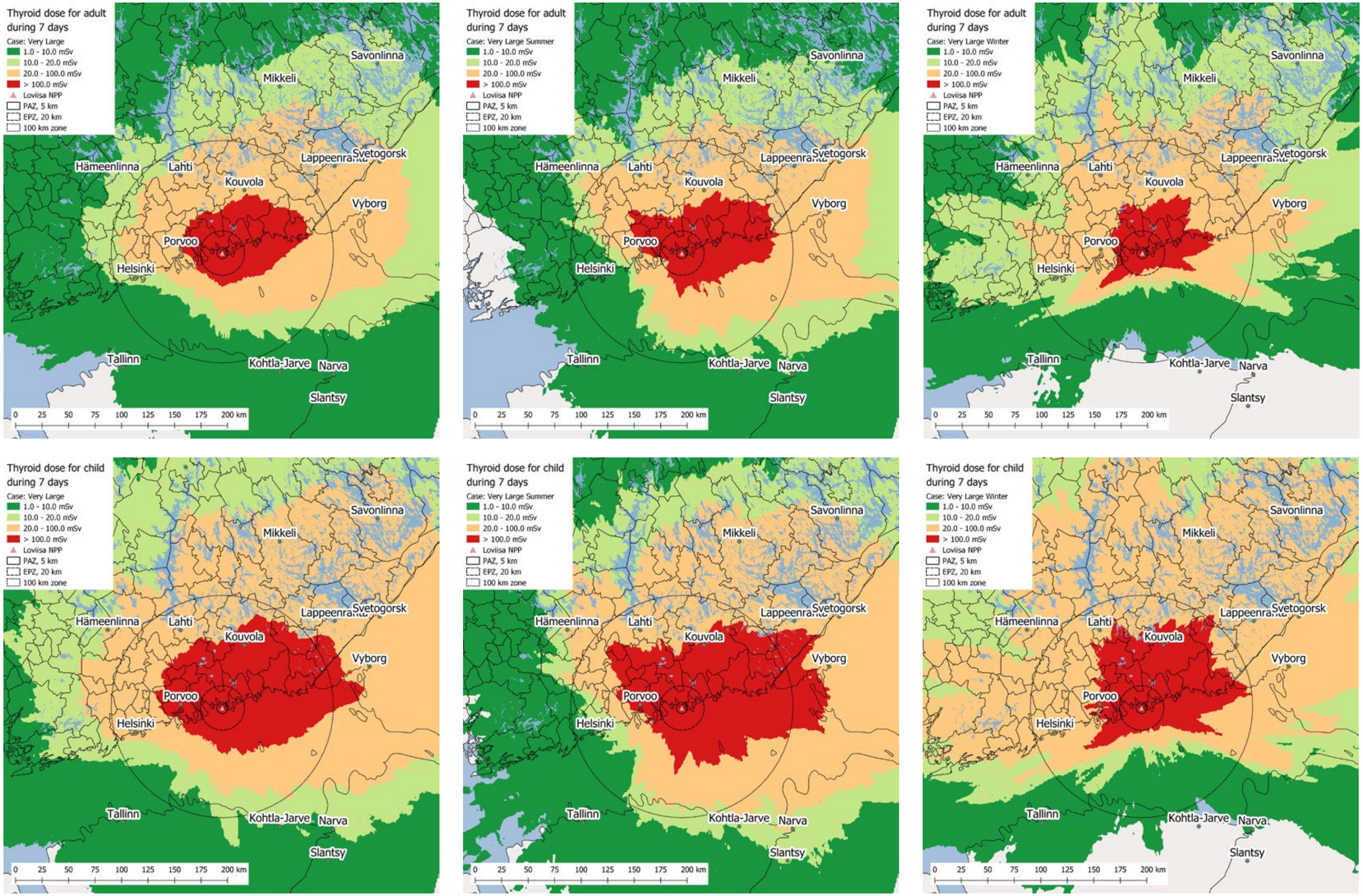

FIGURE 5.17. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Very Large case at Loviisa using 95th percentile all year (left panels), summer (middle) and winter (right) data.

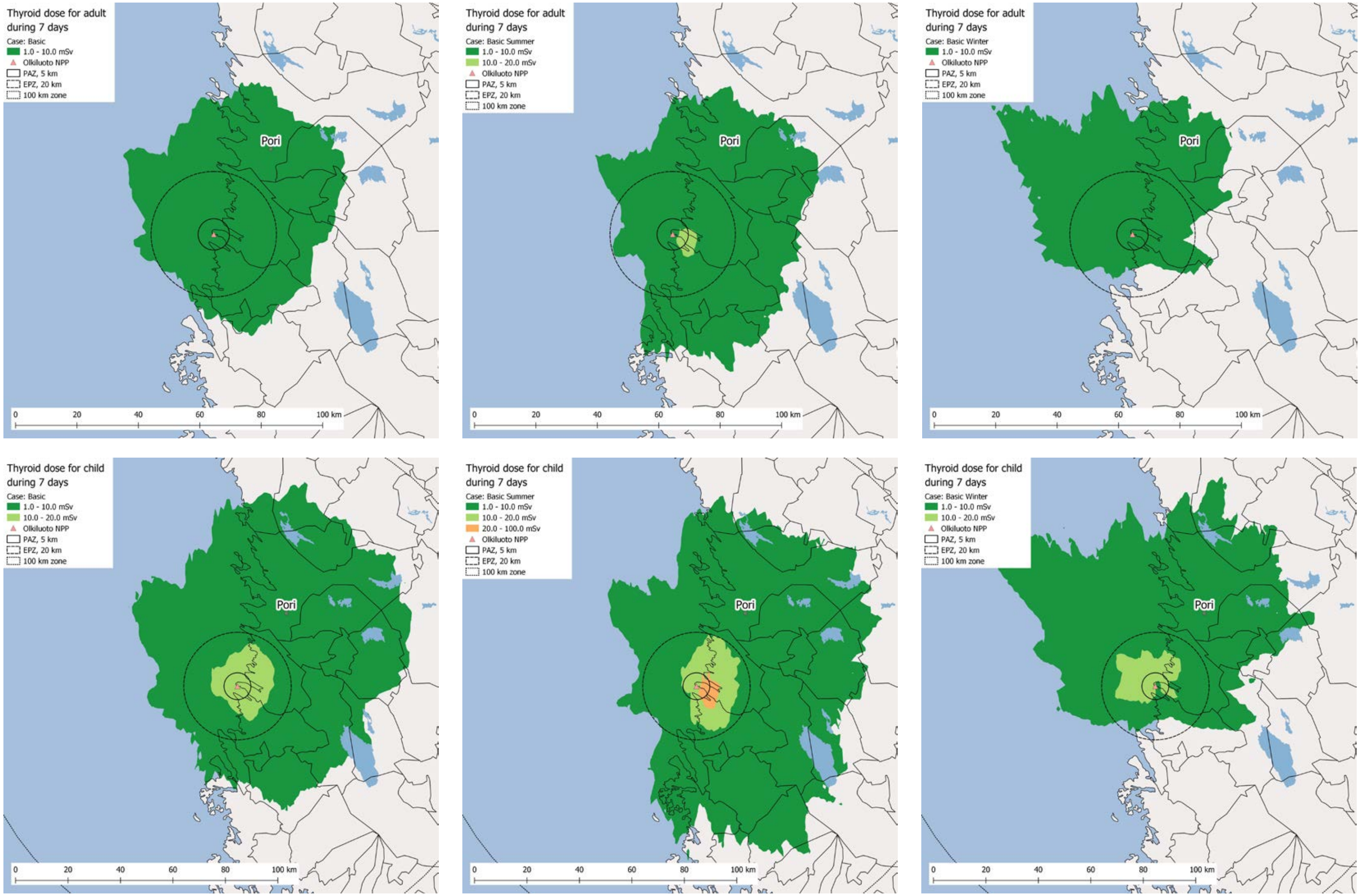

FIGURE 5.18. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Basic case at Olkiluoto 1 & 2 using 95th percentile all year (left panels), summer (middle) and winter (right) data. Note different length scales.

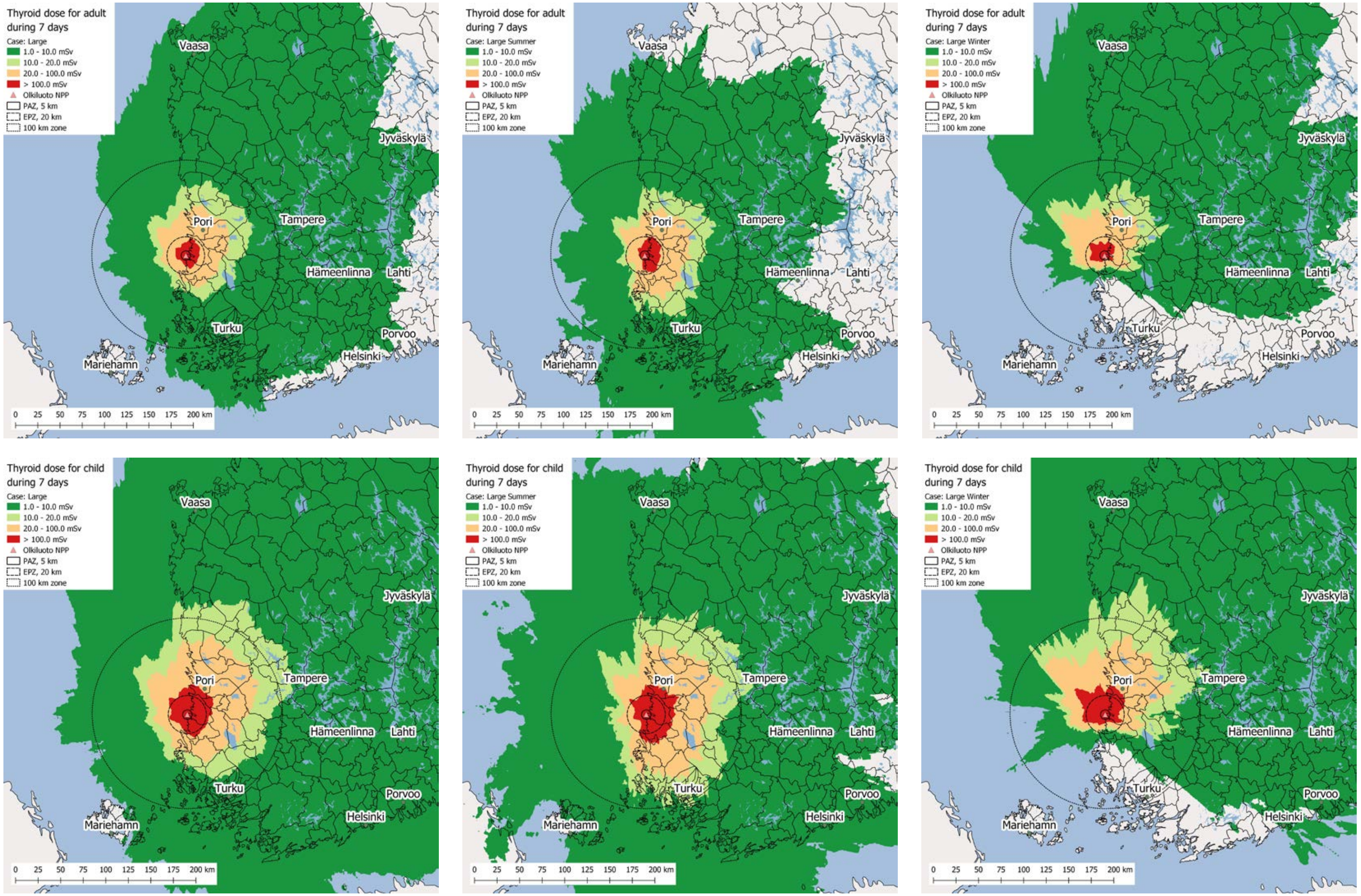

FIGURE 5.19. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Large case at Olkiluoto 1 & 2 using 95th percentile all year (left panels), summer (middle) and winter (right) data.

