

March 2023

MNRISKS: Minnesota statewide screening of health risks from air pollution

Analysis of air emissions data to show potential cumulative health impacts from all sources of air pollution.

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This report is available in alternative formats upon request, and online at www.pca.state.mn.us.

Document number: aq9-29

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1. Summary

The Minnesota Pollution Control Agency (MPCA) strives to ensure Minnesota's outdoor air is healthy for all to breathe. Regulatory programs focused primarily on emissions from individual industrial facilities, can prove insufficient to capture the potential cumulative health impacts from all sources of air pollution. The MPCA began to develop tools in the early 2000s that would give a broader picture of the sources of air pollution in Minnesota and the potential health risks posed to residents from cumulative exposure. This tool development was in partnership with Lakes Environmental and the EPA.

This document describes the Minnesota air toxics risk-screening tool known as *MNRISKS*. During the initial development of *MNRISKS*, the U.S. Environmental Protection Agency (EPA) and the MPCA convened a peer review panel of experts in the field of human health risk assessment to evaluate the plan and provide guidance on continued development. The initial version of *MNRISKS* was based on 1999 emissions data, and the tool is updated with new emissions and sources every three years in coordination with the release of EPA's latest emission inventory. More information on the National Emissions Inventory cycle is available at EPA's [Air Emissions Inventories](#).

The emissions inventory includes the following source types:

1. Point sources (e.g. Permitted facilities)
2. Nonpoint sources (e.g. backyard fires, residential heating)
3. Onroad mobile sources (e.g. Cars, Trucks, Heavy duty vehicles)
4. Non-road mobile sources (e.g. ATVs, boats, construction equipment)

The inventory for these source groups includes both criteria pollutants and air toxics.

Chapter 2 gives an introduction and overview of the tools and methods used to develop *MNRISKS*. Chapter 3 describes the emission inventory and sources of emissions included in the tool. Chapter 4 explains the air dispersion modeling process; the results of which are used along with the chemical and physical properties of each pollutant to calculate media concentrations (Chapter 5). An individual's potential exposure is then calculated from the media concentrations based on the risk scenario selected (Chapter 6). Cancer and non-cancer risks are predicted for each pollutant by comparing a hypothetical individual's total exposure to health benchmarks (Chapter 7).

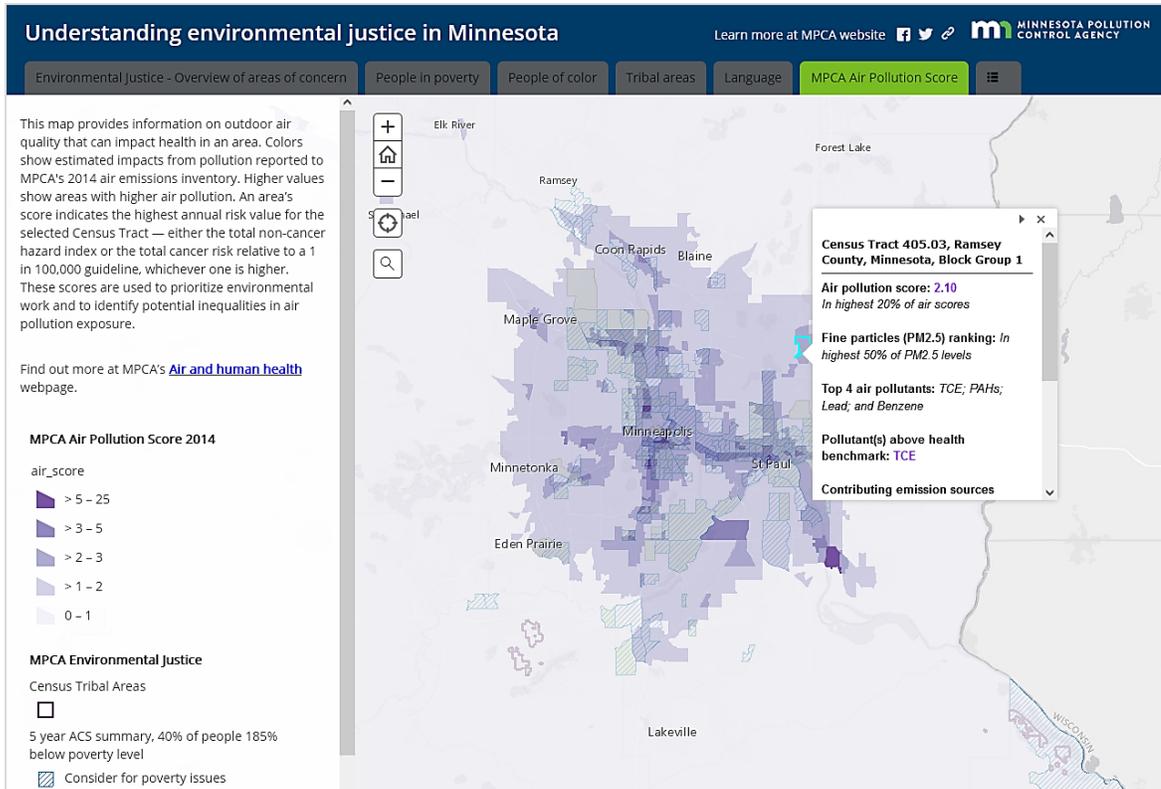
The results of these modeling steps are compiled into a database that is accessible with a graphical user interface. Results can be displayed geospatially as isopleths, individual points, or in numerous flexible formats. The data can be exported and displayed in a variety of formats to illustrate specific features of risk such as source culpability, comparisons to monitored concentrations, source category comparisons, and environmental equity analyses.

MNRISKS is an essential tool for understanding air pollution in Minnesota. It is used in a number of ways across MPCA programs:

1. Providing a picture of cumulative background air concentrations and risks.
2. Focusing and refining the air emissions inventory.
3. Prioritizing pollutants and sources according to air concentrations and health risks for grants, air programs, and resource allocation.
4. Comparing modeled concentrations with monitoring data to evaluate monitor siting.
5. Providing a list of facilities that require additional emissions work and focus.

- Evaluating air quality-related equity concerns. Providing online maps of for source and pollutant comparisons in areas of environmental justice concern.

MPCA areas of environmental justice concern



2. Introduction

Historically, most regulatory efforts at the MPCA focused on industrial point sources of criteria pollutants and projects requiring an air emissions permit. Risk evaluations of air emissions were conducted for new and expanding facilities only when criteria pollutant based emission thresholds had been exceeded. In public meetings during the regulatory processes for these facilities, citizens often raised questions about the potential impacts from proposed emissions, especially in context of the existing air pollution levels from other sources. Past work in Minnesota, as well as the EPA's National Air Toxic Assessment (NATA) showed that non-point and mobile sources, along with point sources, emit significant amounts of air toxics.

The MPCA needed the capacity to better understand and communicate the impacts of air toxics from all sources of air pollution (point, mobile and nonpoint) on a geospatially resolved scale that would take into account the movement of pollutants in the air and other media. In short, there was a need for a tool that would assess the multimedia impacts from all emissions. MPCA entered into a partnership with Lakes Environmental to develop such a tool now known as the Minnesota Risk Screening tool (*MNRISKS*).

MNRISKS is used to conduct risk-based prioritizations such as evaluating and comparing impacts from source types or industrial sectors; identifying areas where specific chemicals are of concern; or comparing differences in impacts (and the effects of possible interventions) in any area of Minnesota. It can also be used to evaluate the potential impacts of proposed changes in rule, statute or policy. In this document the term "risk" is used to represent estimates of additional lifetime cancer risk and non-cancer hazard impacts.

