Using GIS and Spatial Statistics to Analyze the Chernobyl Consequences

Konstantin Krivoruchko
kkrivoruchko@esri.com

Introduction

On April 26, 1986, at 1:23 a.m., a chain reaction occurred in the Chernobyl reactor, creating explosions that blew off the reactor's heavy steel and concrete lid. From Chernobyl in the former Union of Soviet Socialist Republics (now in the Ukraine), radiation spread across Europe in perhaps the most catastrophic industrial event in the planet's history. Radioactive particles remained suspended in the atmosphere for many days and were distributed as far as Scandinavia, the United Kingdom, and Greece.

Distance between Chernobyl and Stockholm is greater than one thousand miles, see figure 1, but Sweden was more polluted than neighboring to Belarus countries because of the radioactive rain several days after the catastrophe.

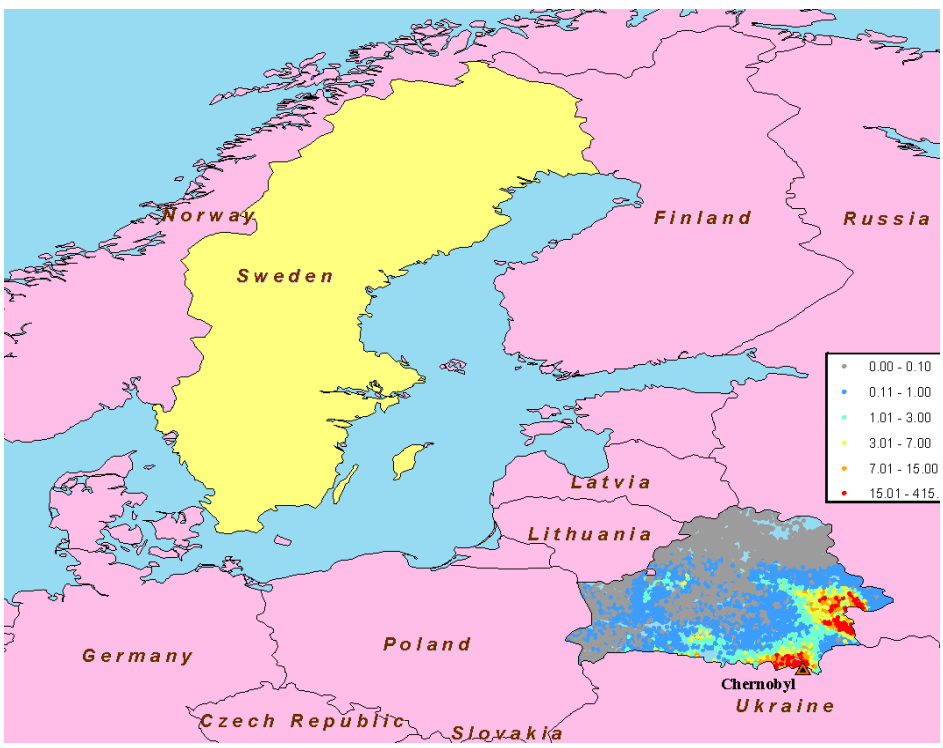

Figure 1. Sweden and Belarus. Sweden is shown in yellow and cesium data are displayed over the Belarus territory. Dark gray indicates low value of radiocesium soil contamination, blue shows territories with relatively low contamination, and warm colors indicate high contamination.

The wind roses on April 26-30, 1986, were such that about 70 percent of the radioactive dust from Chernobyl fell on Belarus. Figure 2 shows wind direction over the Belarus territory in April 1986.