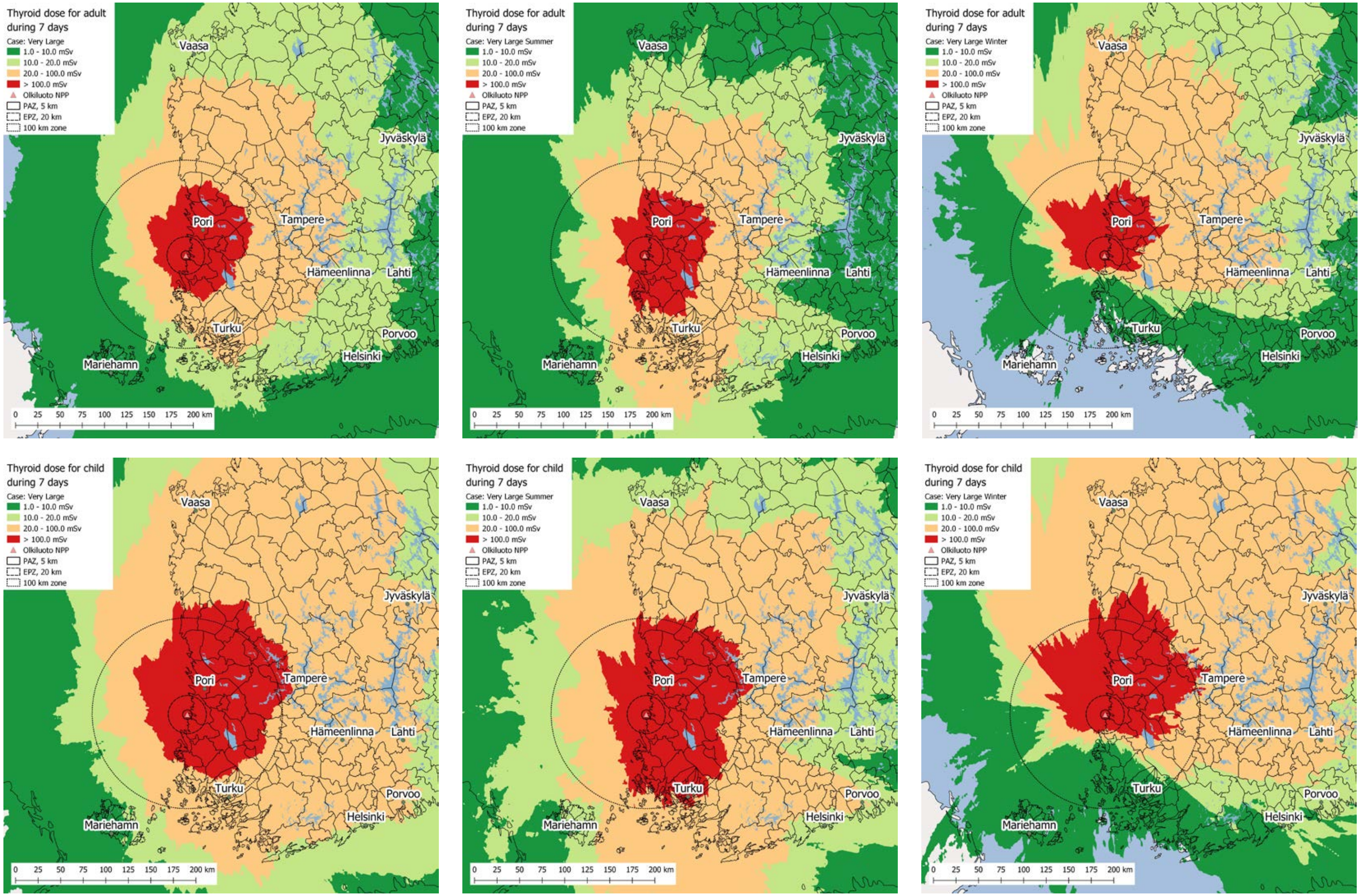

FIGURE 5.20. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Very Large case at Olkiluoto 1 & 2 using 95th percentile all year (left panels), summer (middle) and winter (right) data.

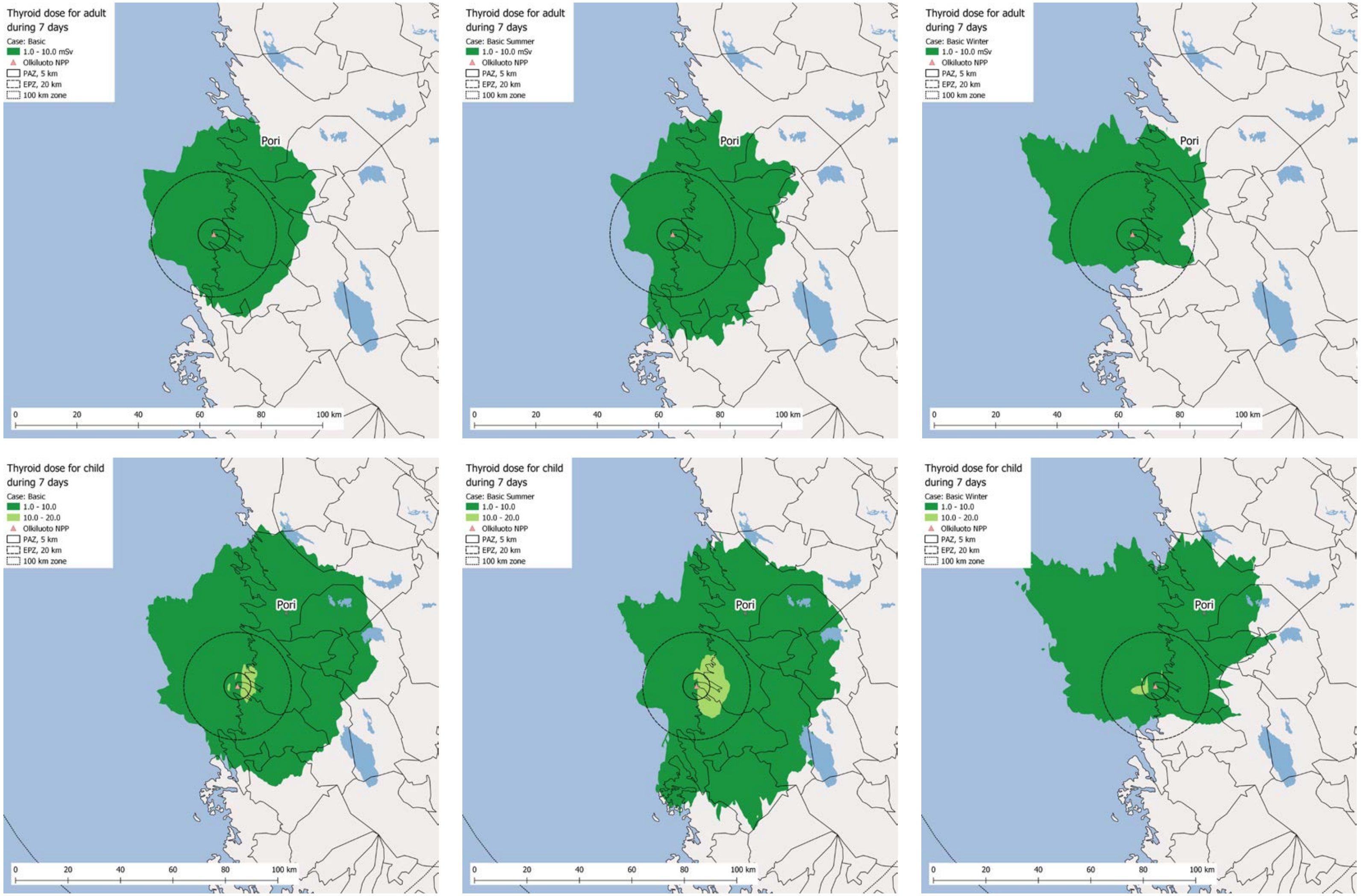

FIGURE 5.21. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Basic case at Olkiluoto 3 using 95th percentile all year (left panels), summer (middle) and winter (right) data. Note different length scales.

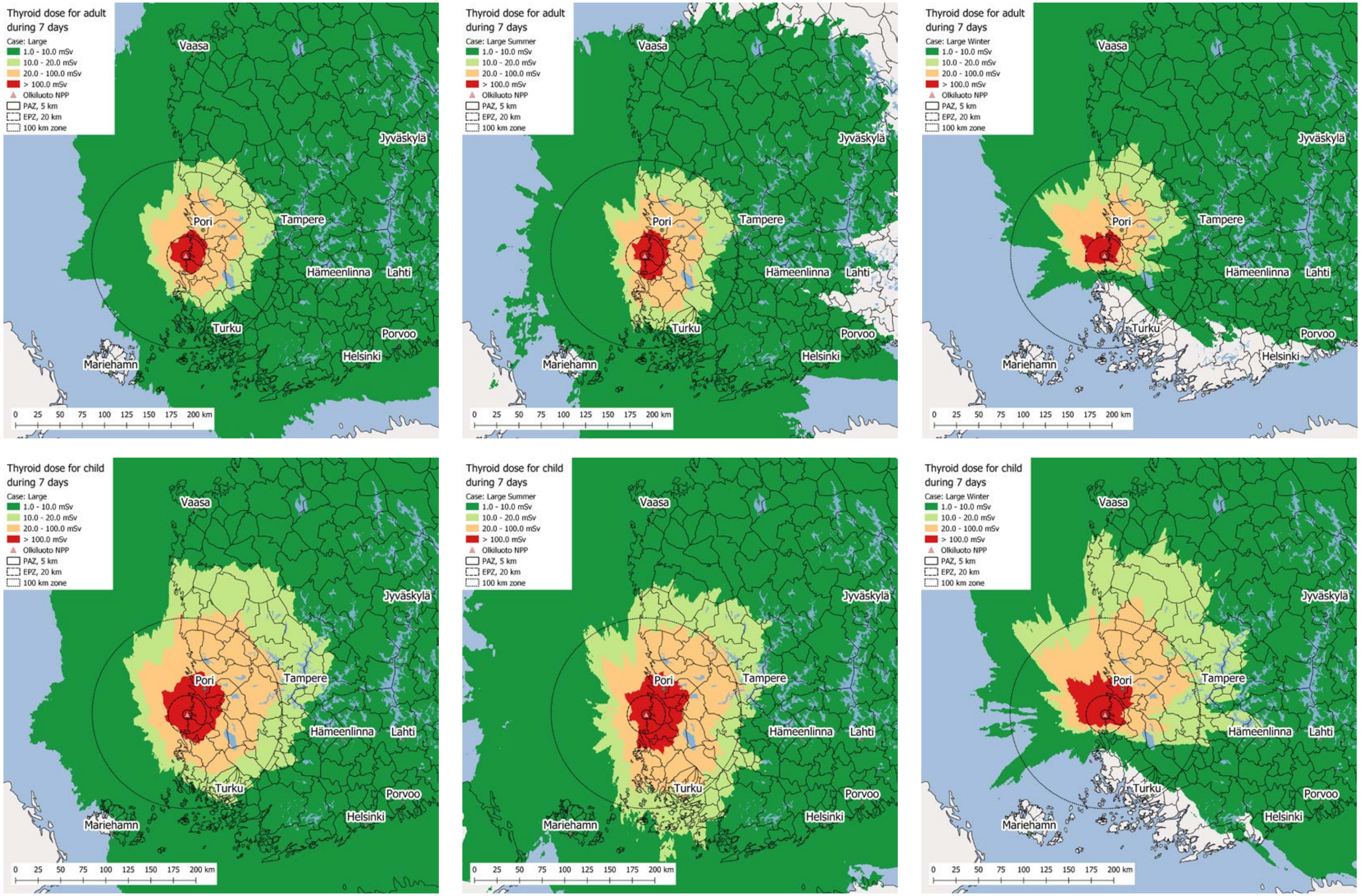

FIGURE 5.22. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Large case at Olkiluoto 3 using 95th percentile all year (left panels), summer (middle) and winter (right) data.

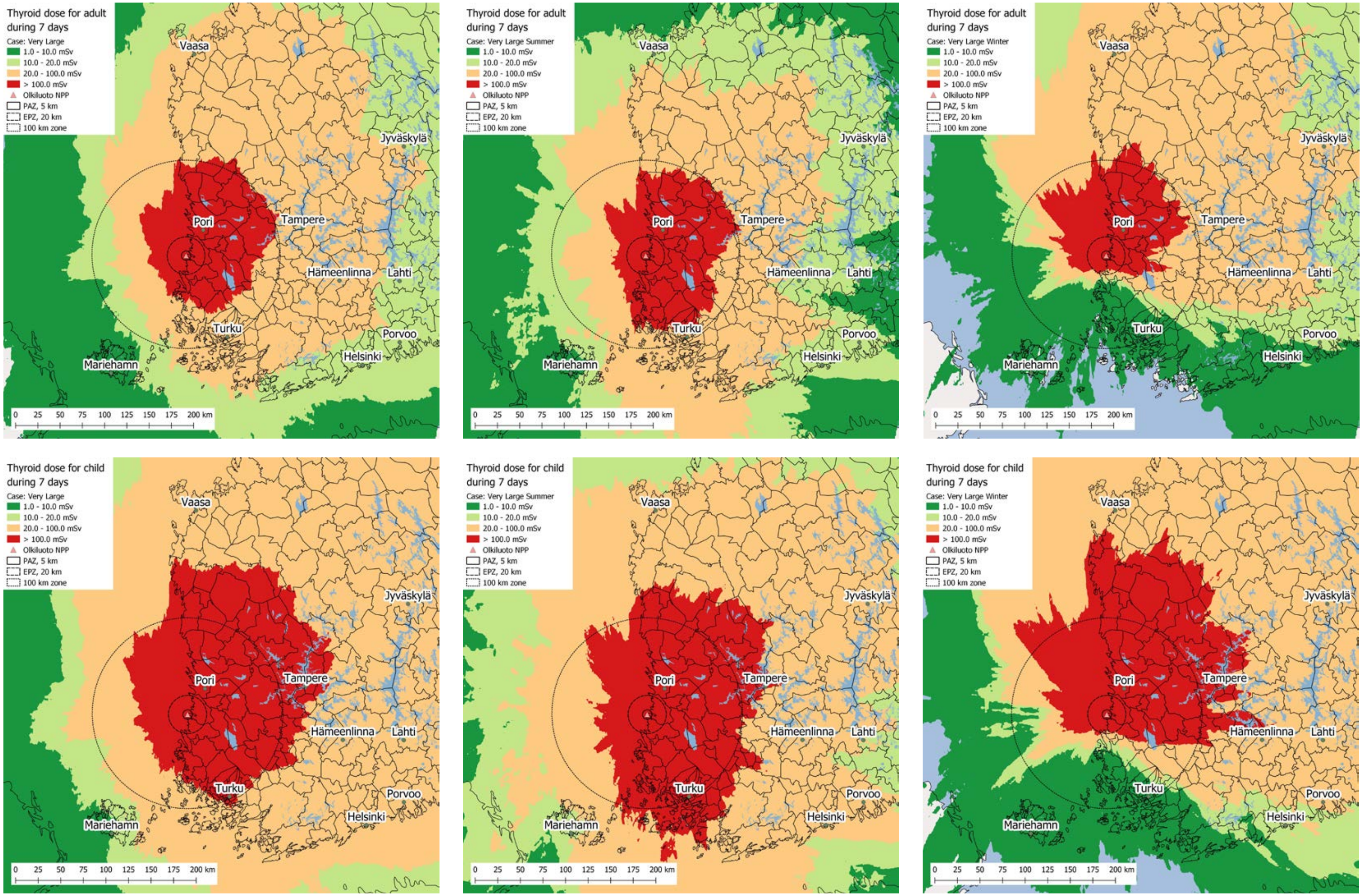

FIGURE 5.23. Adult's (upper panels) and child's (lower) thyroid dose in 7 days for a Very Large case at Olkiluoto 3 using 95th percentile all year (left panels), summer (middle) and winter (right) data.