MNRISKS is designed to provide an easy-to-use, robust system to facilitate screening-level human health risk information across Minnesota. MPCA's most current emissions inventory data for point, nonpoint, and mobile sources are input for air dispersion modeling. The modeling results are combined with spatial data to perform a statewide multi-pathway risk assessment to evaluate:

- Individual sources
- Source categories
- Industrial sectors
- Specific chemicals or groups of chemicals
- Demographic groups
- Geographic areas
- Exposure pathways for residents, farmers, and fish eaters

2.1 Methods

MNRISKS begins with the tri-annual emissions inventory. The Minnesota emissions inventory includes point sources, nonpoint sources, and mobile sources. Point source data are associated with the location of the individual emissions source. Nonpoint and mobile source data are inventoried at the county level and then processed by MPCA staff into specific source categories at a refined geospatial scale. These data, including source release parameters, are used as inputs to the EPA recommended air dispersion model, which generates pollutant air concentrations and soil deposition rates. The resulting media concentrations are further tracked through fate and transport modeling and risk assessment protocols following EPA recommended methods documented in the Human Health Risk Assessment Protocol or HHRAP (EPA 2005).

The following is a list of the methods and tools employed by *MNRISKS*:

1. *MNRISKS* uses the most current air toxics emissions inventory data for point, nonpoint and mobile sources together with existing databases containing Minnesota's meteorology, point source locations and stack parameters, and data reflecting the spatial distribution of non-point source emissions.
2. *MNRISKS* uses EPA's recommended air dispersion model, AERMOD, to calculate hourly- and annual-average air concentrations for vapor, particle and particle-bound chemical phases resulting from emissions from every source in the Minnesota emissions inventory. Pollutant concentrations are modeled at over 90,000 receptor points across Minnesota.
3. *MNRISKS* predicts uptake from water into fish, and from soils into vegetables, meat, and dairy products using algorithms from the HHRAP. Risk calculations also estimate concentrations in Minnesota's water bodies, soils and vegetation based on deposition to these media from the air.
4. *MNRISKS* predicts cancer risks and acute and non-cancer hazard indices. The risks can be exported for any combination of sources, pollutants, endpoints and geographic area.
5. *MNRISKS* includes mercury modeling to estimate mercury concentrations in surface water.

2.1.1 Emissions inventory

In cooperation with EPA's national emissions inventory, the MPCA conducts a complete emissions inventory every three years that includes all source categories and all air toxics (around 250 pollutants).

2.1.2 AERMOD and air dispersion modeling

The EPA's air dispersion modeling guidance (40 CFR 51, Appendix W) and risk assessment guidance (EPA 2005) outline standardized approaches to performing air dispersion modeling for human health risk assessments. These methods are followed by *MNRISKS* to model hourly- and annual-average air concentrations for vapor, particle, and particle-bound chemical phases. Air dispersion modeling uses unit emissions that represent the $\mu\text{g}/\text{m}^3$ impact per 1 g/sec of emissions. These emission rates are applied in the risk modeling step to calculate pollutant concentrations at all receptor points.

2.1.3 IRAP-h view and human health risk assessment

Risk modeling for the statewide cumulative risk screening is conducted following the methodologies in the HHRAP. More specifically, the HHRAP implements the guidance in the following EPA documents:

- *Methodology for Assessing Health Risks Associated with Multiple Pathways of Exposure to Combustor Emissions*, which contains specific equations and inputs recommended in the reference below (<https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=55525&CFID=62997541&CFTOKEN=75735101>).
- *Risk Assessment Guidance for Superfund: Volume I Human Health Evaluation Manual (RAGS)*, <https://www.epa.gov/risk/risk-assessment-guidance-superfund-rags-part>,
- *Exposure Factors Handbook* (<https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252>)
- *Integrated Risk Information System (IRIS)*, <https://www.epa.gov/iris>.

The HHRAP guidance summarizes the procedures, equations, and inputs required to perform multi-pathway risk evaluations. The HHRAP guidance is implemented using the risk assessment software IRAP-h View™ developed by Lakes Environmental.

The exposure routes for the three main risk scenarios include:

1. Resident risks including exposure via:
 - Inhalation
 - Soil ingestion
 - Home-grown above and below ground produce consumption

2. Farmer risks including exposure via:
 - Inhalation
 - Soil ingestion
 - Home-grown produce consumption
 - Home-bred meat and dairy consumption

3. Fisher risks including exposure via:
 - Inhalation
 - Fish consumption
 - Home-grown produce consumption

2.1.4 Geographic information system tools

MNRISKS incorporates GIS capabilities compatible with commonly used spatial analysis and visualization tools such as ESRI products, Tableau visualizations, and R packages. Examples of the types of features and base maps used in *MNRISKS* include:

- Aerial photography and satellite imagery
- Land Use Land Cover maps from the USGS
- Demographic data sets from the U.S. Census Bureau
- Site specific GIS maps or shapefiles

These maps are used to visualize and evaluate emission inputs, source allocation, and multi-pathway parameters. A sample of the spatial layers used in *MNRISKS* are shown in Figure 1.

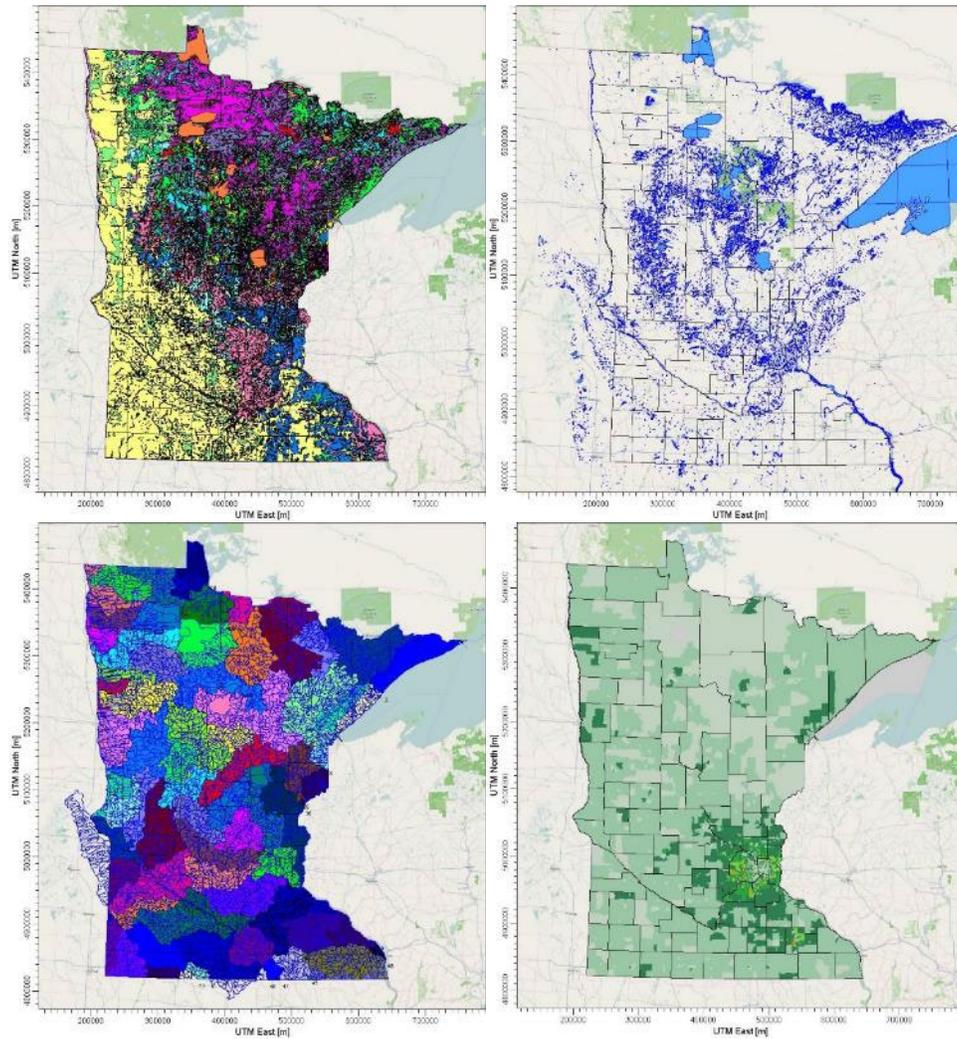


Figure 1. Maps used in *MNRISKS*. Clockwise from upper left: land use, water bodies, median household income, watersheds (minor divisions within colored major watersheds).