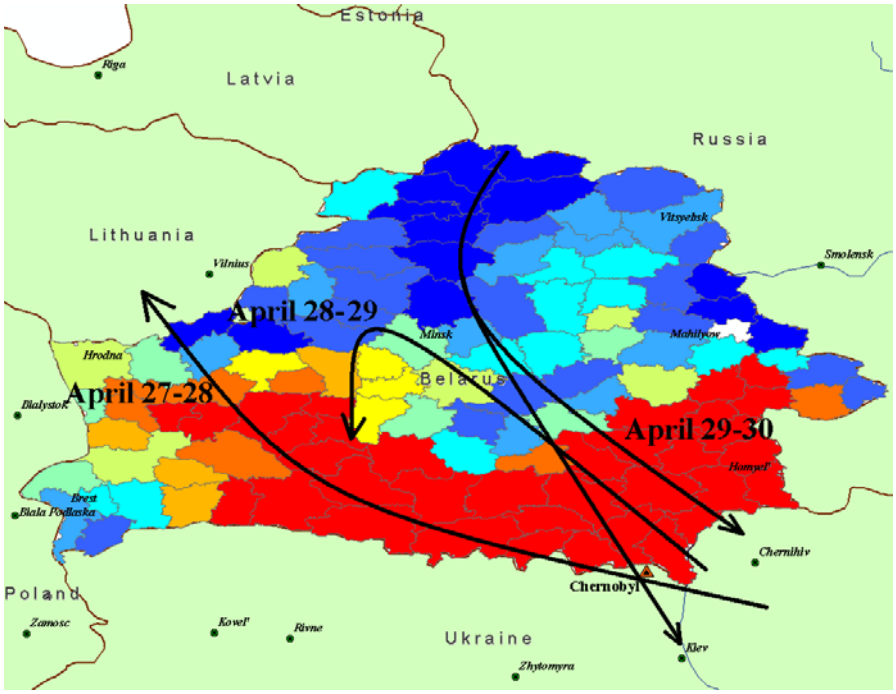

Figure 2. Wind direction over the Belarus territory in April 1986. Using filtered kriging, Byelorussian districts are colored according to the probability that thyroid cancer rates in children exceeded one case per 10,000. Red represents the highest probability and cycles through the spectrum to blue, the lowest probability.

Because of the long half-life of radiocesium (about 30 years), the main radioactive atom or radionuclide deposited across Europe, agricultural effects continue to last many years after immediate health effects cease. For this reason, it is important to assess the eventual health effects of radiocesium consumed through contaminated food. GIS and spatial statistics have provided valuable tools in the analysis of the long-term effects of radioactive exposure to affected populations.

Much research has been done about the three main issues: health, environmental, and sociological consequences of the catastrophe. This paper discusses very generally the importance of GIS and spatial statistics in the analysis of short- and long-term effects of the radioactive exposure of the population in two European countries, Belarus and Sweden. We discuss why radioactive exposure has consequences on human health, the importance of using GIS shortly after the disaster, and application of GIS and spatial statistics for decision-making to protect the population years after the catastrophe.

Consequences of Radioactive Exposure on Human Health

As the contamination was invisible, the release of radionuclides into the surrounding environment showed little hint of disaster. However, when released into the atmosphere, each radioactive particle has a probability of forcing changes in both DNA and the immune system, changes that in turn can decrease an individual's ability to cope with even low levels of radiation. Radioactive fall-out from the atmosphere is stored within soils, from here transferring into vegetation and upwards through the food chain, and ultimately increasing the likelihood of cancer. In the case of environmental chemical pollution, risk of serious diseases may increase significantly. As detailed below, ArcGIS and the Geostatistical Analyst extension were used to perform detailed analysis of radiation contamination and its links to health.

Before the 20th Century, concentrated radionuclides were mostly confined within the earths crust and remained harmless to humans. Technological development has resulted in the dispersal of such elements at a greatly accelerated rate. The ground nuclear weapon tests in the middle of the twentieth century released plutonium into the wider environment. Prior to the tests, plutonium was concentrated in uranium and thorium ores at the estimated levels of 10^{-9} – 10^{-7} Bequerel/gram, with each Bequerel representing one radioactive decay per second. In Belarus, the tests resulted in the increase of plutonium concentration levels in upper soil layers to 10^{-5} – 10^{-4} Bq/g. After the Chernobyl accident, the concentration of plutonium in upper soil layers in southern Belarus increased to alarming values of 0.1 – 0.2 Bequerel/gram.