TABLE 5.6. Adult's median thyroid dose in 7 days inside the PAZ (< 5 km) and EPZ (< 20 km), and the maximum and median distances for exceeding the dose of 1, 10, 20 and 100 mSv. The values analyzed for all year, summer and winter data using Basic, Large, and Very Large releases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median dose d < 5 km (mSv)	median dose d < 20 km (mSv)	maximum distance for 1 mSv (km)	median distance for 1 mSv (km)	maximum distance for 10 mSv (km)	maximum distance for 20 mSv (km)	median distance for 20 mSv (km)	maximum distance for 100 mSv (km)	median distance for 100 mSv (km)
Hanhikivi	Basic	all	6.4	3.6	50	25	-	-	-	-	-
		summer	7.3	4.1	50	27	8	-	-	-	-
		winter	4.9	2.7	67	32	-	-	-	-	-
	Large	all	270	150	>300	170	110	74	36	31	15
		summer	300	170	>300	160	120	75	39	29	16
		winter	200	110	>300	210	160	110	51	40	18
	Very Large	all	2700	1500	>300	230	>300	280	130	110	52
		summer	3000	1700	>300	230	>300	240	120	120	56
		winter	2000	1100	>300	220	>300	>300	190	160	72
Loviisa	Basic	all	5.4	3.1	62	24	-	-	-	-	-
		summer	5.5	3.1	71	28	-	-	-	-	-
		winter	5.2	2.8	51	23	-	-	-	-	-
	Large	all	89	50	250	120	83	56	22	10	6
		summer	90	52	280	120	100	65	25	16	7.7
		winter	85	47	270	130	68	47	20	8.7	5.5
	Very Large	all	900	500	>300	210	250	180	84	83	33
		summer	910	520	>300	200	280	200	86	100	38
		winter	860	470	>300	210	270	190	82	68	30
Olkiluoto 1 & 2	Basic	all	6.9	3.7	51	25	-	-	-	-	-
		summer	7.1	4	51	28	8.8	-	-	-	-
		winter	5.5	3.2	61	26	-	-	-	-	-
	Large	all	170	89	>300	160	82	55	28	19	9.5
		summer	170	96	270	140	85	57	31	22	12
		winter	130	79	>300	180	84	66	29	20	9.6
	Very Large	all	1700	890	>300	210	>300	210	100	82	40
		summer	1700	970	>300	210	270	190	99	85	44
		winter	1300	790	>300	210	>300	250	130	84	42
Olkiluoto 3	Basic	all	4.6	2.4	38	20	-	-	-	-	-
		summer	4.7	2.6	43	23	-	-	-	-	-
		winter	3.7	2.2	46	21	-	-	-	-	-
	Large	all	290	150	>300	190	110	76	37	28	14
		summer	290	160	>300	170	110	75	40	31	17
		winter	230	130	>300	210	120	80	38	35	15
	Very Large	all	2900	1500	>300	210	>300	290	140	110	55
		summer	2900	1600	>300	220	>300	250	130	110	57
		winter	2300	1300	>300	200	>300	>300	170	120	58

TABLE 5.7. Child's median thyroid dose in 7 days inside the PAZ (< 5 km) and EPZ (< 20 km), and the maximum and median distances for exceeding the dose of 1, 10, 20 and 100 mSv. The values analyzed for all year, summer and winter data using Basic, Large, and Very Large releases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median dose d < 5 km (mSv)	median dose d < 20 km (mSv)	maximum distance for 1 mSv (km)	median distance for 1 mSv (km)	maximum distance for 10 mSv (km)	median distance for 10 mSv (km)	maximum distance for 20 mSv (km)	median distance for 20 mSv (km)	maximum distance for 100 mSv (km)	median distance for 100 mSv (km)
Hanhikivi	Basic	all	14	7.8	77	37	16	8.1	-	-	-	-
		summer	16	8.9	95	40	19	9.9	8.6	5.8	-	-
		winter	11	5.8	120	51	20	9.7	-	-	-	-
	Large	all	580	330	>300	200	180	80	120	55	47	23
		summer	660	370	>300	200	170	83	120	59	48	25
		winter	440	240	>300	210	210	110	160	75	64	30
	Very Large	all	5800	3300	>300	230	>300	200	>300	180	180	80
		summer	6600	3700	>300	230	>300	200	>300	160	170	83
		winter	4400	2400	>300	220	>300	210	>300	210	210	110
Loviisa	Basic	all	12	6.7	96	39	17	7.4	-	-	-	-
		summer	12	6.9	120	45	23	9.2	4.4	3.7	-	-
		winter	11	6.1	78	36	15	7.1	-	-	-	-
	Large	all	190	110	>300	160	130	53	86	35	28	12
		summer	200	110	>300	150	140	58	110	40	36	13
		winter	190	100	>300	200	110	47	69	32	26	11
	Very Large	all	1900	1100	>300	210	>300	160	260	120	130	53
		summer	2000	1100	>300	210	>300	150	290	120	140	58
		winter	1900	1000	>300	210	>300	200	280	140	110	48
Olkiluoto 1 & 2	Basic	all	15	8	78	38	17	8.5	-	-	-	-
		summer	15	8.7	79	41	19	11	8.8	5.4	-	-
		winter	12	7.1	81	39	18	8.8	-	-	-	-
	Large	all	370	190	>300	190	130	63	87	42	33	17
		summer	370	210	>300	180	120	64	87	45	38	20
		winter	290	170	>300	210	150	66	87	43	42	18
	Very Large	all	3700	1900	>300	210	>300	190	>300	160	130	63
		summer	3700	2100	>300	220	>300	180	280	140	120	64
		winter	2900	1700	>300	200	>300	210	>300	190	150	66
Olkiluoto 3	Basic	all	10	5.3	61	30	8.8	4.9	-	-	-	-
		summer	10	5.7	61	33	13	8.4	-	-	-	-
		winter	8	4.7	73	32	9	5.1	-	-	-	-
	Large	all	620	330	>300	200	170	85	120	57	47	23
		summer	630	360	>300	200	160	83	110	59	49	26
		winter	490	290	>300	210	200	99	130	60	58	24
	Very Large	all	6200	3300	>300	220	>300	200	>300	190	170	85
		summer	6300	3600	>300	220	>300	200	>300	170	160	83
		winter	5000	2900	>300	200	>300	210	>300	210	200	99

5.2 Deposition

In the intermediate phase of a nuclear emergency, assessment of cesium and strong gamma emitter deposition after the passage of the radioactive cloud is important to estimate land contamination levels and the need for protective actions. The deposition of cesium and strong gamma emitters 48 hours after the release were calculated for four NPP sites in Finland and for three hypothetical release scenarios.

The areas where cesium and strong gamma emitter deposition 100 kBq/m^2, 1 MBq/m^2 and 10 MBq/m^2 may be exceeded in Basic, Large and Very Large cases are shown in Figs 5.24–5.29. In general, the deposition maps correlate well with wind roses (see Fig. 4.1). However, the wind direction towards the continent seems slightly more dominant in deposition maps than in the dose maps presented in previous section. In Loviisa, winds from the south-west dominate while in Hanhikivi and Olkiluoto winds from south and south-west are dominant in the wind roses with most of the wind strengths. The numerical results of the analysis for cesium and strong gamma emitter deposition, and the maximum and median distances for exceeding depositions of 100 kBq/m^2, 1 MBq/m^2 and 10 MBq /m^2 in Basic, Large and Very Large cases are shown in Tables 5.8–5.9. In the Basic case, deposition of cesium of 100 kBq/m^2 is exceeded only inside the PAZ while slightly elevated deposition may be observed also inside the EPZ. The median deposition of cesium varies from 16 kBq/m^2 to 55 kBq/m^2 inside the PAZ and from 2.3 kBq/m^2 to 4.3 kBq/m^2 inside the EPZ. In the Basic case, the median deposition of strong gamma emitters varies from 1.0 MBq/m^2 to 1.7 MBq/m^2 inside the PAZ and from 410 kBq/m^2 to 620 kBq/m^2 inside the EPZ. In the Basic case, deposition of strong gamma emitters of 1 MBq/m^2 is exceeded only inside the PAZ and the median distance for exceeding it varies from 5.0 km to 9.6 km. The median distance for exceeding deposition of strong gamma emitters of 100 kBq/m^2 varies from 34 km to 44 km while maximum distance for exceeding it may be up to 140 km. Furthermore, slightly elevated deposition of strong gamma may be observed over 100 km distances from all NPP sites.

In Large cases, the median deposition of cesium varies from 320 kBq/m^2 to 2.2 MBq/m^2 inside the PAZ and from 56 kBq/m^2 to 170 kBq/m^2 inside the EPZ. In Large cases, deposition of cesium may exceed 1 MBq/m^2 inside the PAZ and EPZ while in Hanhikivi and Olkiluoto 3 deposition of cesium may also exceed 10 MBq/m^2 inside the PAZ. The medium distance for exceeding deposition of cesium of 100 kBq/m^2 varies from 20 km to 130 km while it may be exceeded at distances up to 260 km. In Large cases, the median deposition of strong gamma emitters varies from 21 MBq/m^2 to 68 MBq/m^2 inside the PAZ and from 8.6 MBq/m^2 to 25 MBq/m^2 inside the EPZ. In Large cases, deposition of strong gamma emitters of 10 MBq/m^2 is exceeded also outside the EPZ and the maximum distance for exceeding it varies from 29 km to 58 km while the median distance remains below 25 km. Strong gamma concentration of 1 MBq/m^2 may be exceeded at considerable distances from the NPP sites and the maximum distances for exceeding it vary from 130 km to 260 km. For example, 1 MBq/m^2 can be exceeded in Kemi and Oulu (release from Hanhikivi), Porvoo and Kouvola (Loviisa), and Turku and Tampere (Olkiluoto 3). In the Large cases, the deposition of strong gamma emitters of 100 kBq/m^2 may be exceeded beyond the distance considered (> 300 km) from the NPP sites.

In Very Large cases, the median deposition of cesium varies from 3.2 MBq/m^2 to 22 MBq/m^2 inside the PAZ and from 560 kBq/m^2 to 1.7 MBq/m^2 inside the EPZ. Deposition of cesium of 10 MBq/m^2 may be exceeded only inside the PAZ and EPZ. Median distance for exceeding 1 MBq/m^2 varies from 20 km to 130 km while maximum distance for exceeding it may be up to 260 km. For example, releases from Hanhikivi may cause deposition of cesium of over 1 MBq/m^2 in Kemi and Oulu. In Very Large cases, the deposition of cesium of 100 kBq/m^2 may be exceeded beyond the distance considered (> 300 km) from the NPP sites. In Very Large cases, the median deposition of strong gamma emitters varies from 210 MBq/m^2 to 680 MBq/m^2 inside the PAZ and from 86 MBq/m^2 to 260 MBq/m^2 inside the EPZ. The deposition of strong gamma emitters of 10 MBq/m^2 may be exceeded far beyond the EPZ in all NPP sites and the median distance for exceeding it varies from 55 km to 100 km while the maximum distance may be up to 260 km. For example, 10 MBq/m^2 can be exceeded in Kemi and Oulu (release from Hanhikivi), Porvoo and Kouvola (Loviisa), and Turku and Tampere (Olkiluoto 3). In Very Large cases, the deposition of strong gamma emitters of 1 MBq/m^2 may be exceeded beyond the distance considered (> 300 km) from the NPP sites.

The variations between summer and winter seasons are very significant in Large and Very Large cases. The difference is larger than in the case of doses and dose rates compared in the previous section. The precipitation during the winter season causes more frequent wet deposition than in the summer. The difference is particularly large in releases from Hanhikivi. During the winter season, the dispersion towards the north and north-east are dominant directions of dispersion that can be seen in the deposition maps. During the summer season the dose maps are more evenly distributed to all directions. However, the directions away from the continent are slightly less prominent than directions toward the continent and along the coast. In Loviisa, directions toward the east are more prominent than during the winter season. In Basic cases, the seasonal variations are negligible in terms of the depositions. In general, the depositions caused by releases from Hanhikivi and Olkiluoto 3 in Large and Very Large cases are higher than in Loviisa and Olkiluoto 1 and 2 due to the larger radionuclide inventory. However, the probability of a severe accident is lower for modern NPPs than for older ones.