2.1.5 Data processing

A simplified data processing flow is presented in Figure 2 below.

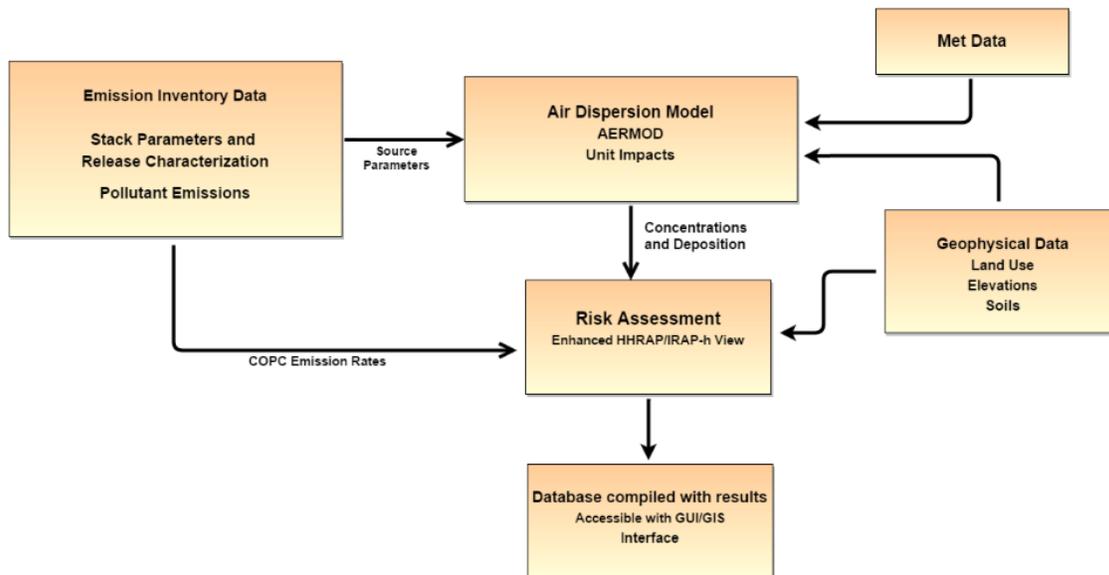


Figure 2. Simplified dataflow in *MNRISKS*.

2.2 Other cumulative air toxic risk studies

Other cumulative risk systems have been developed elsewhere, including the EPA National Air Toxics Assessment (NATA, <https://www.epa.gov/national-air-toxics-assessment>), the Residual Risk Report to Congress ([Residual Risk Report to Congress, EPA- 453/R-99-001](#)), the California MATES program (Multiple Air Toxics Exposure Study), and RAIMI (the Regional Air Impact Modeling Initiative).

2.3 Uncertainties

MNRISKS uses generally accepted human health risk assessment methods. However, the air toxic risk assessment field is evolving and methods, parameters, and models are frequently updated. Any simulation is subject to uncertainty, and a system as complex as *MNRISKS* is no exception. Uncertainties fall into two general categories, inaccuracies in input data and limitations in the parameterization of the processes captured in the modeling.

Given accurate input data, the uncertainty of air dispersion models is described by the EPA [40 CFR 51, Appendix W] as being on the order of a factor of two. Among the model inputs (e.g. emissions, meteorology data, stack parameters, land use) the emissions data are generally recognized as the greatest source of error (Pratt et al. 2012).

Many of the potential uncertainties in *MNRISKS* are described in the HHRAP:

1. Cancer and non-cancer health benchmarks are used as the criteria to judge the impact of a given pollutant. These benchmarks are uncertain and may over or underestimate risk.
 - a. Health risks are limited by inherent uncertainties. They are not definitive lines or absolute boundaries. Unknowns such as gaps in data, differences in individual susceptibility, and extrapolation of animal studies to humans are accounted for by incorporating a margin of safety when establishing a health benchmark. Assessments of risk to human health are often limited to available emissions data. A pollutant that reacts to form another toxic pollutant cannot be adequately addressed when risk is based only on emission data.

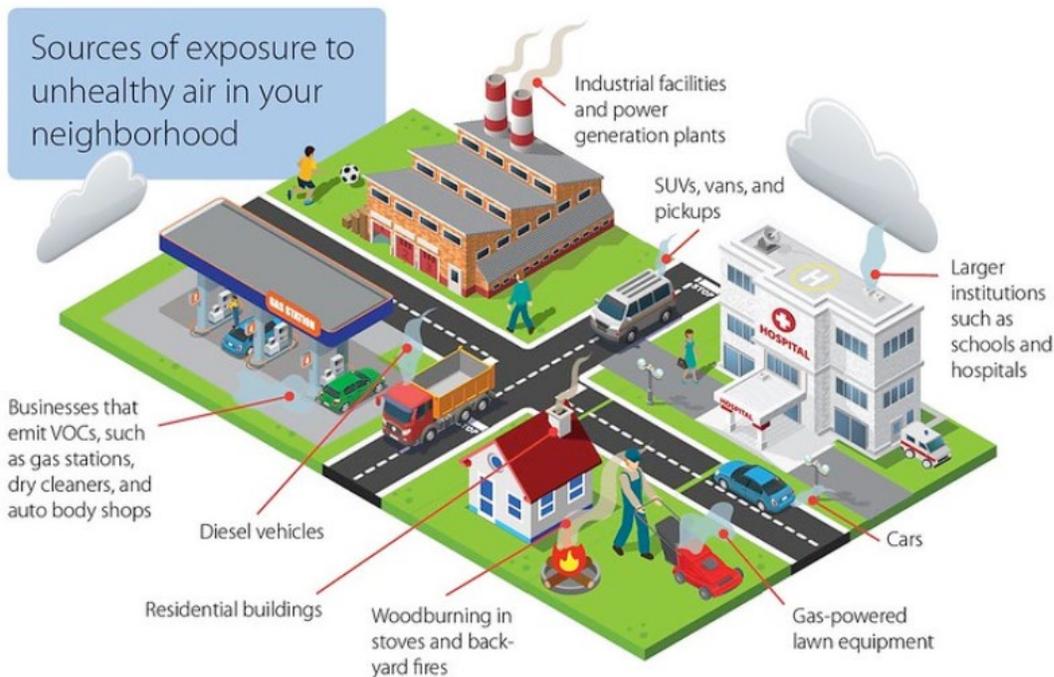
2. *MNRISKS* evaluates outdoor air concentrations, which are used as a surrogate for exposure. In reality exposure is a complex integration of multiple indoor, outdoor, in transit, and other exposures from a multitude of sources.
3. Uncertainties in the emissions inventory data. For example, point source emissions are reported with a variety of specificity and verification. Some point source emissions are assigned to a single stack at each facility, while other facilities are modeled with detailed source information for individual stacks. Some mobile source emissions are apportioned to Census block groups, while high-traffic emissions are apportioned to individual roadway segments. Nonpoint and non-road source emissions for some categories are estimated based on national average activity levels and not on specific measurements.
4. Air dispersion modeling impacts are limited to an area extending 20-50 kilometers from the source, so impacts beyond this distance are not captured.