Nowadays internal exposure from intake of food contaminated by radiocesium contributes to more than half of the whole radiation dose received by Byelorussian people. Income of the inhabitants of villages in southern Belarus does not afford them access to non-contaminated food. They consume vegetables, potatoes, and milk produced on their own contaminated personal properties as well as mushrooms and berries from nearby forests.
After intake, cesium is quickly absorbed and distributed almost uniformly in the human body. It is removed from the body through kidneys. Assuming that people are eating locally grown food and that cesium intake is constant throughout the year, approximate cesium absorption can be estimated as the following. If the daily cesium intake is q_0, the accumulated amount of cesium in the body on subsequent days is the following:

Day	**Activity**
1	q_0
2	$q_0 \cdot e^{-\lambda_e} + q_0$
3	$q_0 \cdot e^{-2\cdot\lambda_e} + q_0 \cdot e^{-\lambda_e} + q_0$
...	
N	$q_0 \cdot e^{-(n-1)\cdot\lambda_e} + q_0 \cdot e^{-(n-2)\cdot\lambda_e} + \ldots + q_0 \cdot e^{-\lambda_e} + q_0$

Here λ_e is the effective speed of elimination of the radionuclide from the body due to biology and radioactive decay. For adults $\lambda_e \approx 0.0063$ 1/day.
Summing up the geometric progression, we can estimate the amount of cesium in the body in n days as: $q(n) = q_0 \frac{e^{-(n+1)\cdot\lambda_e} - 1}{e^{-\lambda_e} - 1}$. Cesium accumulation in the human body at constant intake eventually slows down due to the exponential nature of the radioactive decay, as well as due to the elimination of the radionuclide from the body by metabolism. Accumulation of cesium in a human body through the contaminated food in rural Belarus in 1993 is displayed in figure 3.

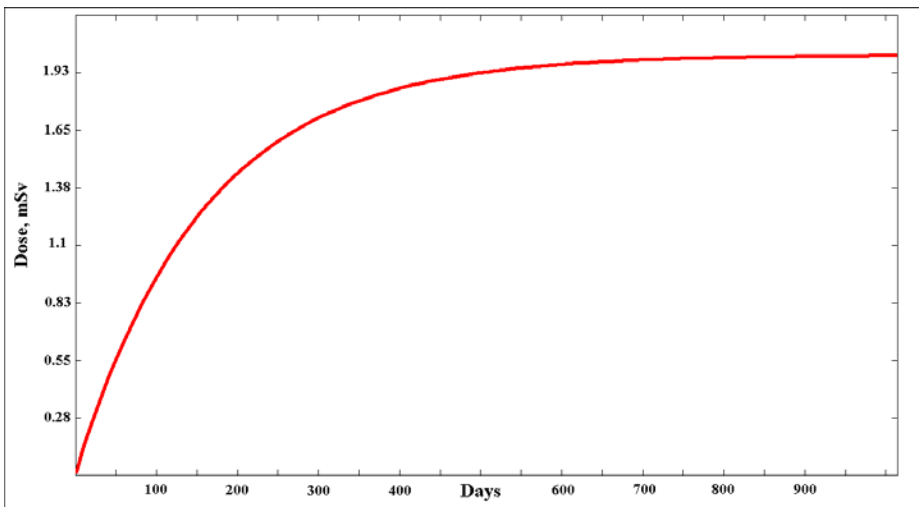

Figure 3. Accumulation of cesium through contaminated food in rural Belarus in 1993, in milliSieverts.

According to the legislation, the maximum radiation dose in unrestricted areas shall be such that an individual would not receive a dose in excess of one milliSievert to the whole body per year.
In southern Belarus, a person can receive a one milliSievert dose during the summer only by eating regular food. If this person leaves this territory and moves to a non-contaminated place, three months later there will still be a half of the dose in his or her body.