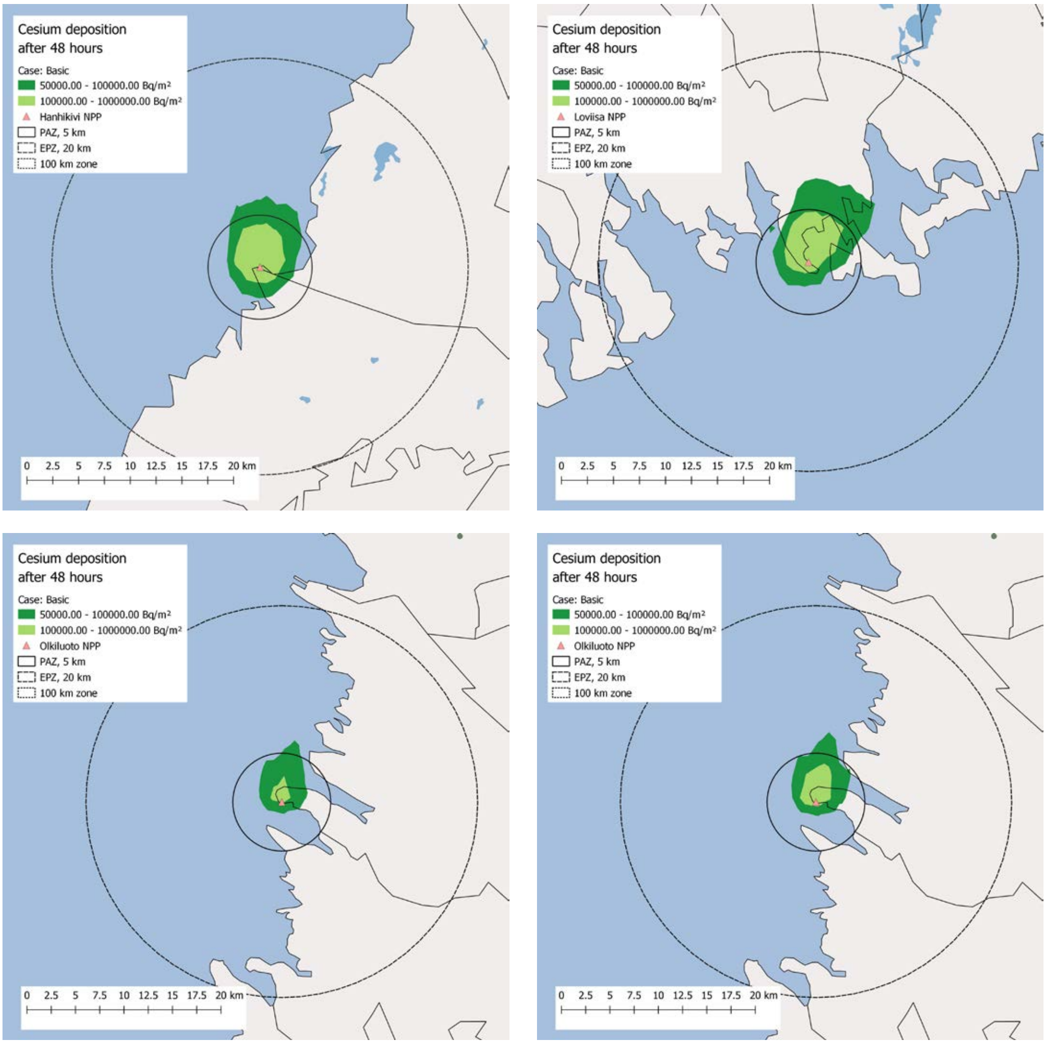

FIGURE 5.24. Deposition of cesium after 48 h in a Basic case at Hanhikivi (upper left panel), Loviisa (upper right), Olkiluoto 1 & 2 (lower left) and Olkiluoto 3 (lower right). Note that the length scales vary.

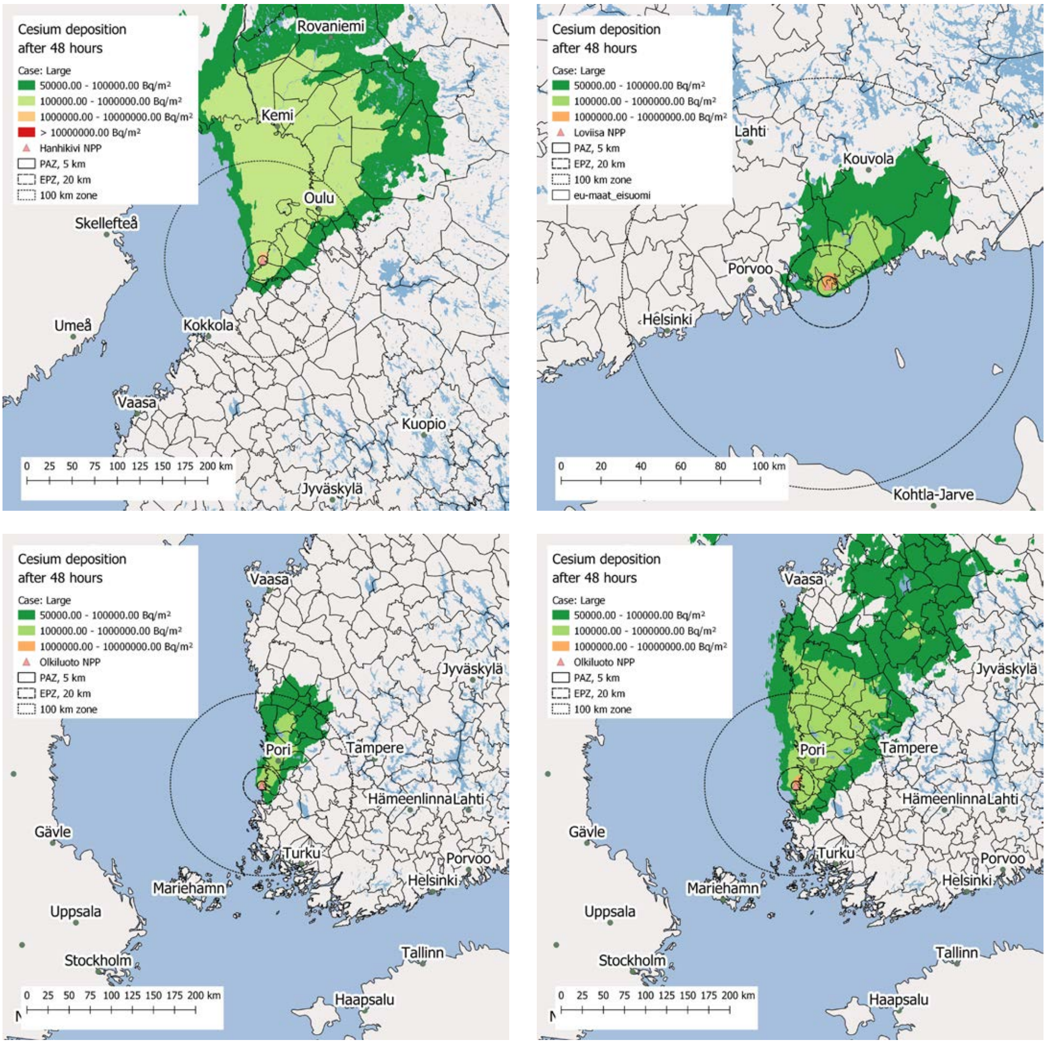

FIGURE 5.25. Deposition of cesium after 48 h in a Large case at Hanhikivi (upper left panel), Loviisa (upper right), Olkiluoto 1 & 2 (lower left) and Olkiluoto 3 (lower right). Note that the length scales vary.

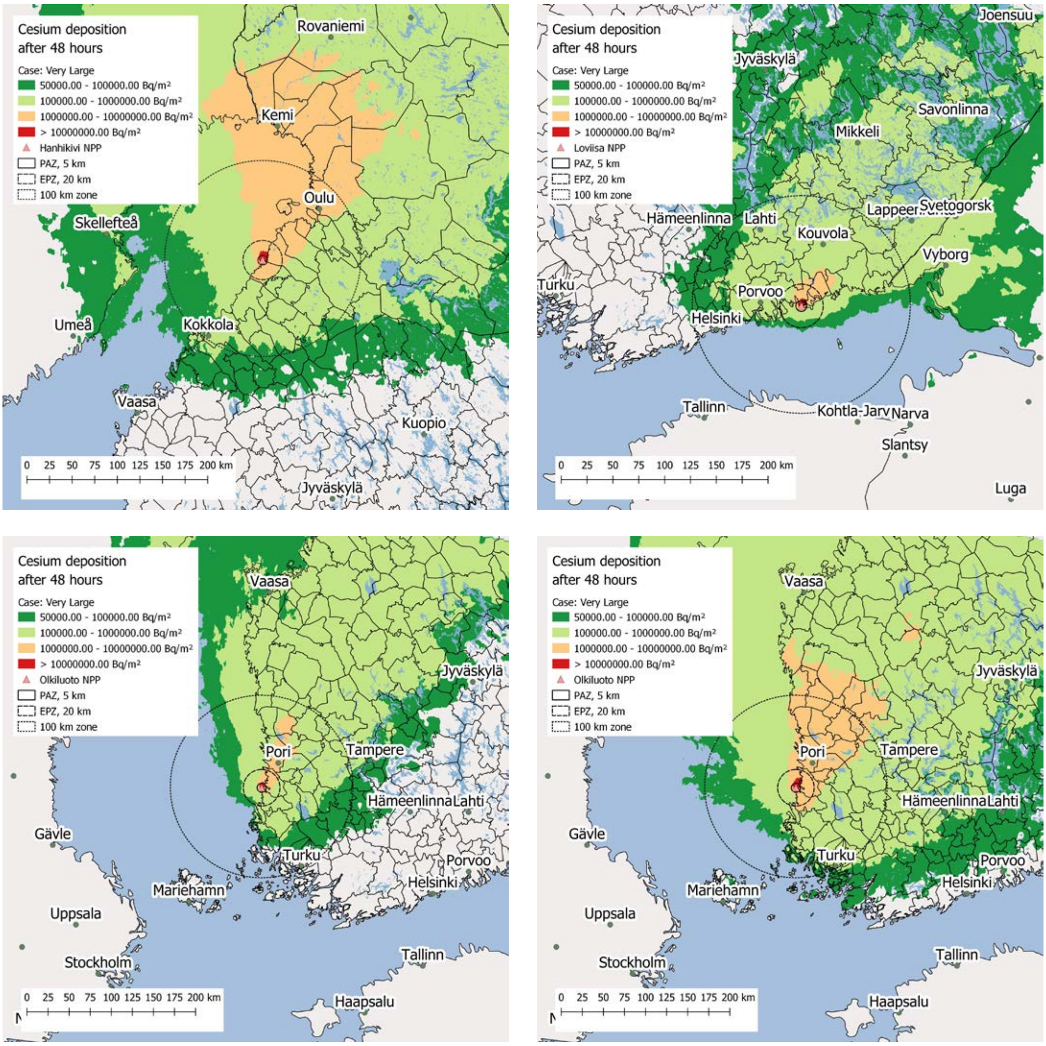

FIGURE 5.26. Deposition of cesium after 48 h in a Very Large case at Hanhikivi (upper left panel), Loviisa (upper right), Olkiluoto 1 & 2 (lower left) and Olkiluoto 3 (lower right). Note that the length scales vary.

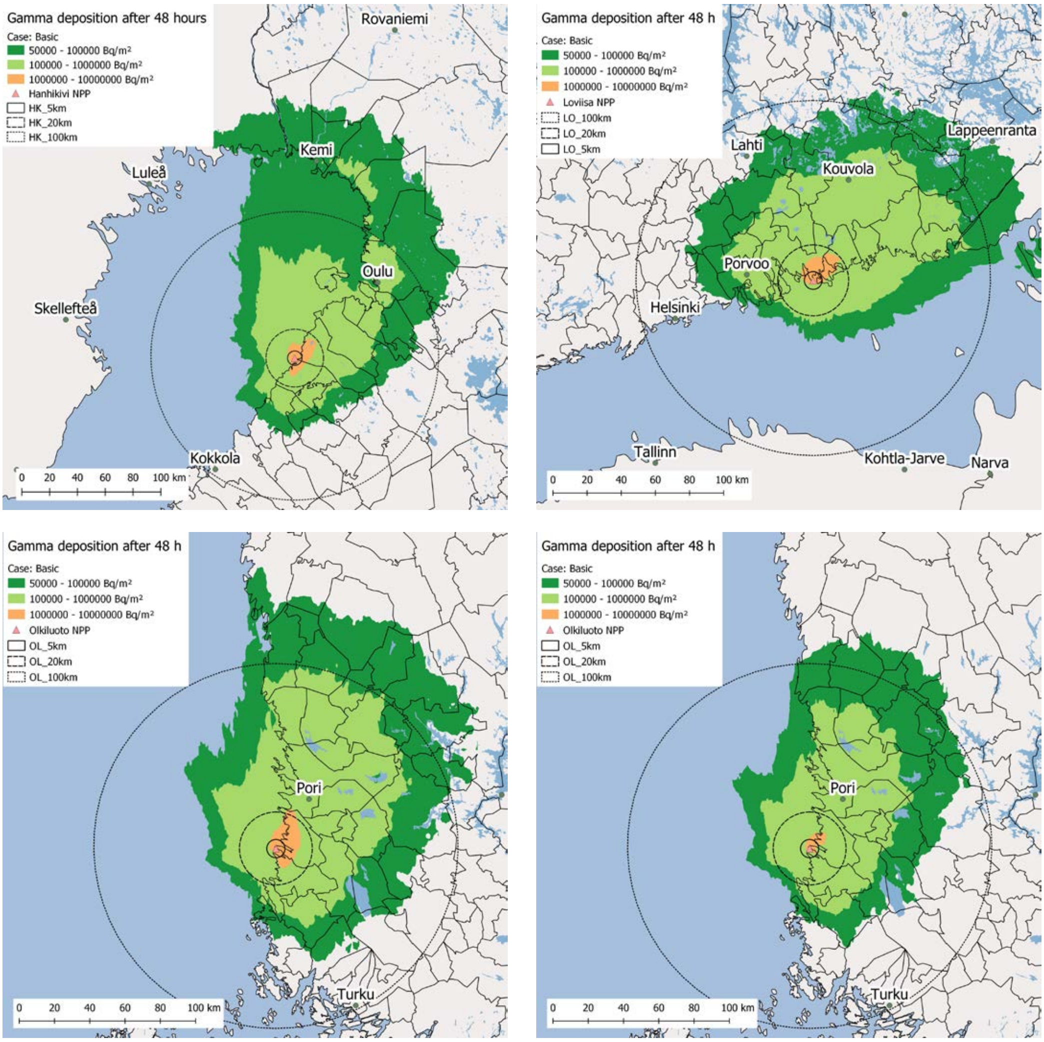

FIGURE 5.27. Deposition of strong gamma emitters after 48 h in a Basic case at Hanhikivi (upper left panel), Loviisa (upper right), Olkiluoto 1 & 2 (lower left) and Olkiluoto 3 (lower right). Note that the length scales vary.