2.3 Air monitoring

There are two main types of tools for investigating air pollution, modeling tools like *MNRISKS* and air monitoring. These two tools complement one another. Air monitoring provides the most accurate information at the monitoring site, but it is relatively expensive and limited to a few locations and pollutants. On the other hand, modeling is faster, and captures many pollutants and locations at relatively low cost. However, models are subject to uncertainties in the input data and the parameters available for the chemical and physical processes that disperse, react, and deposit pollutants.

Given the uncertainties in modeling, it is important to validate model predictions against measurements to evaluate how well the model is performing. The use of monitoring data to check model performance is often termed calibration or validation of the model. The calibration process is an exercise in reducing uncertainty and improving the model agreement with measurements. Model-monitor comparisons for *MNRISKS* are presented in section 4.6 of this document.

3. Emissions data



3.1 Introduction

MNRISKS uses emissions data from permitted facilities and a wide variety of smaller non-permitted and dispersed sources like on-road mobile sources, non-road mobile sources, and dozens of categories of nonpoint sources. The MPCA maintains an air emissions inventory system in which emissions of criteria pollutants are tabulated annually. Every three years a more comprehensive emissions inventory is compiled with emissions of over 250 pollutants from all source categories. This triennial emissions inventory comprises the data used in *MNRISKS*. Minnesota emissions data are also tabulated in the EPA National Emissions Inventory (NEI). The MPCA and EPA cooperate in developing emissions inventories, and the two systems are often identical, although in some cases small differences arise for various reasons. More information about the emissions inventory is available on the [MPCA website](#).

Characterization of emissions and physical parameters of each source is required for the air dispersion and risk modeling. The data requirements are unique and specific to each source type. When available, emissions data and stack parameters for permitted point sources are taken directly from past modeling demonstrations, otherwise inputs are drawn from the emissions inventory.

For many non-permitted sources, such as landfills, dry cleaners and crematoria, locational data may be available but not detailed release parameters. These sources, often referred to as “allocated point sources”, are typically characterized as volume sources for modeling purposes.

Several categories of sources are not represented with precise locational data in the emissions inventory system. These categories include nonpoint sources, on-road mobile sources, and non-road mobile sources. The nonpoint and mobile source emissions are compiled by Source Classification Code (SCC). For *MNRISKS*, the SCC categories are combined into a smaller number of groupings of sources that are similar. The nonpoint categories are treated as either volume sources or nonpoint sources in the AERMOD air dispersion model.

Emissions for most nonpoint categories are inventoried at the county level in the MPCA emission inventory. To achieve greater geospatial resolution in the emissions, the county emissions are apportioned into Census block groups. This apportioning is performed using surrogates that capture the demographic, activity, land use, and other characteristics that represent the ways a given category occurs within a county. An overview of the categories and subcategories of nonpoint and mobile sources included in *MNRISKS* is shown in Table 1. A more complete list of subcategories and the surrogates used for apportioning to Census block groups is given in Appendix B.

Table 1. Source categories and subcategories for mobile and nonpoint sources.

| On-road Mobile Sources | Non-Road Mobile Sources | Nonpoint Sources |
|-------------------------------|---|---|
| Gas vehicles | Airports (Ground Support, Ground Operations, & Inflight Operations) | Agricultural Fires, Wildfires & Prescribed Burning |
| Diesel vehicles | Commercial Marine Vessels | Landfills, Composting |
| | Pleasure Craft (Boats) | Crematoria |
| | Railroads (Switchyard & Line Haul Operations) | Dry Cleaners |
| | Agricultural Equipment | Feedlots |
| | Recreation Equipment | Food & Kindred Products |
| | Industrial / Commercial Equipment | Health Services |
| | Lawn & Garden Equipment | Industrial, Commercial & Institutional Boilers |
| | | Residential Wood Combustion (Outdoor Wood Boilers & Recreational Fires, Indoor Devices) |
| | Construction & Mining Equipment | Miscellaneous Roadway Emissions |
| | Logging Equipment | Miscellaneous Agriculture & Pesticide |
| | | Non-industrial Consumer & Commercial Activities |
| | | Open Burning |
| | | Petroleum & Products Storage & Transport |
| | | Residential Fuel Combustion |

3.2 Point sources

Point sources are defined as large stationary sources that require an air emissions permit from the MPCA. These facilities are required to report their emissions of criteria pollutants annually. Every three years MPCA compiles an inventory of emissions of air toxics pollutants. Most facilities report their air toxics emissions to MPCA, although there is no requirement to do so as air toxics reporting is mostly voluntary. MPCA determines air toxics emissions from non-reporting sources using information about fuel use, process activities, EPA’s Toxics Release Inventory (TRI) data, and published emission factors.

The MPCA point source emissions inventory includes information about source locations, stack parameters and other release conditions. Stack parameters are required data in the MPCA air permitting system. For most point sources, the source location consists of a single set of coordinates that may represent the location of the street address, the facility centroid, the main stack, or other feature. When only a single location is available for a facility, all release points are co-located and assigned the same set of spatial coordinates. The largest facilities that are subject to federal permitting regulations under Title

V of the Clean Air Act are required by the MPCA to submit model information requests containing precise information about each release point, the property boundary, and the locations and dimensions of nearby buildings that influence wind flow. This information is used in *MNRISKS* when available.

The MPCA and EPA have compiled an extensive inventory of air emissions for Minnesota. However, some caveats should be kept in mind when interpreting *MNRISKS* results. Emissions are tabulated as annual totals of actual emissions (not permit allowable emissions). Fluctuations during the year are not accounted for in *MNRISKS*. Process upset conditions may result in elevated air toxic emissions that may last from a few minutes to days. Upset emissions are sometimes, but not always, included in the annual emissions inventory. Since the air dispersion model uses annual emissions distributed evenly across every hour of the year, it does not reflect the short-term maximum emissions at a facility or other source. As a result, the one-hour average concentrations used in calculating acute inhalation risk do not reflect upset or other peak emission conditions.

Buildings that cause plume downwash may increase the short-term ground level air concentration near a facility. However, emission inventories do not commonly contain information on buildings that may affect the dispersion of emissions from point sources. This is the case for the Minnesota emissions inventory. For the Title V facilities (approximately 70 facilities) that have submitted model information including the location of individual stacks, buildings, and property boundaries, the potential building downwash effects are included in the modeling for these facilities.

3.3 Nonpoint sources

Nonpoint sources are defined by EPA's [NEI program](#):

Nonpoint sources include emissions estimates for sources that individually are too small in magnitude to report as point sources. In practice, the nonpoint category includes all emissions from stationary sources that do not have air emissions permits. These emissions sources are included in the NEI as a county total or tribal total. Examples include residential heating, commercial combustion, asphalt paving, and commercial and consumer solvent use.

The MPCA emissions inventory tabulates nonpoint emissions from hundreds of SCCs at the county level. For *MNRISKS*, these emissions categories are aggregated into a handful of groupings. Figure 3 shows the Census block groups in Minnesota (US Census, 2010). They vary in size from 0.4 to 3,887 square kilometers. The larger block groups are found in more remote areas of the state with lower population densities. The smaller block groups are found in more urban areas with higher population densities. The boundary of each block group is simplified to a polygon with no more than 30 vertices. This simplification allows the block groups to be modeled as *polygon area sources* in AERMOD.