Radioactive Rain in Sweden

Detailed meteorological data is very important in the early hours following accidents that produce large amounts of chemical or radioactive emission. Even before measurements of radionuclide contamination are collected on the ground, rainfall data can be used to identify territories where immediate countermeasures should be taken. In 1986, Sweden's meteorological network consisted of more than 700 meteorological monitoring stations. Taking into account wind direction and the distance from Chernobyl to the Swedish border, one could assume that the rain a few days after the accident was radioactive.

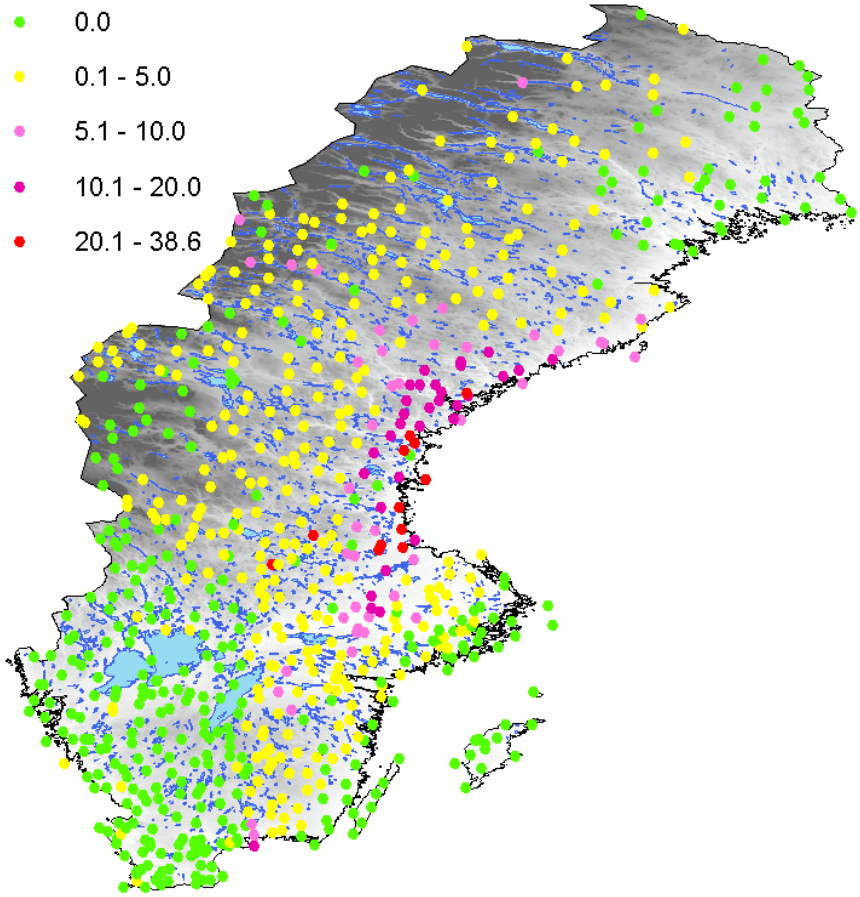

Figure 4. Swedish rainfall observations in millimeters three days after the Chernobyl accident are mapped using data from the European Comission's Institute for Environment and Sustainability, Ispra, Italy..

In general, no matter how dense the monitoring network, there are many areas where observations are not available, and predictions to unsampled locations are required to identify affected territories. However, another important aspect comes into play while predicting the data: each prediction is associated with prediction uncertainty and this uncertainty can be crucial for the decision-making. One possible way to combine predictions and prediction uncertainties is to create a surface of the probability that a certain threshold rainfall value was exceeded.