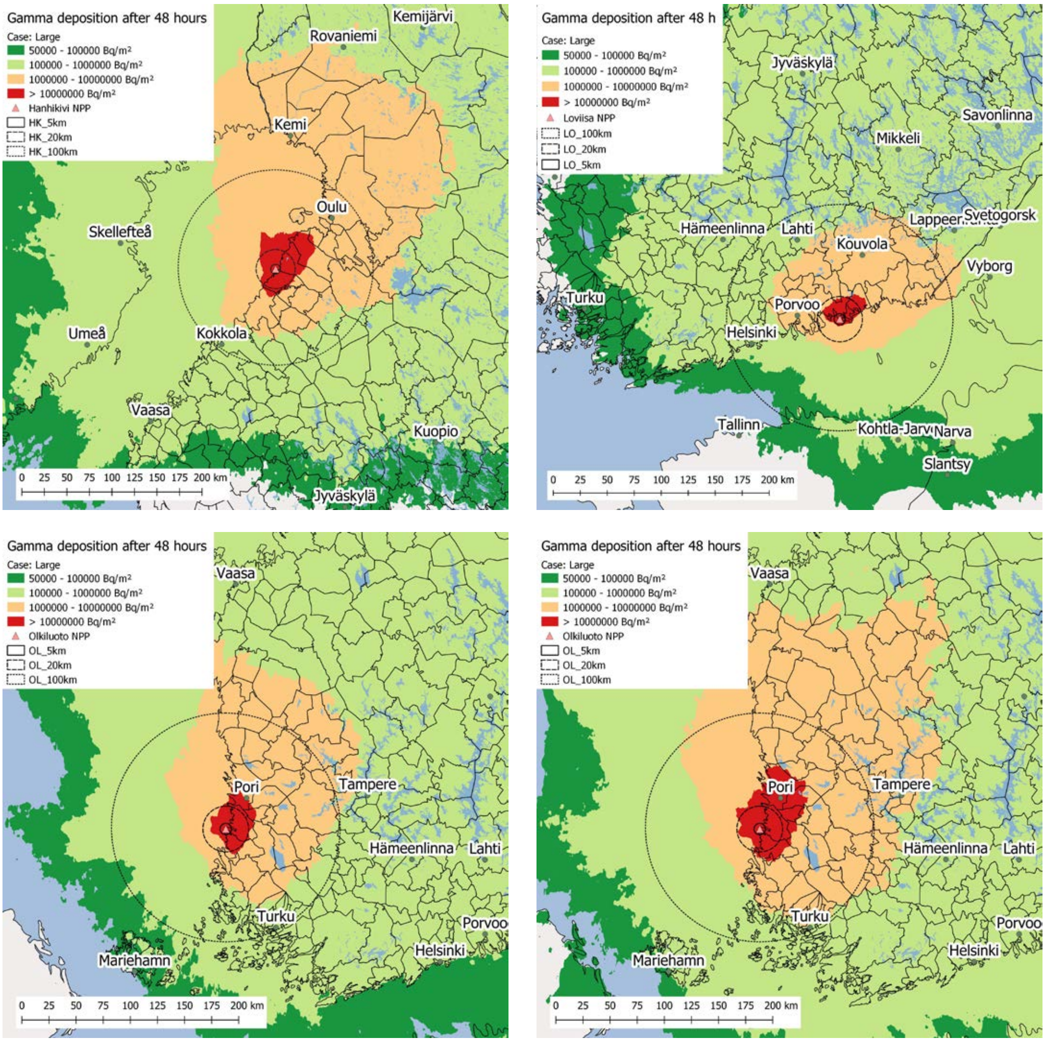

FIGURE 5.28. Deposition of strong gamma emitters after 48 h in a Large case at Hanhikivi (upper left panel), Loviisa (upper right), Olkiluoto 1 & 2 (lower left) and Olkiluoto 3 (lower right). Note that the length scales vary.

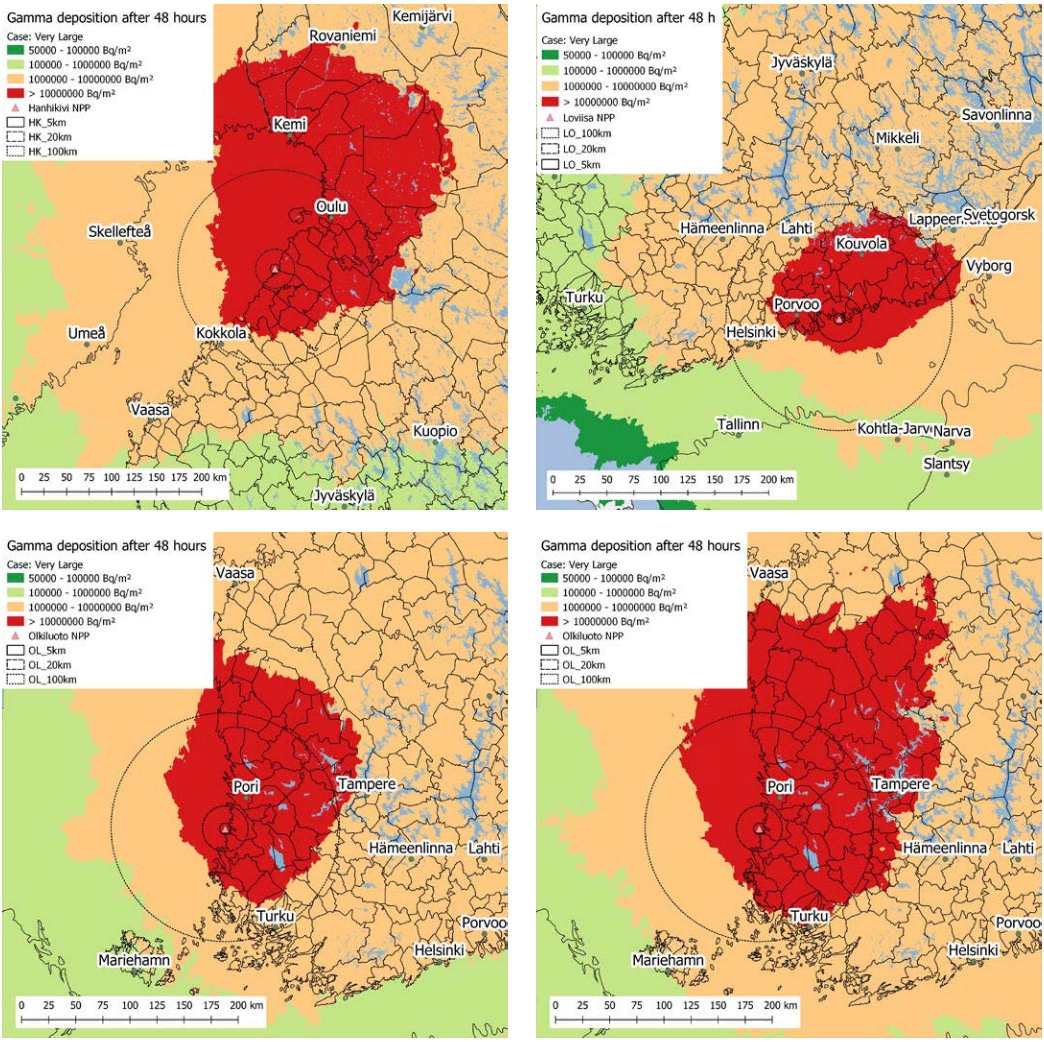

FIGURE 5.29. Deposition of strong gamma emitters after 48 h in a Very Large case at Hanhikivi (upper left panel), Loviisa (upper right), Olkiluoto 1 & 2 (lower left) and Olkiluoto 3 (lower right). Note that the length scales vary.

TABLE 5.8. Median deposition of cesium inside the PAZ (< 5 km) and EPZ (< 20 km), and the maximum and median distances for exceeding the deposition of 100 kBq/m^2, 1 MBq/m^2 and 10 MBq/m^2. The values analyzed for all year, summer and winter data using Basic, Large, and Very Large releases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median deposition d < 5 km (MBq/m^2)	median deposition d < 20 km (MBq/m^2)	maximum distance for 100 kBq/m^2 (km)	median distance for 100 kBq/m^2 (km)	maximum distance for 1 MBq/m^2 (km)	median distance for 1 MBq/m^2 (km)	maximum distance for 10 MBq/m^2 (km)	median distance for 10 MBq/m^2 (km)
Hanhikivi	Basic	all	0.055	0.0043	3.6	2.2	-	-	-	-
		summer	0.094	0.0062	3.8	2.1	-	-	-	-
		winter	0.076	0.0039	8.1	4.5	-	-	-	-
	Large	all	2.2	0.17	220	130	9.9	4.8	1	0.51
		summer	3.9	0.25	180	44	16	4.7	2	1.2
		winter	3.1	0.16	>300	190	54	13	3.3	1.4
	Very Large	all	22	1.7	>300	200	220	130	9.9	4.8
		summer	39	2.5	>300	180	180	44	16	4.7
		winter	31	1.6	>300	210	>300	190	54	13
Loviisa	Basic	all	0.052	0.0029	4.4	2.7	-	-	-	-
		summer	0.052	0.003	5.3	2.3	-	-	-	-
		winter	0.14	0.0067	24	8.6	-	-	-	-
	Large	all	0.85	0.047	41	20	6.8	3.3	-	-
		summer	0.84	0.048	32	12	6.2	2.8	-	-
		winter	2.2	0.11	100	54	31	13	-	-
	Very Large	all	8.5	0.47	>300	140	41	20	6.8	3.3
		summer	8.4	0.48	>300	120	32	12	6.2	2.8
		winter	22	1.1	>300	190	100	54	31	13
Olkiluoto 1 & 2	Basic	all	0.013	0.0023	2.8	1	-	-	-	-
		summer	0.017	0.0037	1.4	0.81	-	-	-	-
		winter	0.013	0.0021	7.8	3.4	-	-	-	-
	Large	all	0.32	0.056	97	44	5.1	2.8	-	-
		summer	0.41	0.088	110	32	3.7	1.9	-	-
		winter	0.31	0.049	>300	100	26	13	-	-
	Very Large	all	3.2	0.56	>300	190	97	44	5.1	2.8
		summer	4.1	0.88	>300	150	110	32	3.7	1.9
		winter	3.1	0.49	>300	210	>300	100	26	13
Olkiluoto 3	Basic	all	0.016	0.0029	3.1	1.4	-	-	-	-
		summer	0.02	0.0043	2.8	1	-	-	-	-
		winter	0.015	0.0024	8.8	4.1	-	-	-	-
	Large	all	1	0.17	260	87	15	5.6	-	-
		summer	1.2	0.26	280	87	7.3	3	1.4	0.6
		winter	0.92	0.15	>300	190	90	47	5.1	2.9
	Very Large	all	10	1.7	>300	200	260	87	15	5.6
		summer	12	2.6	>300	180	280	87	7.3	3
		winter	9.2	1.5	>300	210	>300	190	90	47