The surrogates used for apportioning county level nonpoint emissions into block groups are shown in Appendix B. As an example, the nonpoint grouping *A_RESIFUEL* represents several categories of residential fuel combustion. The surrogate used to apportion the county level emissions is the fraction of single-family households located in a block group. If block group X contains 10% of the single-family households in its county, then it will be apportioned 10% of the county emissions from residential fuel combustion.

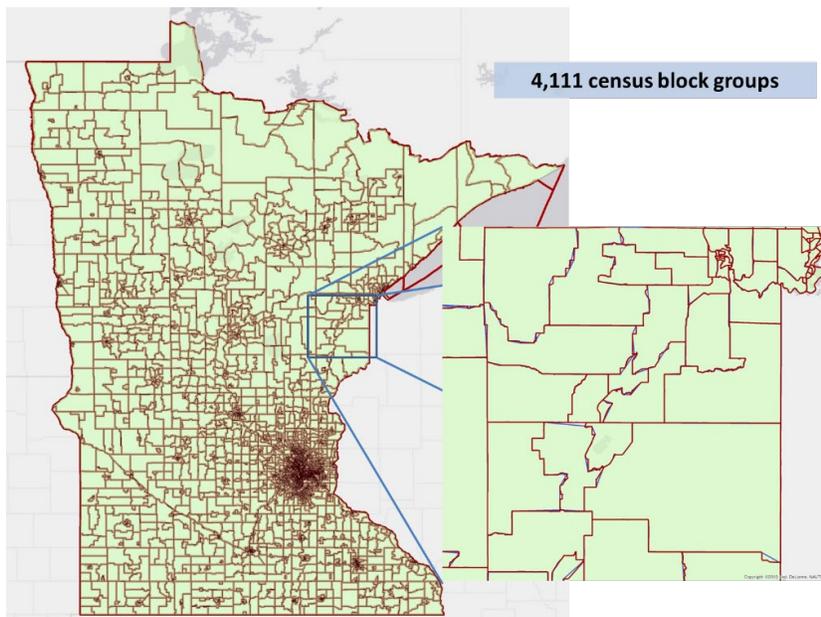


Figure 3. Block groups in Minnesota. The enlarged inset shows the simplification to polygons with 30 or fewer vertices.

3.4 Mobile sources

Mobile sources consist of two major subcategories:

1. On-road mobile sources including motorcycles, cars, trucks, and buses.
2. Non-road mobile sources including aircraft, railways, boats, construction equipment, farm equipment, snowmobiles, lawn and garden equipment, and other small engines.

3.4.1 On-road mobile sources

On-road emissions in the NEI are tabulated by both fuel and vehicle types. For *MNRISKS*, the on-road emissions are aggregated into two categories: conventional gas and diesel. The initial county level emissions are apportioned into block groups using vehicle kilometers traveled (VKT). The Minnesota Department of Transportation develops the VKT data and is available online at <http://www.dot.state.mn.us/traffic/data/>.

The emissions for high traffic roadway segments (>10,000 AADT) are treated separately. Figure 4 shows the high traffic segments. These segments are split into 100 meter lengths, each of which is represented as a volume source in the air dispersion model. The fraction of each block group's VKT on the high traffic segments is used to apportion the emissions between high traffic and low traffic categories. The total emissions from the high traffic segments are apportioned to each of the 100-meter volume sources according to the VKT on that segment. Emissions on the high traffic segments are assigned scalars depending on the time of day, season, and holidays. These scalars are developed from transportation studies and the EPA MOVES model.

The emissions on the lower traffic segments are apportioned to block groups within each county according to the fraction of the county VKT in the block group (after subtracting the VKT from the high traffic segments).

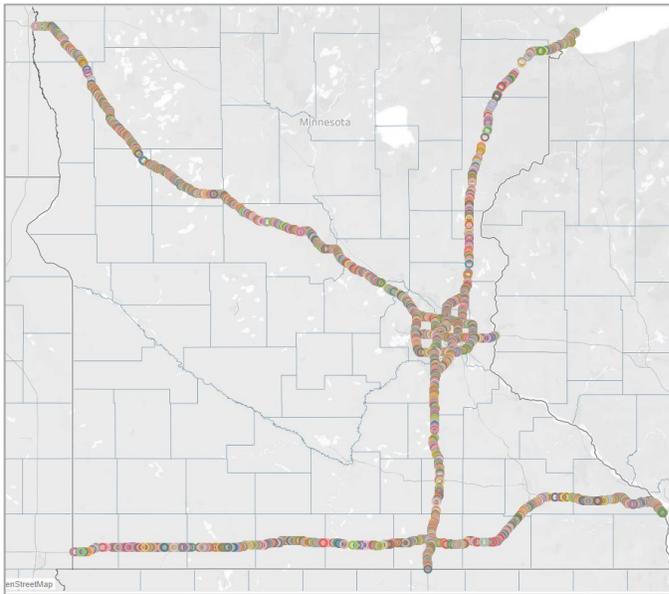


Figure 4. High traffic roadway segments in Minnesota. These segments are modeled as AERMOD volume sources located every 100 meters along the roadway.

3.4.2 Non-road mobile sources

Non-road emissions are combined into 11 categories (see Appendix B). County emissions from the MPCA emissions inventory are apportioned to block groups using the surrogates following the same methods outlined for nonpoint sources. The exception is airports. Airport related emissions include ground support emissions, aircraft emissions at the airport and in-flight emissions of lead (Pb). Larger airports with specific emission information are modeled individually and represented as large volume sources in the air dispersion model. The remaining aircraft related emissions are apportioned to block groups according to the number of airports in each block group.

3.5 Allocated point sources

Allocated point sources do not fall into the categories described above. They include smaller point sources that are not part of the MPCA air permitting system but whose emissions are tabulated individually. These sources consist of landfills, dry cleaners, POTWs (sewage treatment plants), and crematories. Some of the larger sources within these categories are permitted and treated as point sources. Each of the allocated point sources is represented as a volume source in the air dispersion model. The size of the emission sources for these categories is estimated from satellite imagery.

3.6 Emissions inventory uncertainties

3.6.1 Point sources

Point sources are generally permitted and therefore have the best, although not perfect, spatial accuracy. Emissions from each facility (with the exception of those submitting model information reports) are represented as a single location. Similarly, stack parameters for many facilities are based on industry-wide averages for similar sources.

3.6.2 On-road mobile sources

On-road mobile source emissions occur on distinct roadway segments, and the emissions from high traffic segments are modeled as occurring on those exact segments, accounting for both spatial and

temporal variability. These segments make up a significant, but still incomplete, proportion of traffic in Minnesota. On-road mobile source emissions on lower traffic roadway segments are apportioned to census block groups without temporal variability. This simplification makes air dispersion modeling possible, but leads to uncertainties in model predictions of the spatial and temporal occurrence of pollutants. In rural areas, where roads are sparser and block groups larger, this approximation is expected to underestimate risks near major roads and overestimate risks further away from busy roads.

3.6.3 Non-road mobile sources

Some mobile non-road source categories, such as railyards, aircraft, and commercial ports, lend themselves to precise spatial and temporal allocation. However, emissions from the majority of non-road mobile source categories (e.g., lawn and garden equipment, construction equipment, agricultural equipment, boats) are spatially dispersed. Additionally, many non-road mobile source emissions are seasonally dependent. For example, summer emissions are highest for certain categories such as recreational motor boats and lawn mowers. Since *MNRISKS* distributes these emissions evenly across the year, there is additional uncertainty in the modeling results for these sources.

3.6.4 Nonpoint sources

Nonpoint sources, such as residential campfires, are often too numerous and diffuse to assign precise locations. Thus, nonpoint source emissions suffer from similar spatial uncertainties as non-road mobile sources. Similarly, modeling the emissions of these sources uniformly over the course of a year may influence the spatial distribution of modeled results and the location of modeled maxima.