A geostatistical model of spatial data uses the semivariogram, a function of the distance and direction separating two locations, to quantify the spatial correlation in the data. The semivariogram is then used to define the weights in the kriging system that determines the contribution of each data point to the prediction of new values. Kriging refers to geostatistical interpolation techniques that use the statistical properties of observations. These geostatistical techniques quantify the spatial autocorrelation among measured points and account for the spatial configuration of sample points around the prediction

location. Kriging has a measure of prediction uncertainty, allowing the determination of the degree of prediction accuracy.

Figure 5 shows a map of probability that rainfall in Sweden on April 29, 1986, was greater than 6 mm. We used Geostatistical Analyst extension to ArcGIS 8.3 to produce the probability map. Geostatistical Analyst employs several models for the probability mapping, each based on different assumptions. We used ordinary kriging model (after data transformation and detrending) assuming that predictions and prediction standard errors are distributed normally, because diagnostics provided by Geostatistical Analyst had showed that ordinary kriging model performed better than the typically used in geostatistical applications indicator kriging. Interested reader can find two case studies with comparison of different kriging techniques for probability mapping using another Chernobyl related data at *http://www.esri.com/software/arcgis/arcgisxtensions/geostatistical/research_papers.html*.

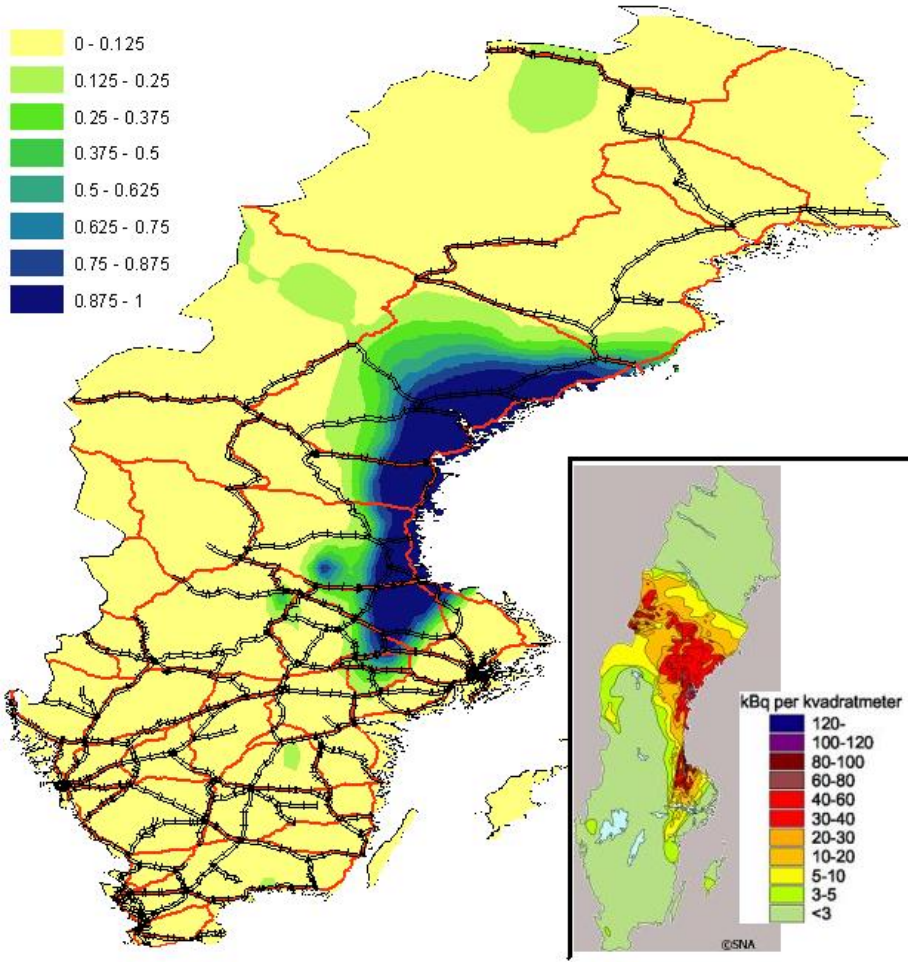

Figure 5. Probability that rainfall was greater than 6 mm on April 29, 1986 in Sweden. Railroads and major roads are also shown to indicate the difference in Swedish population density. In the bottom right, map of radiocesium soil contamination in Sweden found at http://www.sna.se/webbatlas/kartor/vilka.cgi?fritext=cesium is presented.