TABLE 5.9. Median deposition of gamma emitters inside the PAZ (< 5 km) and EPZ (< 20 km), and the maximum and median distances for exceeding the deposition of 100 kBq/m^2, 1 MBq/m^2 and 10 MBq/m^2. The values analyzed for all year, summer and winter data using Basic, Large, and Very Large releases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median deposition d < 5 km (MBq/m^2)	median deposition d < 20 km (MBq/m^2)	maximum distance for 100 kBq/m^2 (km)	median distance for 100 kBq/m^2 (km)	maximum distance for 1 MBq/m^2 (km)	median distance for 1 MBq/m^2 (km)	maximum distance for 10 MBq/m^2 (km)	median distance for 10 MBq/m^2 (km)
Hanhikivi	Basic	all	1.7	0.62	140	42	19	7.9	-	-
		summer	2.2	0.66	80	36	19	9.1	-	-
		winter	1.1	0.41	180	95	21	9.2	-	-
	Large	all	68	25	>300	200	250	120	55	22
		summer	93	27	>300	210	180	81	50	23
		winter	45	17	>300	200	>300	170	73	32
	Very Large	all	680	260	>300	230	>300	200	250	120
		summer	930	270	>300	230	>300	210	180	81
		winter	450	170	>300	220	>300	200	>300	170
Loviisa	Basic	all	1.3	0.52	92	43	19	8.5	-	-
		summer	1.4	0.47	92	38	17	7.6	-	-
		winter	1.5	0.59	98	46	26	13	-	-
	Large	all	21	8.6	>300	180	130	55	29	13
		summer	22	7.7	>300	170	120	51	30	11
		winter	24	9.7	>300	190	150	60	37	17
	Very Large	all	210	86	>300	210	>300	180	130	55
		summer	230	77	>300	210	>300	170	120	51
		winter	240	98	>300	210	>300	190	150	60
Olkiluoto 1 & 2	Basic	all	1.5	0.61	100	44	23	9.6	-	-
		summer	1.6	0.61	84	40	16	8.9	-	-
		winter	1	0.57	150	60	24	12	-	-
	Large	all	36	15	>300	190	170	73	41	16
		summer	40	15	>300	180	140	66	35	17
		winter	25	14	>300	210	>300	100	54	21
	Very Large	all	360	150	>300	210	>300	190	170	73
		summer	400	150	>300	220	>300	180	140	66
		winter	250	140	>300	200	>300	210	>300	100
Olkiluoto 3	Basic	all	1	0.41	84	34	12	5	-	-
		summer	1.1	0.42	75	32	10	5.4	-	-
		winter	0.68	0.38	110	48	20	8.5	-	-
	Large	all	62	25	>300	200	260	100	58	25
		summer	69	26	>300	200	210	90	56	25
		winter	42	23	>300	210	>300	160	78	33
	Very Large	all	620	250	>300	220	>300	200	260	100
		summer	690	260	>300	220	>300	200	210	90
		winter	420	240	>300	200	>300	210	>300	160

5.3 Activity concentrations in the air

In an NPP accident, the gamma emitters in the air cause radiation dose directly from the cloud and via inhalation. In the early phase of the emergency, the majority of the radiation dose is accumulated via these dose routes and thus it is necessary to estimate the duration of high concentrations of strong gamma emitters in the air. The durations when strong gamma concentrations exceed 1 kBq/m^3 and 10 kBq/m^3 were estimated for four NPP sites in Finland and for three hypothetical release scenarios.

Due to the relatively short duration of the releases (3–12 h), the duration for exceeding the considered concentrations remains relatively short with respect to durations for exceeding dose rates of 1, 10 and 100 µSv/h (see Sec. 5.1). Hence, only the numerical results of the analysis for median durations for exceeding each strong gamma concentration inside the PAZ and EPZ, and the maximum and median distances for exceeding durations of 1, 24 and 48 h are shown in Tables 5.10–5.11. Note that the duration of exceeding the strong gamma concentration of 1 kBq/m^3 or 10 kBq/m^3 does not exceed 24 h in any of the cases considered here.

In Basic cases, the median duration for exceeding strong gamma concentration of 1 kBq/m^3 is about 4 h inside the PAZ and varies from 3 to 4 h inside the EPZ. The strong gamma concentration may be higher than 1 kBq/m^3 longer than 1 h at distances varying from 89 km to 110 km while median distance for exceeding it remains below 45 km. In the Basic case, median duration for exceeding strong gamma concentration of 10 kBq/m^3 varies from 2 h to 4 h inside the PAZ and is about 1 h inside the EPZ. The strong gamma concentration may be higher than 10 kBq/m^3 longer than 1 h at distances varying from 21 km to 29 km while the median distance for exceeding it remains below 14 km.

In Large cases, the median duration for exceeding strong gamma concentration of 1 kBq/m^3 is varies from 4 h to 6 h inside the PAZ and varies from 4 to 5 h inside the EPZ. In Large cases, duration of 1 h for exceeding strong gamma concentration of 1 kBq/m^3 may be exceeded beyond the considered distance (> 300 km) from the NPP sites. In Large cases, the median duration for exceeding strong gamma concentration of 10 kBq/m^3 is about 4 h inside the PAZ and EPZ. The strong gamma concentration may be higher than 10 kBq/m^3 longer than 1 h at distances varying from 150 km to 230 km while median distance for exceeding it remains below 120 km.

In Very large cases, median duration for exceeding strong gamma concentration of 1 kBq/m^3 varies from 6 h to 9 h inside the PAZ and from 5 to 7 h inside the EPZ. In Very Large cases, the median duration for exceeding strong gamma concentration of 10 kBq/m^3 varies from 4 h to 6 h inside the PAZ and from 4 h to 5 h inside the EPZ. In Very Large cases, duration of 1 h for exceeding strong gamma concentrations of 1 kBq/m^3 and 10 kBq/m^3 may be exceeded beyond the distance considered (> 300 km) from the NPP sites.

Seasonal variations between summer and winter are not significant in any of the cases considered. This indicates that the air concentration and radiation dose accumulated from the radioactive substances in the air do not significantly depend on the season. Based on the observation made in previous section, it can be concluded that the seasonal differences in dose rates, effective dose and thyroid dose are dominated by seasonal variation of wet deposition.

TABLE 5.10. The median durations for gamma concentration exceeding 1 kBq/m^3 inside PAZ (< 5 km) and EPZ (< 20 km), and the maximum and median distances for exceeding the concentration for over 1, 24 and 48 h. The values analyzed for all year, summer and winter data using Basic, Large, and Very Large releases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median duration d < 5 km (h)	median duration d < 20 km (h)	maximum distance for 1 h (km)	median distance for 1 h (km)	maximum distance for 24 h (km)	median distance for 24 h (km)	maximum distance for 48 h (km)	median distance for 48 h (km)
Hanhikivi	Basic	all	4	4	110	53	-	-	-	-
		summer	4	4	110	54	-	-	-	-
		winter	4	3	150	71	-	-	-	-
	Large	all	6	5	>300	200	-	-	-	-
		summer	8	6	>300	210	-	-	-	-
		winter	4	4	>300	210	-	-	-	-
	Very Large	all	9	7	>300	230	-	-	-	-
		summer	12	11	>300	230	-	-	-	-
		winter	7	5	>300	220	-	-	-	-
Loviisa	Basic	all	4	3	140	57	-	-	-	-
		summer	4	3	150	62	-	-	-	-
		winter	4	3	120	53	-	-	-	-
	Large	all	4	4	>300	180	-	-	-	-
		summer	5	4	>300	160	-	-	-	-
		winter	4	4	>300	210	-	-	-	-
	Very Large	all	6	5	>300	220	-	-	-	-
		summer	7	5	>300	210	-	-	-	-
		winter	4	4	>300	210	-	-	-	-
Olkiluoto 1 & 2	Basic	all	4	4	110	54	-	-	-	-
		summer	4	4	100	55	-	-	-	-
		winter	4	4	120	56	-	-	-	-
	Large	all	4	4	>300	200	-	-	-	-
		summer	5	4	>300	190	-	-	-	-
		winter	4	4	>300	210	-	-	-	-
	Very Large	all	6.1	5	>300	210	-	-	-	-
		summer	8	6	>300	220	-	-	-	-
		winter	4	4	>300	200	-	-	-	-
Olkiluoto 3	Basic	all	4	3	89	45	-	-	-	-
		summer	4	3	88	47	-	-	-	-
		winter	3	3	97	46	-	-	-	-
	Large	all	4	4	>300	200	-	-	-	-
		summer	6	5	>300	210	-	-	-	-
		winter	4	4	>300	210	-	-	-	-
	Very Large	all	7	6	>300	220	-	-	-	-
		summer	9	7	>300	220	-	-	-	-
		winter	4	4	>300	200	-	-	-	-

TABLE 5.11. The median durations for gamma concentration exceeding 10 kBq/m^3 inside the PAZ (< 5 km) and EPZ (< 20 km), and the maximum and median distances for exceeding the concentration for over 1, 24 and 48 h. The values analyzed for all year, summer and winter data using Basic, Large, and Very Large releases from nuclear reactors in Hanhikivi, Loviisa and Olkiluoto.

site	release type	season	median duration d < 5 km (h)	median duration d < 20 km (h)	maximum distance for 1 h (km)	median distance for 1 h (km)	maximum distance for 24 h (km)	median distance for 24 h (km)	maximum distance for 48 h (km)	median distance for 48 h (km)
Hanhikivi	Basic	all	3	1	29	14	-	-	-	-
		summer	3	2	28	16	-	-	-	-
		winter	3	2	35	16	-	-	-	-
	Large	all	4	4	220	100	-	-	-	-
		summer	5	4	200	99	-	-	-	-
		winter	4	4	260	140	-	-	-	-
	Very Large	all	6	5	>300	200	-	-	-	-
		summer	8	6	>300	210	-	-	-	-
		winter	4	4	>300	210	-	-	-	-
Loviisa	Basic	all	3	1	29	13	-	-	-	-
		summer	2.5	1	40	16	-	-	-	-
		winter	3	1	27	12	-	-	-	-
	Large	all	4	4	150	72	-	-	-	-
		summer	4	4	190	77	-	-	-	-
		winter	4	4	170	70	-	-	-	-
	Very Large	all	4	4	>300	180	-	-	-	-
		summer	5	4	>300	160	-	-	-	-
		winter	4	4	>300	210	-	-	-	-
Olkiluoto 1 & 2	Basic	all	3	1	28	14	-	-	-	-
		summer	3	2	28	16	-	-	-	-
		winter	3	1	30	14	-	-	-	-
	Large	all	4	4	170	85	-	-	-	-
		summer	4	4	160	83	-	-	-	-
		winter	4	4	200	97	-	-	-	-
	Very Large	all	4	4	>300	200	-	-	-	-
		summer	5	4	>300	190	-	-	-	-
		winter	4	4	>300	210	-	-	-	-
Olkiluoto 3	Basic	all	2	1	21	9.9	-	-	-	-
		summer	2.5	1	22	13	-	-	-	-
		winter	2	1	19	9.7	-	-	-	-
	Large	all	4	4	230	120	-	-	-	-
		summer	4	4	220	110	-	-	-	-
		winter	4	4	300	140	-	-	-	-
	Very Large	all	4.1	4	>300	200	-	-	-	-
		summer	6	5	>300	210	-	-	-	-
		winter	4	4	>300	210	-	-	-	-

5.4 Comparison to operational intervention levels and dose criteria

The previous sections analyzed the duration for exceeding different external dose rates, the effective and thyroid doses of unprotected people, the amount of deposited radioactive substances, and the duration for exceeding different concentrations of radioactive substances in the air. These quantities are used as OILs or dose criteria for protective actions (see Sec. 3.3). In this section, OILs and dose criteria are compared to the results of analyses. In a real NPP emergency, the protective actions would be taken based on analyses and assumptions about how the situation will evolve using the OILs and dose criteria as guidance in decision making. The simplified comparison of the OILs and dose criteria, and analyzed data of Basic, Large and Very Large cases are shown in Table 5.12. Note that if a site emergency or general emergency is declared, evacuation and iodine prophylaxis are warranted inside the PAZ, and sheltering indoors and iodine prophylaxis are warranted inside the EPZ (see Sec. 3.3). These protective actions are warranted regardless of the magnitude of the estimated release or expected excess of dose criteria or OILs.

TABLE 5.12. Simplified comparison of OILs and dose criteria with analyzed data of Basic, Large and Very Large cases. For effective and thyroid doses, and deposition of strong gamma emitters and deposition of cesium entries not exceeded ("-"), exceeded on some of the sites ("/"), and exceeded on all sites ("X") are used while for duration of dose rates and gamma concentrations in the air entries not exceeded ("-"), exceeded for over 1 hour (> 1 h), exceeded for over 1 day (> 24 h), and exceeded for over 2 days (> 48 h) are used.

Operational intervention level/ Dose criteria	**Basic**				**Large**				**Very Large**			
	PAZ/ EPZ	**20–100 km**	**100–300 km**	**> 300 km**	**PAZ/ EPZ**	**20–100 km**	**100–300 km**	**> 300 km**	**PAZ/ EPZ**	**20–100 km**	**100–300 km**	**> 300 km**
Dose rate > 10 µSv/h	-	-	-	-	> 48 h	> 1 h	-	-	> 48 h	> 24 h	> 24 h	-
Dose rate > 100 µSv/h	-	-	-	-	-	-	-	-	> 48 h	> 24 h	-	-
Effective dose > 1 mSv	-	-	-	-	X	X	-	-	X	X	X	/
Effective dose > 10 mSv	-	-	-	-	/	/	-	-	X	X	-	-
Effective dose > 20 mSv	-	-	-	-	/	-	-	-	X	X	-	-
Thyroid dose adult > 100 mGy	-	-	-	-	X	/	-	-	X	X	/	-
Thyroid dose child > 10 mGy	X	-	-	-	X	X	X	-	X	X	X	X
Strong gamma emitter deposition > 1 MBq/m^2	X	-	-	-	X	X	X	-	X	X	X	X
Strong gamma emitter deposition > 10 MBq/m^2	-	-	-	-	X	X	-	-	X	X	X	-
Cesium deposition > 1 MBq/m^2	-	-	-	-	X	-	-	-	X	X	/	-
Cesium deposition > 10 MBq/m^2	-	-	-	-	/	-	-	-	X	-	-	-
Gamma air concentration > 1 kBq/m^3	>1 h	>1 h	>1 h	-	>1 h	>1 h	>1 h	>1 h	>1 h	>1 h	>1 h	>1 h
Gamma air concentration > 10 kBq/m^3	>1 h	>1 h	-	-	>1 h	>1 h	>1 h	>1 h	>1 h	>1 h	>1 h	>1 h

5.4.1 Duration when external dose rates exceed 1, 10 and 100 μSv/h

The external dose rate is constantly measured using a network of on-line sensors inside and around the NPP. Also, STUK operates a national dose rate monitoring network covering the whole country. In a nuclear emergency, the instruments are used to detect movement of released radioactive substances and to estimate the need for protective actions. The duration when the external dose rate exceeds 1, 10 and 100 μSv/h is considered when deciding on protective actions if the effective doses cannot be evaluated.