4. Air dispersion modeling

4.1 Introduction

This chapter presents the general approach to air modeling employed in *MNRISKS* for conducting multi-pathway, neighborhood level analysis of health risks from air pollution. The emission release characteristics developed following the methods outlined in Chapter 3 are used as inputs to an air dispersion model to estimate pollutant concentrations in air and pollutant deposition, or vapor transfer to surfaces including soil, water, and vegetation.

Table 2 lists the source-specific data needs to perform air and risk modeling.

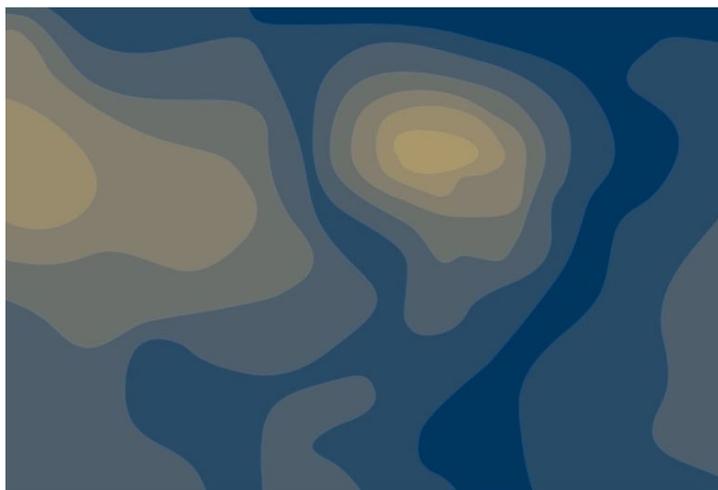


Table 2. Required source-specific data for air dispersion modeling.

| | Point Sources | Fugitive Sources Characterized as Volumes | Fugitive Sources Characterized as Areas |
|---------------------------|---|--|--|
| Physical Characteristics | <ul style="list-style-type: none"> - Stack height [m] - Base elevation [m] - Stack diameter [m] - Stack gas exit velocity [m/s] - Stack gas exit temp. [K] - Stack location coordinates - Locations and dimensions of nearby buildings | <ul style="list-style-type: none"> - Area [m²] - Release height [m] - Base elevation [m] - Coordinates - Initial lateral and vertical dimensions | <ul style="list-style-type: none"> - Area [m²] - Release height [m] - Initial vertical dimension - Base elevation [m] - Polygon vertex coordinates |
| Emissions Characteristics | <ul style="list-style-type: none"> - Contaminant CAS number - Emission rate [g/s] | <ul style="list-style-type: none"> - Contaminant CAS number - Emission rate [g/s] | <ul style="list-style-type: none"> - Contaminant CAS number - Emission rate [g/s] |

Notes

m meters

m/s meters/second

K Kelvin

g/s grams/second

CAS Chemical Abstract Service

¹ Pollutant specific emissions are applied post-AERMOD

Air dispersion and deposition modeling in *MNRISKS* uses the EPA recommended air dispersion model, AERMOD, and follows (with a few minor changes noted below) the EPA recommended procedures in the Human Health Risk Assessment Protocol or HHRAP.

For each source, air dispersion modeling is performed using unit emissions to estimate six categories of concentration phases and deposition:

1. Air concentration of vapor phase pollutants
2. Air concentration of particle phase pollutants
3. Air concentration of particle bound pollutants
4. Dry and wet deposition of vapor phase pollutants
5. Dry and wet deposition of particle phase pollutants
6. Dry and wet deposition of particle-bound pollutants

Emission rates are assigned to the appropriate vapor, particle or particle-bound model runs depending on the fraction of each pollutant in the vapor phase (F_v). This step occurs in the risk modeling stage that follows air dispersion modeling and is described in Chapter 7 of this document. Some pollutants occur exclusively in one phase, while other pollutants may occur in multiple phases depending on their chemical and physical properties.

4.2 Model input requirements

MNRISKS requires the following inputs for air dispersion and deposition modeling:

1. Land use data are processed by the EPA's AERSURFACE tool using land cover data from the U.S. Geological Survey (USGS) National Land Cover Data archives. AERSURFACE matches the land cover categories to seasonal values of albedo, Bowen ratio, and surface roughness. The data have a spatial resolution of 30 meters, mapped using an Albers Conic Equal Area projection, and based on a 21-category classification scheme.
2. Meteorological data are taken from available data sources (19 stations in 2017). The data are processed using AERMET, a meteorological data preprocessor for AERMOD, following MPCA recommended [procedures](#). AERMET processes commercially available or custom on-site met data and creates two files: a surface data file (SFC) and a profile data file (PFL). Each source is modeled using the met data from either the closest or most representative meteorology station.
3. Source release characterization consisting of source type, source parameters, source location, and surrounding buildings.
4. Spatial coordinates of discrete receptors in meters. Receptors are placed according to the following scheme across the state (see Figure 5):
 - At 3,000 meter spacing across the state
 - At 300 meter spacing in urban areas (population density > 1,000 people/mile)
 - At each Block group centroid (4,111 receptors)
 - An 8 receptor perimeter around point sources in the emission inventory
 - The diameter of the ring is set to coincide with the maximum modeled concentration for each facility
 - At 10 meter intervals along property boundaries for facilities with previous modeling
 - Receptors on property boundaries or within 10 meters of each other are removed

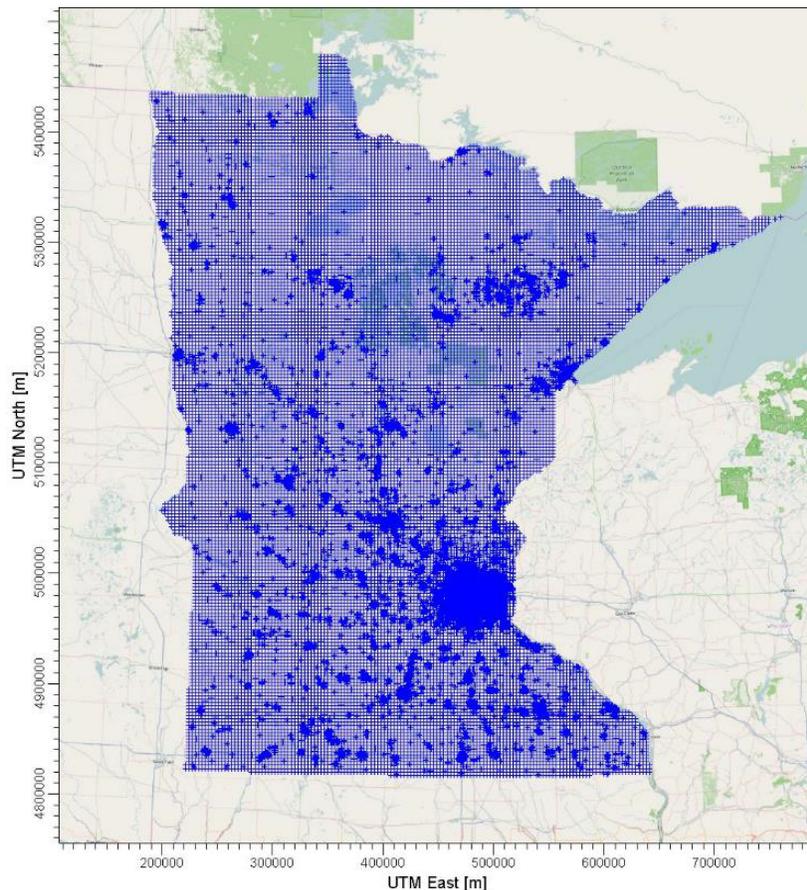


Figure 5. Risk receptors included in *MNRISKS*.