Rain on April 29 was cause for radiocesium soil contamination in the central and eastern parts of the country. Contamination of other Swedish areas was caused by rainfall in the following several days. It is obvious that the rain was the only possible reason for the radioactive fallout and good meteorological data would allow authorities to take countermeasures immediately, without waiting for actual data on soil and air contamination with radionuclides.

Thyroid Cancer Rates in Belarussian Children

During the first days after the accident, residents of Belarus absorbed large radiation doses through their thyroid glands via inhalation of contaminated air and through consumption of contaminated food, mostly cow's milk and fresh vegetables. The population was not informed about the nuclear accident and the necessity of iodine prophylaxis. (Iodine prophylaxis is very effective and simple: individuals swallow a stable iodine pill and iodine occupies thyroid gland, thus preventing radioactive iodine absorption.)
Prior to the Chernobyl accident there was approximately one case of thyroid cancer per year for the entire child population of Belarus. As a result of irradiation by short-lived radionuclides, including radioactive iodine, there has been a steady increase in the number of new cases over time. The spatial distribution of the cumulative incidence rate over 10 years (1986-95) reaches as many as 1.72 cases per 1000 children in Bragin, 1.68 in Narovlya, and 1.28 in Hoiniki districts, the districts closest to Chernobyl, figure 6. Data were provided by the Sakharov Institute of Radioecology, Minsk, Belarus.

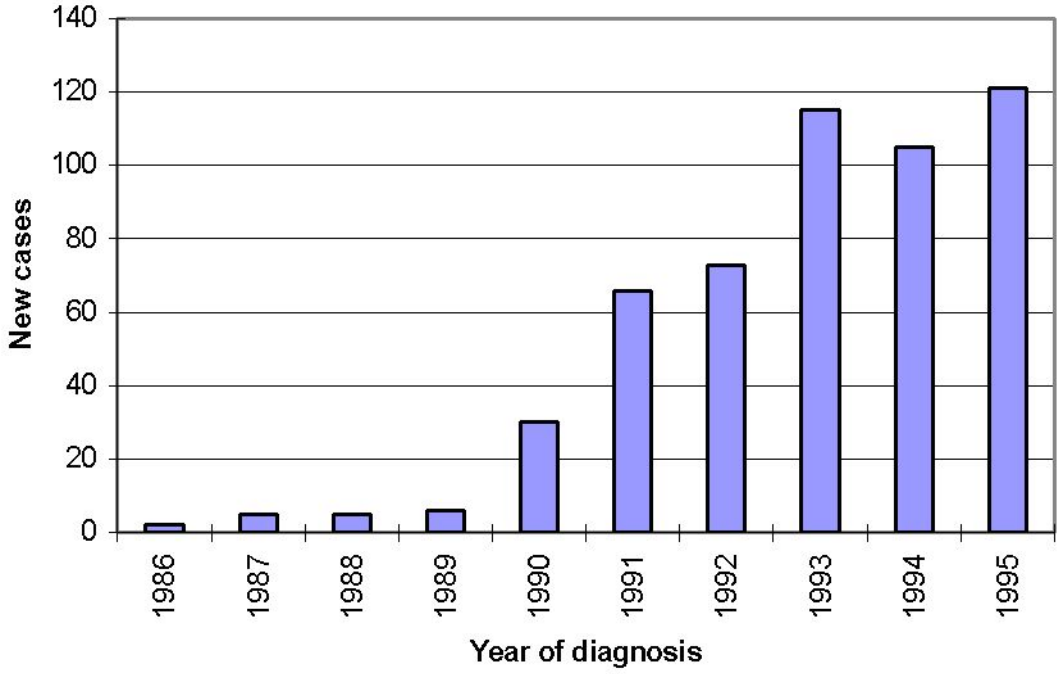

Figure 6. New cases of thyroid cancer per year in Belarussian individuals who were under 15 in 1986.