In Basic cases, external dose rates of 10 or 100 μSv/h are not exceeded, and protective actions are not needed in terms of OILs for dose rate. A dose rate of 1 μSv/h may, however, be exceeded inside the EPZ and in some rare cases slightly outside of it. In this case, protective actions for securing primary production may be needed.

In Large cases, the recommendation to limit being outside is needed as external dose rates of 10 μSv/h may be exceeded. Inside the PAZ and EPZ, the recommendation to limit being outside may be needed for a longer period (> 24 h) while outside the EPZ the duration when the dose rate exceeds 10 μSv/h may be over 24 h only in some rare cases. OILs for the recommendation to limit being outside may be exceeded for shorter periods of time up to 40–110 km distances from the NPP sites. An external dose rate of 100 μSv/h is not exceeded in Large cases and other protective actions are not expected in terms of OILs for dose rate.

In Very Large cases, evacuation of people is mainly needed inside the PAZ and EPZ when the duration that the dose rate exceeds 100 μSv/h may be over 48 h. In addition, evacuation of people from very small areas outside the EPZ may be needed. The dose rate of 100 μSv/h may be exceeded up to 42–110 km away from the NPP site and in such cases iodine prophylaxis and sheltering indoors are required as protective actions. The dose rate of 10 μSv/h may be exceeded in large areas and in major population centers close to the NPP sites. In these cases, the recommendation to limit being outside and iodine prophylaxis for children and pregnant females should be taken. In Large and Very Large cases, a dose rate of 1 μSv/h is exceeded in large areas extending beyond the distance considered (> 300 km) from the NPP sites. Hence, in these cases protective actions for securing primary production are needed for large areas.

5.4.2 Effective dose of unprotected adult

For practical reasons, the effective doses were estimated in this study using dose coefficients of 7 days for external dose and of lifetime for dose via inhalation. However, the dose criteria for some of the protective actions are given using an integration time of 2 days (see Tables 3.1 and 3.2). The effective and thyroid doses determined in section 5.1 may overestimate the doses with a shorter integration time and may be used as conservative estimates when comparing them with dose criteria. In terms of effective dose, only the effective dose of an unprotected adult is used when the need for protective actions are estimated. It must be noted, however, that based on the analysis, the effective dose of an unprotected child will be higher than that of adult.

In Basic cases, it is not expected that an effective dose of 1 mSv will be exceeded, and protective actions are not needed in terms of dose criteria for effective dose.

In Large cases, sheltering indoors may be needed inside the PAZ and EPZ in Hanhikivi, Olkiluoto 1&2 and Olkiluoto 3 as the effective dose of 10 mSv may be exceeded. Furthermore, in Hanhikivi and Olkiluoto 3 sheltering indoors may be needed also slightly outside of the EPZ and evacuation may be needed inside the PAZ and EPZ as an effective dose of 20 mSv may be exceeded. The recommendation to limit being outside, in turn, may be needed due to large releases from all the considered NPP sites. Dose criteria for the recommendation to limit being outside and iodine prophylaxis for children and pregnant females may be exceeded up to 67–98 km away from the NPP sites.

In Very Large cases, evacuation of people is needed inside the PAZ and EPZ as the effective dose of 20 mSv may be exceeded. In addition, evacuation of considerably large areas reaching up to 41–66 km away from the NPP sites may be needed. The effective dose of 10 mSv may be exceeded at distances up to 67–98 km away from the NPP sites and in such cases iodine prophylaxis and sheltering indoors are required as protective actions. Dose criteria for the recommendation to limit being outside and iodine prophylaxis for children and pregnant females may be reached in large areas and in major populations centers more than 300 km away from the NPP sites.

In Large and Very Large cases, greater protective actions may be needed, or the actions should be extended to larger areas based on the dose criteria for effective doses than based on the OILs for dose rates. According to the analyses, larger areas should be evacuated in Very Large cases and evacuation may be needed also in Large cases inside the PAZ and EPZ. Furthermore, sheltering indoors may be needed inside the PAZ and EPZ in Large cases, and the recommendation to limit being outside and iodine prophylaxis may be needed for larger areas in Large and Very Large cases. The difference could be partly explained by the conservativeness in the calculation of effective doses as 7-day dose coefficients were applied for doses from deposition instead of 2-day dose coefficients. However, the majority of the effective dose accumulates directly from the cloud and via inhalation, and the dose criteria for evacuation is given according to effective dose accumulated for 7 days.

5.4.3 Thyroid dose of unprotected adult and child

For practical reasons, the thyroid doses were estimated in this study using dose coefficients of 7 days for external dose and of lifetime for dose via inhalation (see Sec. 4.3). The dose criteria for thyroid doses and iodine prophylaxis are taken as a complementary protective action for sheltering indoors for adults and for the recommendation to limit being outside for children and pregnant females.

In Basic cases, an adult's thyroid dose of 100 mGy is not expected to be exceeded, and protective actions are not needed in terms of dose criteria for the adult's thyroid dose.

In Large cases, an adult's thyroid dose of 100 mGy is expected to be exceeded inside the PAZ and EPZ due to releases from all NPP sites. Furthermore, in Hanhikivi and Olkiluoto 3 the adult's thyroid dose of 100 mGy may be exceeded slightly outside of the EPZ. According to dose criteria, iodine prophylaxis should be warranted in those areas.

In Very Large cases, an adult's thyroid dose of 100 mGy is expected to be exceeded on large areas and iodine prophylaxis should be warranted in areas reaching up to 83–110 km away from the NPP sites.

In general, the areas for iodine prophylaxis agree rather well with the sheltering indoors that should be taken based on the dose criteria set for effective doses. However, based on the thyroid doses, iodine prophylaxis should be warranted in larger areas than the analysis of dose rates suggests. The area for exceeding an adult's thyroid dose of 100 mGy is larger than the area where a dose rate of 100 μSv/h is exceeded in Very Large cases, and the dose rate of 100 μSv/h is not exceeded in Large cases while a thyroid dose of 100 mGy is expected to be exceeded inside the PAZ and EPZ in all NPP sites, and even slightly outside the EPZ in Hanhikivi and Olkiluoto 3. The difference could be partly explained by the conservativeness in the calculation of effective doses as 7-day dose coefficients were applied for external doses from deposition instead of 2-day dose coefficients. However, the majority of thyroid dose accumulates via inhalation of iodine isotopes, and inhalation dose is not affected by the difference of dose coefficients.

In Basic cases, a child's thyroid dose may exceed 10 mGy inside the PAZ and EPZ in all NPP sites and iodine prophylaxis should be warranted inside the EPZ.

In Large cases, a child's thyroid dose of 10 mGy is expected to be exceeded in large areas and iodine prophylaxis should be warranted in areas reaching up to 130–170 km away from the NPP sites.

In Very large cases, a child's thyroid dose of 10 mGy is expected to be exceeded in large areas and in major population centers over 300 km away the NPP sites. Hence, iodine prophylaxis should be warranted for great distances from the NPP sites.

In all studied release cases, the areas where iodine prophylaxis should be warranted for children and pregnant females are larger than the areas where the recommendation to limit being outside should be taken according to dose criteria for the recommendation to limit being outside based on exceeding a dose rate of 10 μSv/h. The analysis also shows that child's thyroid dose of 10 mGy is exceeded in larger areas in all studied release cases than the analysis of an adult's effective dose of 1 mSv suggests. The protective actions for exceeding these dose criteria are thyroid prophylaxis. The results of the analysis agree better with those for a child's effective dose (see Sec. 5.1). However, the child's effective dose is not used as a dose criterion for the recommendation to limit being outside (see. Tables 3.1 and 3.2). This demonstrates that the content of the radioactive release has a considerable effect on the relation of the thyroid and effective doses. Hence, the content of the release must be carefully considered, and it is beneficial to consider the thyroid and effective doses separately as their assessment may lead to different outcomes.

5.4.4 Contamination of land due to deposition of strong gamma emitters and cesium

The strong gamma emitters and cesium are deposited while the cloud of radioactive substances is passing by the area. After the cloud has passed, the deposited radionuclides are the only source for radiation dose. While some of the radionuclides have relatively short half-lives (i.e., I-131), some others remain in the ecosystem for decades (i.e., Cs-137). To this end, it is beneficial to determine the total deposition of strong gamma emitters that can be used to estimate protective actions needed in the short term and the deposition of cesium for longer term estimations. Note that the analysis performed here does not consider that some of the radionuclides may infiltrate and diffuse into the ground and reduce the direct dose rate from the deposition, especially in the long term.

In Basic cases, the land inside the PAZ and EPZ may become highly contaminated with deposition of strong gamma emitters and thus the recommendation to limit being outside and iodine prophylaxis for children and pregnant females should be warranted. As the analyzed radionuclides have half-lives of over 8 days, temporary relocation may be needed inside the PAZ and EPZ due to land contamination. Furthermore, the land around the NPP sites may be contaminated (> 100 kBq/m^2) up to 84–140 km away from the sites.

In Large cases, the land may become extremely contaminated (see Table 3.3) with deposition of strong gamma emitters up to 29–58 km away from the NPP sites, and in those areas sheltering indoors and iodine prophylaxis should be warranted. The deposition of strong gamma emitters may exceed the level set for highly contaminated land in large areas (130–260 km) and in major population centers close to the NPP sites, and the recommendation to limit being outside and iodine prophylaxis for children and pregnant females should be warranted. Furthermore, the land around the NPP sites may be contaminated (> 100 kBq/m^2) beyond the distance considered (> 300 km) from the NPP sites.

In Very Large cases, the deposition of strong gamma emitters may exceed the level set for extremely contaminated land (see Table 3.3) in large areas (130–260 km) and in major population centers close to the NPP sites. In these cases, sheltering indoors and iodine prophylaxis should be warranted. Furthermore, the land may be contaminated (> 100 kBq/m^2) or highly contaminated (1 MBq/m^2) in considerable areas extending beyond the distance considered (> 300 km) from the NPP sites. Thus, the recommendation to limit being outside and iodine prophylaxis for children and pregnant females may be warranted in areas with considerable size.

In general, the OILs of deposition of strong gamma emitters are exceeded in considerably larger areas than what is found in the analyses performed for dose rates. However, precipitation and wet deposition are the main contributors of the deposition for the 95th percentile data. This leads to a situation where the amount of wet deposition dominates the analysis. In a real-life scenario, more emphasis should be given to areas with precipitation during the passage of the radioactive cloud. However, the analyses demonstrate that precipitation during the emergency may warrant countermeasures in areas that are far away from the NPP site.

In Basic cases, deposition of cesium of 1 MBq/m^2 is not exceeded and thus there is no need for the permanent relocation of people. However, deposition of cesium of 100 kBq/m^2 may be exceeded inside the PAZ and warrants long-term restrictions for land use in the area.

In Large cases, deposition of cesium of 1 MBq/m^2 may be exceeded inside the PAZ and EPZ and may warrant temporary or even permanent relocation of people from these areas if the land cannot be decontaminated so that activity reaches a reasonable level. Deposition of cesium of 100 kBq/m^2 may be exceeded in large areas reaching up to 100–260 km away from the NPP site and warrant long-term restrictions for land use in large areas.

In Very Large cases, deposition of cesium of 1 MBq/m^2 may be exceeded in areas reaching up to 20–130 km away from the NPP sites and may warrant temporary or even permanent relocation of people from these areas if the land cannot be decontaminated so that it reaches a reasonable activity level. Deposition of cesium of 100 kBq/m^2 may be exceeded in considerable areas reaching beyond the distance considered (> 300 km) from the NPP sites and warrant long-term restrictions for land use in large areas.

The analyses for deposition of cesium demonstrate that some of the other deposited radioactive substances decay away and long-term protective actions are not needed for areas as large as the analysis for deposition of strong gamma emitters indicate. Furthermore, the deposition of cesium dilutes naturally due to infiltration and diffusion into the soil and to some extent land can be decontaminated. These processes reduce the direct dose rate from the deposition and may lead to smaller contamination levels of land and less restrictive protective actions than the results of this study indicate.

5.4.5 Duration of activity concentrations of 1 kBq/m^3 and 10 kBq/m^3

In the early phase of an emergency, activity concentration in the air forms the most important source of radiation dose. Hence, the protective actions should be taken before the cloud of radioactive substances arrives at the area under consideration. Fortunately, sheltering indoors is an effective protective action that considerably reduces the radiation dose accumulating from the passing cloud.

In Basic cases, sheltering indoors may be needed for a short period (1–3 h) as air concentration of 10 kBq/m^3 may be exceeded inside the PAZ and EPZ, and in some rare cases slightly outside of the EPZ (< 29 km). Furthermore, OILs for the recommendation to limit being outside may be exceeded for longer than one hour up to 89–110 km distances from the NPP sites.

In Large cases, sheltering indoors may be needed for about 4 h inside the PAZ and EPZ while sheltering indoors may be needed for longer than one hour 150–230 km away from the NPP sites. In addition, 1 kBq/m^3 may be exceeded beyond the distance considered (> 300 km) from the NPP sites and thus the recommendation to limit being outside may be needed in considerable areas.