4.2.1 Source types

Sources that can be represented as a stack or vent are modeled in AERMOD as explicit release points with required stack parameters. Other sources are represented as area¹ or volume sources. Nonpoint (area) and mobile source (both onroad and nonroad) emissions are apportioned to Census block groups to improve spatial resolution as described in sections 3.3 and 3.4. The onroad high traffic sources, fugitive releases at permitted facilities, and allocated point sources are represented as model volume sources.

4.2.2 Phase partitioning

Air pollutants may be present in the atmosphere as gases or particles depending upon the chemical and physical properties of the pollutant and upon the atmospheric conditions. Pollutants with high vapor pressures tend to exist mainly or exclusively in the gas phase and are usually emitted from a source in that form. Pollutants with low vapor pressures tend to exist primarily in the particle phase. Pollutants with intermediate vapor pressures may exist in the gas phase, the particle phase, or both—or they may move from one phase to another as conditions, such as temperature, change.

¹Note that there is a distinction between a nonpoint (or area) source in the emissions inventory and a modeled area source. The nonpoint sources in the emissions inventory are described in section 3.3. Model sources are represented as a stack or vent, a volume, or an area. In the case of a model area source, the emissions are distributed evenly within the coordinates defining the area. The emissions from a modeled volume source are represented as a three dimensional volume of specified dimensions and initial dispersion coefficients.

These semi-volatile pollutants are often emitted in the gas phase because temperatures are often high during release. As plumes cool, these pollutants condense on pre-existing particles and become particle bound. This condensation process depends on the amount of surface area available on pre-existing particles. Most of the available surface area on atmospheric particles occurs on small particles in the ultrafine size range (Figure 6). For this reason, particle bound pollutants tend to occur on smaller particles than pollutants originally emitted in the particle phase. The dispersion and deposition of these smaller particles is different from larger particles and are modeled separately. Particle-bound phase modeling is based on surface area weighting, while particle phase modeling is mass weighted.

HHRAP separates air modeling runs in to vapor, particle, and particle-bound phases. The distribution of mass away from the source is very sensitive to the deposition and removal processes of particles. For very small particles (diameter less than 1 micron) and vapor contaminants, the mass distribution is dominated by the dispersive characteristics of the air flow. For larger particles, the added effects of deposition closer to the source, and subsequent removal of the deposited mass at the surface nearer the source, lowers concentrations in the air and downwind deposition rates (EPA 2005).

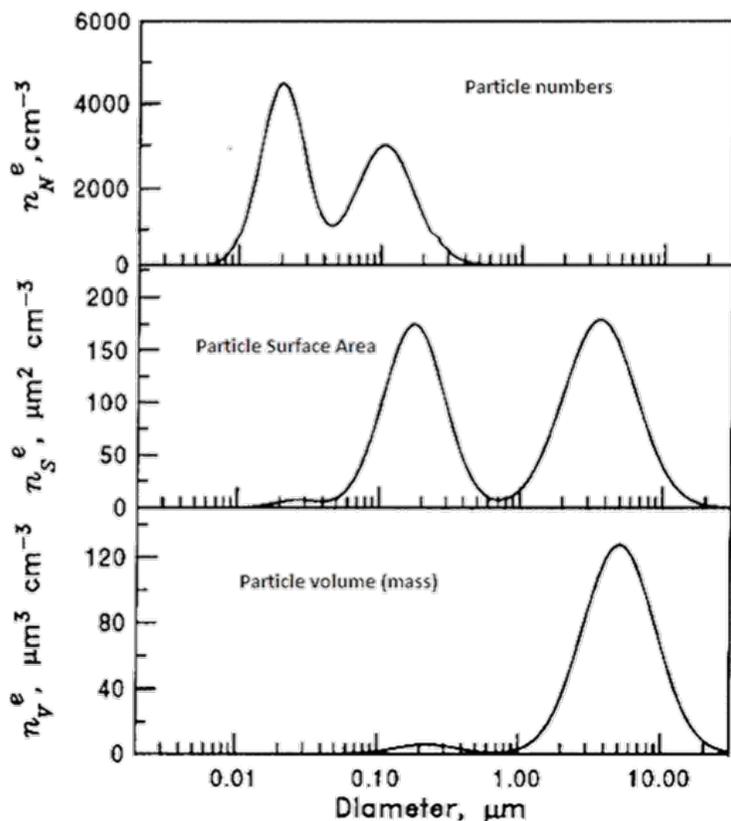


Figure 6. Size distributions of atmospheric particle numbers, surface area, and volume. Volume is approximately equivalent to mass for many particles. (Seinfeld and Pandis 1998)

The tendency of a contaminant to be present in a vapor or particulate phase is expressed as the fraction of the contaminant air concentration in the vapor phase (F_v):

- Vapor Phase $F_v = 1.0$
- Particle-bound Phase $0.05 < F_v < 1.0$
- Particle Phase $F_v \leq 0.05$

The vapor phase is modeled to evaluate volatile organic contaminants that are assumed to occur in the vapor phase as molecules of the contaminant (i.e., contaminants with $F_v = 1.0$). AERMOD outputs for the vapor phase are air concentrations and dry and wet vapor deposition.

The particle-bound phase is modeled to evaluate the fraction of organic contaminants that upon release to the atmosphere condense onto the surface of particulates. AERMOD outputs for the particle-bound phase are air concentration, dry deposition, wet deposition, and total (wet + dry) deposition. The portion of contaminants in the particle-bound phase is dependent on the particulate surface area available for chemical adsorption. Therefore, a surface area weighted particle-size distribution is a required input for the particle-bound phase modeling run.

The particle phase is modeled to evaluate most metals and organic contaminants with low volatility, which are assumed to partition to the particle phase. AERMOD outputs for particle phase runs are air concentration, dry deposition, wet deposition, and total (wet + dry) deposition. Particle size is the main determinant of the dispersion and deposition of airborne particles. For the particle-phase modeling run, deposition is calculated from the particle size and density, and modeled on a mass-weighted basis. Further details can be found in AERMOD and HHRAP guidance documents (EPA 2005).

For sources that are clearly identified as elevated stacks or vents, it is assumed that the potential for particulate to be emitted is high and separate air modeling runs are conducted to represent both particle and particle-bound phases. Fugitive emission sources are assumed to have a low potential for particulate emissions and only a vapor phase run is made. If a fugitive source emits particles, the vapor phase modeling results will tend to under predict the air concentration and deposition near the sources, and over predict the impacts further away from the source.

In cases where measured or reported particle data are not available, the HHRAP recommends that 100% of the particulate mass released be treated as having a diameter of one micrometer. This treatment applies to both the particle and the particle-bound phase air modeling runs. The basis of this assumption is that a particle one micrometer in diameter has nominal terminal velocity, remaining suspended in the air with dispersion behavior similar to vapor phase contaminants, but allowing phase allocation of mass, particle deposition, and removal by the model. A sensitivity study conducted by EPA Region 6 (EPA 2003) identified that air modeling is not sensitive to this assumption unless the actual particle density is greater than 2 g/cm^3 .

4.2.3 AERMOD input files

An AERMOD input file is structured into five sections:

- Control pathway
- Source pathway
- Receptor pathway
- Meteorological pathway
- Output pathway

The following subsections describe the specific parameter values input to each pathway for execution of the AERMOD modeling runs for risk assessment.