If data are aggregated over polygonal regions as in the case of thyroid cancer, a geostatistical approach will limit proximity measure between data to the distance between the centroids of the polygons. In our situation, distance between locations should be based on meteorological data, and not on straight-line distance. Also, cancer rates violate the assumption of stationarity that is fundamental to the definition of the semivariogram. Stationarity is a term meaning that statistical properties do not depend on exact locations, so the mean (expected value) of a variable at one location is equal to the mean at another location. Even more importantly, variance should be constant in the area under investigation, and the covariance between any two locations depends only on the vector that separates them, not on their exact locations.
The assumption of stationarity provides statistical replication in a spatial setting. When this assumption is violated, maps constructed from kriging that rely on such a biased semivariogram may be misleading. We used filtered kriging (that is prediction of new value to the data location, assuming that data are contaminated by measurement error) and map in figure 2 above should be used just as qualitative information because of difficulties with geostatistical approach using aggregated data. Models and tools for aggregated data are our special interest for the development of the next version of Geostatistical Analyst.

A fundamental question in the spatial analysis of thyroid cancer data is the relationship between thyroid cancer incidence and spatial distribution of radioactive iodine. However, a unique feature of the relationship between thyroid epidemics and exposure in Belarus is that available epidemiological data are much more reliable than information on radioiodine deposition. Because reliable measurements of radioiodine are not available, researchers often use readily available cesium data. However, distribution of these short- and long-lived radionuclides is very different (for instance, radioiodine was not found in Sweden in April 1986), and such a comparison is not scientific.
The ArcGIS Geostatistical Analyst extension allows analysts to perform these analyses within the ArcGIS environment and create a map that is both accurate and visually accessible for a range of viewers from educators to decision-makers. Since thyroid cancer is primarily caused by irradiation by short-lived radionuclides, a continuous map of thyroid cancer risk can help in the identification of population irradiation by short-lived radionuclides at the very first days after the accident. Such a map can provide useful information on the cause of other chronic diseases that can arise as the result of irradiation as well as from other environmental and sociological factors.

Food Contamination in Belarus

Today, internal exposure from food contaminated by radiocesium contributes to more than half of the whole radiation dose received by Byelorussian people. Income of the inhabitants of villages in southern Belarus does not afford them access to

noncontaminated food. They consume vegetables, potatoes, and milk produced on their own, often contaminated, personal properties. This diet is often supplemented with mushrooms and berries from nearby forests.
More than 50,000 measurements of radiocesium in the main types of food were collected by the Byelorussian Institute of Radiation Safety in 1993. There is no linear relationship between cesium soil and food contaminations. A number of factors influence the uptake of radionuclides from soil to plants, including the level of soil contamination, the soil type, the meteorological conditions at the time of radionuclide deposition, and the type and extent of counter measures. The cases of radiocesium exceeding the upper permissible level in food were published in the institute's information bulletins, which may potentially help families at high risk. As radiocesium contamination is not distributed uniformly, either geographically or within different types of food, probabilistic mapping is especially valuable in understanding and informing populations at risk.

Figure 7 presents data samples of radiocesium concentration in milk and a map of probabilities that the 75% of upper permissible level for milk was exceeded. We choose threshold less than the upper permissible level, because there are many uncertainties in the data and it is better to overestimate risk than not to identify areas where actual contamination is high. We choose milk as an example because it contributes to 36% of the internal dose from food intake for the adult population in 1993 based on the information for 120 rural settlements for which we had at least 50 measurements for each of the eight food diet components, see top left corner in figure 7.