In Very Large cases, sheltering indoors may be needed for 5–9 h inside the PAZ and EPZ. The OIL for sheltering indoors and the recommendation to limit being outside may be exceeded needed for longer than one hour beyond the distance considered (> 300 km) from the NPP sites.

While the protective actions may be needed in considerable areas according to the analyses of activity concentrations, the duration for exceeding the high activity concentrations remain relatively short. The duration of activity concentration in the air correlates with the duration of release. In this study, a relatively short duration was used for the releases and thus the durations of high activity concentrations in the air are rather short in comparison to analyses performed for e.g., dose rate. The duration of the releases was set to be rather short mainly due to the objective of seeing the worst-case scenarios locally as the effect of changing weather would not dilute the airborne radioactive substances very rapidly. In this sense, the analyses for effective and thyroid dose, cesium, and deposition of strong gamma emitters, and the need for related protective actions are conservative, while the duration of activity concentration may be underestimated in comparison to releases with longer duration.

5.5 Comparison to current emergency planning zones

In the previous section, different OILs, dose criteria and the need for protective actions were estimated using the examined releases from Hanhikivi, Loviisa and Olkiluoto. The estimations were done based on analyses of duration when different external dose rates are exceeded, effective and thyroid doses of unprotected people, amount of deposited radioactive substances, and duration when different concentrations of radioactive substances are exceeded. The simplified presentation of distances where the OILs and dose criteria examined are exceeded (See Table 5.12) can be used to estimate the sufficiency of current emergency planning zones (i.e., PAZ and EPZ). Based on the analysis, the gamma concentration in the air may exceed OILs of 1 kBq/m^3 and 10 kBq/m^3 for a short period of time in all cases and is not considered here in this section. This is due to the relatively short duration of the releases and the aim of demonstrating the conservative estimates for dose rates, doses, and depositions. The conservativeness of a release can also be seen in areas where 1 kBq/m^3 and 10 kBq/m^3 are exceeded for a short period of time.

Based on the analyses, most of the measures studied remain below the OILs and dose criteria in Basic cases. However, dose criteria for a child's thyroid dose and OILs for deposition of strong gamma emitters of 1 MBq/m^2 may be exceeded inside the PAZ and EPZ. Other measures are not exceeded even inside the emergency planning zones. It can be concluded that, when using a design-based release of 100 TBq of Cs-137, it is highly unlikely that any of urgent protective actions are needed outside the PAZ and EPZ. In an emergency, it is plausible that only the protective actions performed prior to the release are needed and the current emergency planning zones are valid in Basic cases. However, in the intermediate phase, temporary relocation of people may be needed inside the PAZ and EPZ due to land contamination if wet deposition is formed due to precipitation.

In Large cases, the OILs, and dose criteria for the recommendation to limit being outside is exceeded inside the PAZ and EPZ and in some cases it may be exceeded slightly outside of the EPZ. Furthermore, the dose criteria for iodine prophylaxis for children and pregnant females may be exceeded at distances up to 170 km from the NPP sites. Furthermore, in some cases dose criteria for sheltering indoors and even evacuation are also needed inside the PAZ and EPZ. It can be concluded that it is unlikely that sheltering indoors or evacuation are needed outside the PAZ and EPZ during the early phase of the emergency. In the intermediate phase of Large cases, temporary relocation of people may be needed inside the PAZ and EPZ due to deposition of strong gamma emitters. The temporary relocation due to land contamination may also be needed outside of emergency planning zones if wet deposition is formed due to precipitation.

In Very large cases, all the OILs and dose criteria are exceeded, and it is highly likely that permanent relocation is needed inside the PAZ and EPZ. Most of the protective actions including permanent or temporary relocation are needed outside the EPZ and less restrictive protective actions (i.e., recommendation to limit being outside and iodine prophylaxis) are needed beyond the area considered. In Very Large cases, the existence of the PAZ and EPZ is important so that the protective actions can be targeted first on areas with severer effects and higher risks.

In general, weather conditions play an important role when the need for protective actions outside the PAZ and EPZ are considered. In NPP accidents with releases on the scale of the Large or Very Large cases, it is highly likely that protective actions are needed outside the EPZ. However, the prevailing weather conditions affect the direction of the airborne radioactive substances and thus detailed location-specific plans for potential protective actions would be challenging to target outside of the current emergency planning zones. Furthermore, the precipitation near the NPP site causes wet deposition of the radioactive substances that may become so large that temporary relocation may be needed. When the same analysis is performed using the 50th percentile of the data, the OILs and dose criteria are exceeded mainly inside the PAZ and in some cases inside the EPZ. In this sense, it is reasonable that the emergency planning zones have rather short distances compared to the maximum distances of potential effects. It is reasonable that in an emergency the protective actions are performed first inside the PAZ and then extended for the EPZ and outside the EPZ according to the existing weather conditions.

In current Finnish regulation, the EPD and ICPD recommended by the IAEA do not exist (IAEA 2015a). However, the recently updated preparedness plan states that in a severe NPP accident sheltering indoors, the recommendation to limit being outside and protecting primary production of foodstuff could be needed as protective actions at distances up to 100 km, 200 km, and 1,000 km, respectively (STUK 2020). The results of this study reveal that these protective actions are needed beyond the PAZ and EPZ in NPP accidents with releases on the scale of Large or Very Large cases. The distances for protecting primary production of foodstuff could not be precisely evaluated in this study because the area considered was limited to 300 km around NPP sites and thus further study should be performed for a larger area. Furthermore, precise evaluation of an EPD and ICPD would also require linking the results of environmental assessment to the level 2 PRA considering the probability of atmospheric releases. In general, having regulation with an EDP and ICPD could improve the preparedness, co-operation, and communication of different authorities in the event that atmospheric release of radioactive substances occurs from Finnish NPPs. Furthermore, an EPD and ICPD could help authorities target the monitoring and identification of the areas where protective actions would decrease the risk of stochastic effects outside the PAZ and EPZ in release scenarios on the scale of Large and Very Large cases.

6 Conclusions

The aim of this work was to study the potential consequences of hypothetical NPP accidents at Finnish reactor units in operation (Loviisa 1 and 2, and Olkiluoto 1 and 2), in commissioning (Olkiluoto 3) and in the preparatory phase (Hanhikivi 1). The potential consequences were estimated using a probabilistic approach for releases with different magnitudes. In this study, we used three different release scenarios with varying fractions of the total inventory released. In the assessment, the probability and areas of different protective actions needed were estimated. Furthermore, the sufficiency of current emergency planning zones and seasonal variation in the consequences were reviewed. Assessment was performed using external dose rate, effective dose, thyroid dose, deposition of strong gamma emitters, deposition of cesium and concentration of gamma emitters in the air. The basis of the assessment was the OILs and dose criteria defined for these measures (STUK 2020). It should be noted that the considered cases represent situations where containment has lost its integrity due to failure of the severe accident management or closing of the containment during an accident has failed. If integrity of the containment is maintained, the releases, even in severe accidents, will be much less than that of the Basic case, and the consequences, if any, in the environment and to the people will be minor.

It was observed that the external dose rate, dose, deposition, and air concentration maps produced correspond well with the wind roses that have been determined based on measurements by weather stations at each NPP site. Furthermore, the results of dispersion modelling were found to be consistent with the measured weather data. These observations led to the conclusion that the results are reliable and could be used for further studies and in the probabilistic risk assessment.

The assessment revealed that it is highly unlikely that any of OILs or dose criteria will be exceeded outside the PAZ and EPZ in Basic cases. In some cases, dose criteria for a child's thyroid dose or deposition of strong gamma emitters may be exceeded only inside the emergency planning zones. In Large cases, the OILs and dose criteria for the recommendation to limit being outside and iodine prophylaxis for children and pregnant females are exceeded inside the PAZ and EPZ, and they may be exceeded up to about 170 km from the NPP sites. Furthermore, in some cases the dose criteria for sheltering indoors and evacuation are needed mainly inside the PAZ and EPZ. It was concluded that it is highly unlikely that sheltering indoors or evacuation are needed in considerable areas outside the PAZ and EPZ during the early phase of the emergency. However, the temporary relocation of people may be needed in the intermediate phase also outside the PAZ and EPZ due to precipitation and the formation wet deposition. In Very large cases, the importance of the PAZ and EPZ is mainly the practicality for first responders so that they can target the first protective actions at areas close to the NPP with severe effects and higher risks. In Very Large cases, most of the protective actions including permanent or temporary relocation are needed outside the EPZ and less restrictive protective actions (i.e., recommendation to limit being outside and iodine prophylaxis) are needed beyond the area considered (> 300 km).

It was shown that it is highly likely that protective actions are needed outside the current emergency planning zones due to releases on the scale of Large and Very Large cases. When the need for protective actions outside the PAZ and EPZ are considered, weather conditions play important role. The prevailing weather conditions, however, affect the direction of the airborne radioactive substances and thus detailed location-specific plans for potential protective actions would be challenging to target outside of the current emergency planning zones. Furthermore, precipitation causes wet deposition of radioactive substances that may lead to high or even extreme contamination of land and would require temporary or even permanent relocation of people at considerable distances from the NPP sites. Based on the assessment, it is also obvious that the protective actions would be needed only in a limited area outside the current emergency planning zones, depending on prevailing weather conditions. It was concluded based on the results that having an EPD and ICPD may be justified for more effective preparedness planning beyond the PAZ and EPZ. However, setting proper distances for an EPD and ICPD would require a more detailed study linked with level 2 PRA considering the probability of atmospheric releases. Furthermore, for finding a theoretical ICPD, the analysis area should be extended from 300 km used in this study. In general, having a prompt EPD and ICPD could improve the preparedness and co-operation of authorities in the event of an atmospheric release of radioactive substances from Finnish NPPs.

The assessment showed that protective actions are in fair agreement when set based solely either on OILs or dose criteria. For example, the dose criteria for effective dose and an adult's thyroid dose, and OIL for deposition of cesium are exceeded inside similar areas for all the release scenarios considered. However, some inconsistencies were also observed. For example, the dose criteria for dose rates indicate the need for protective actions for smaller areas than the dose criteria for an adult's effective and thyroid dose. This cannot be completely explained by use of 7-day dose coefficients for deposited radioactive substances instead of 2-day dose coefficients as the majority of doses accumulate directly from the cloud and via inhalation, and dose criterion for evacuation is given according to effective dose accumulated for 7 days. Furthermore, the dose criterion for a child's thyroid dose is exceeded for a larger area than the dose criterion for the recommendation to limit being outside in all the cases considered. This demonstrates that the content of the radioactive release must be carefully considered in a severe NPP accident as the amount of released iodine isotopes affect the thyroid dose, while other nuclides make only a small contribution to it. The observation also indicates that it is important to assess effective and thyroid dose separately as their assessment may lead to different outcomes. Furthermore, in the intermediate phase, the OILs for deposition of strong gamma emitters may be exceeded in a much larger area than the levels and dose criteria according to other measures. This was concluded to be caused by wet deposition that dominates in the analysis of deposition when using the 95th percentile of the data. It was also observed that the activity concentration of strong gamma emitters in the air may be exceeded for a short period of time (< 12 h) in much larger areas than the other measures indicate. It was concluded the duration of activity concentration correlates with the duration of release, and as rather short releases were considered in this study, the durations of high activity concentrations remain rather short. It was also concluded that the analyses for effective and thyroid dose, cesium, and deposition of strong gamma emitters, and the need for related protective actions are conservative, while the duration of activity concentration may be underestimated in comparison to releases with a longer duration. In general, the observed inconsistencies demonstrate the importance of having multiple measures, and related OILs and dose criteria, for guiding the decision making. The inconsistencies may also reflect the uncertainties of determining different measures (e.g., dose coefficients). Protective action should be initiated if one of the OILs or dose criteria is exceeded or presumed to be exceeded. These issues are particularly important in the presence of exceptional weather conditions.

The seasonal variations between summer and winter were found to be significant, especially in Very Large cases and when considering cesium and deposition of strong gamma emitters. It was observed that precipitation during the winter season causes more wet deposition than in the summer. The difference was found to be particularly large in releases from Hanhikivi. The seasonal variations were also present in other measures. In general, the dispersion towards the north and north-east were dominant directions of dispersion during the winter season. It was shown that during the summer season the dose maps were more evenly distributed to all directions. However, the maps produced out of summer data show that the directions away from the continent are slightly less prominent than the directions toward the continent and along the coast. In Loviisa, directions toward the east are more prominent in winter than during summer season. In Basic cases, the seasonal variations were found to be negligible in terms of all considered measures.

Based on the study, subjects for further study were recognized. These subjects include:

1. The methods developed could be directly applied to analyze the consequences of small modular reactor accidents and NPP sites in the neighboring countries. The analyses would require review of the area and the parameters of the weather model but otherwise the model should be directly suitable.
2. Analysis performed using multiple integration times (e.g., 2d, 7d, 1y) should be analyzed further. There are time periods used in the Preparedness Guide (STUK 2020) that were not studied in this work. For example, permanent relocation: Annual dose is predicted to be > 50 mSv a year after the accident, and temporary relocation: Monthly dose is predicted to be > 10 mSv a month after the accident.

3. For Large and Very Large cases, it would be beneficial to extend the area considered to better estimate the area of less restrictive protective actions (e.g., protecting primary production and iodine prophylaxis).
4. Setting lengths for an EPD and ICPD results of this study should be linked with ones from a Level 2 PRA of the NPPs. The study could be used to estimate better the need of regulation update and of adding an EPD and ICPD into the regulation.

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