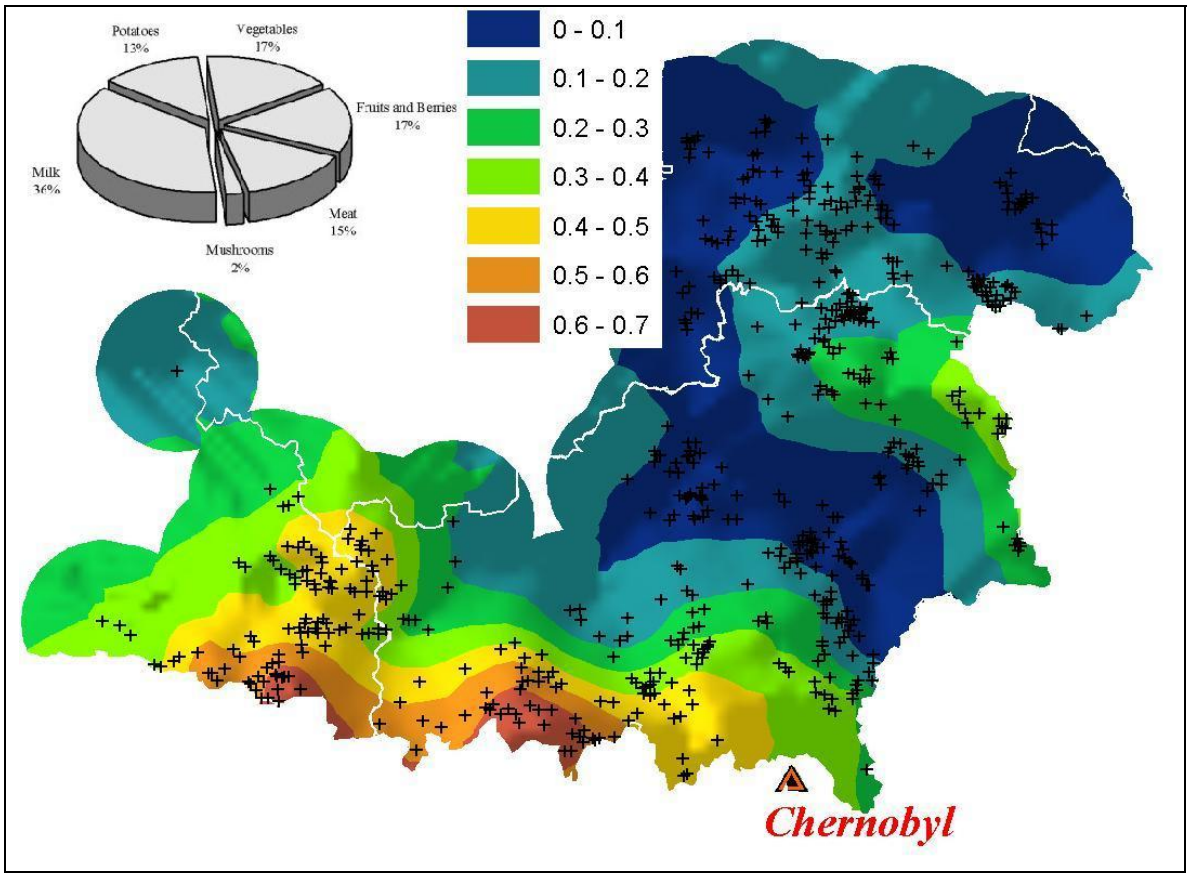

Figure 7. Probability that radiocesium milk contamination exceeded 75% of upper permissible level in southern Belarus in 1993. Disjunctive kriging was used to create this map.

The ArcGIS Geostatistical Analyst extension allows analysts to use repeated observations, supplementary information, and estimated measurement error to filter out this error when predicting to the data location. This allowed the identification of the regions most at risk, areas where contamination of each of the staple foods is high.