The **Control** pathway directs AERMOD to perform specific types of computations. Some key inputs are as:

- Model options: Regulatory default options, concentrations, depositions, removal processes, and urban land use
- Averaging times: one hour and annual

- Terrain elevation: Flat
- Wet and dry deposition
- Plume depletion

The **Source** pathway in the AERMOD input file allows input of source type, locational data, building dimensions, and gas and particle characteristics.

The **Receptor** pathway in the AERMOD input file identifies the locational coordinates of receptor grid nodes and elevation above mean sea level. These data are used by AERMOD as the locations to compute estimates of air concentrations and dry and wet deposition rates. All receptors within 50 km of a point source and within 20 km of an area or volume source are included in the air dispersion modeling.

4.3 Unit emissions method

The unit emissions method relies on the fact that for an individual source the air concentration levels and deposition fluxes vary linearly with the source emission rate. In other words, increasing emissions from the source by 10 times will increase the concentration at the receptor by 10 times. The reason for using this method is to reduce air dispersion modeling processing time. A unit emission is defined as an emission rate of 1 gram/second. If a source is modeled with unit emissions, then the concentrations and deposition of each individual pollutant emitted by the source can be obtained by multiplying the unit emission results by the actual emission rate for each pollutant. Therefore, for sources emitting multiple pollutants, one single air dispersion modeling run will suffice, and risk evaluations can be conducted without requiring additional runs of the air dispersion model.

The one case when this method does not apply is when dry vapor deposition is a significant contributing factor to pollutant concentrations. Calculating dry vapor deposition velocity requires compound-specific air modeling runs rather than the unit emission rate approach. However, dry vapor deposition modeling requires additional pollutant-specific data to implement, and this information is currently limited to only a few dozen pollutants. As more research to measure deposition velocities of more organic compounds under a variety of conditions becomes available, it may be appropriate in the future to develop site- and chemical-specific default vapor dry deposition velocities.

Execution of AERMOD results in unitized annual average and maximum one-hour average air concentration and deposition rates for the vapor, particle, and particle-bound phases. These results are modeled for each emission source at every receptor within a 20/50 km radius. These unitized values are stored in a database and used as inputs in the risk modeling component in which media-specific concentrations and deposition of each contaminant are calculated.

4.4 Secondary formation of reactive contaminants

Some pollutants (e.g., formaldehyde, PM_{2.5}) may be formed in the atmosphere from precursor emissions. These “secondary” pollutants are part of smog or regional haze that may be transported hundreds of kilometers while undergoing chemical and photochemical reactions. The AERMOD model is not capable of simulating these processes. For that reason, secondarily formed concentrations of four pollutants are imported into the *MNRISKS* database from regional modeling performed by EPA. Secondarily formed formaldehyde, acetaldehyde, and acrolein are obtained from the EPA as part of the NATA program which uses a modified version of the CMAQ regional model (Community Multi-Scale Air Quality Model). These secondary organic pollutants are added to the concentrations estimated from primary emissions before risks are evaluated using the total concentrations.

Secondarily formed PM_{2.5} is provided by EPA regional modeling performed with the Comprehensive Air Quality Model with extensions (CAMx) model. Note that criteria pollutants without inhalation health benchmarks, including PM_{2.5} and PM₁₀, are not included in the calculation of risks. These pollutants are included for evaluating air concentrations and model performance.

4.5 Air dispersion modeling uncertainties

Minnesota is a suitable location for plume models like AERMOD. Its fairly uniform topography (flat) and the lack of extensive coastal zones (with the exception of the NE region) provide conditions where these models perform at their best. The EPA indicates (40 CFR 51 Appendix W) that when input data are well known the model accuracy of Lagrangian plume models like AERMOD is on the order of a factor of two. Plume models can provide statistically similar values when compared against measurements, but the precise location and time of impacts may not coincide. Gaussian plume models do not predict an event matched in a given space and time, rather the model results represent the ensemble of events that could occur under a given set of meteorological conditions.

4.6 Model-monitor comparisons

A Model-Monitor comparison is completed for each new version of *MNRISKS*. This comparison is produced in the form of data visualizations including model bias maps, and statistical summaries including: Kendall’s tau correlation coefficient, Mean Bias, Fraction within a factor of two, Pearson correlation coefficient, Root Mean Square Error, Fractional Bias, Mean Gross Error, Normalized Mean Gross Error, Coefficient of Efficiency, and Index of Agreement.

One of the simplest summaries is the number of model-monitor pairs that are within a factor of two. Table 3 provides a summary of *MNRISKS* air concentrations compared to annual mean monitor concentrations. The columns show a count of how many comparisons were within a factor of two, overestimated by more than a factor of, or underestimated by less than half. The higher proportion of receptor-monitor pairs within a factor of two, the better the model performance. An online [Tableau Tool](#) visualizes the model-monitor comparisons. Further details of the statistical analysis are [online](#).

Table 3. Summary statistics for the comparison of 2011 *MNRISKS* modeled concentrations with measurements.

| Pollutant | Under Estimate | Within a Factor of 2 | Over Estimate |
|------------------------|----------------|----------------------|---------------|
| 1,2,4-Trimethylbenzene | 6 | | 1 |
| 1,3-Butadiene | 1 | 7 | 2 |
| 2-Methylnaphthalene | 3 | | |
| Acenaphthene | 1 | 1 | 1 |
| Acenaphthylene | 1 | | 2 |
| Acetaldehyde | | 10 | |
| Acetone | 10 | | |
| Anthracene | 1 | | 2 |
| Barium | 7 | | |
| Benz[a]anthracene | 1 | | 2 |
| Benzene | | 5 | 5 |
| Benzo[a]pyrene | 1 | | 2 |
| Benzo[b]fluoranthene | 1 | | 2 |
| Benzo[e]pyrene | 1 | 1 | 1 |

| Pollutant | Under Estimate | Within a Factor of 2 | Over Estimate |
|------------------------|----------------|----------------------|---------------|
| Benzo[g,h,i]perylene | 1 | | 2 |
| Benzo[j]fluoranthene | 2 | | |
| Benzo[k]fluoranthene | 1 | | 2 |
| Carbon Disulfide | 6 | | |
| Carbon Tetrachloride | | 10 | |
| Carbon Monoxide | | | 1 |
| Chloroform | 5 | 4 | |
| Chloromethane | | 10 | |
| Chromium | 1 | | |
| Chrysene | 1 | | 2 |
| Cobalt | 1 | | |
| Cyclohexane | 9 | 1 | |
| Dibenz[a,h]anthracene | 1 | | 2 |
| Dibenzo[a,e]pyrene | 2 | | |
| Dibenzo[a,i]pyrene | | 2 | |
| Dichloromethane | 10 | | |
| Ethylbenzene | | | 2 |
| Fluoranthene | 1 | | 2 |
| Fluorene | 1 | | 2 |
| Formaldehyde | | 10 | |
| Indeno[1,2,3-cd]pyrene | 1 | | 2 |
| Lead | 1 | 4 | 2 |
| M/P Xylene | | | 7 |
| Manganese | 3 | 4 | 1 |
| Methyl Ethyl Ketone | 6 | 4 | |
| Naphthalene | 1 | | 2 |
| N-Hexane | | 2 | 8 |
| Nickel | 1 | | |
| Nitrogen Dioxide | | | 1 |
| Phenanthrene | 1 | 1 | 1 |
| PM10 | 1 | 3 | 1 |
| PM2.5 | | 8 | 4 |
| SulfurDioxide | | 1 | 2 |
| Tetrachloroethylene | 2 | | |
| Toluene | | | 10 |
| Trichloroethylene | 1 | 3 | 1 |
| Vinyl Acetate | 10 | | |
| Zinc | 6 | 2 | |

5. Media concentrations

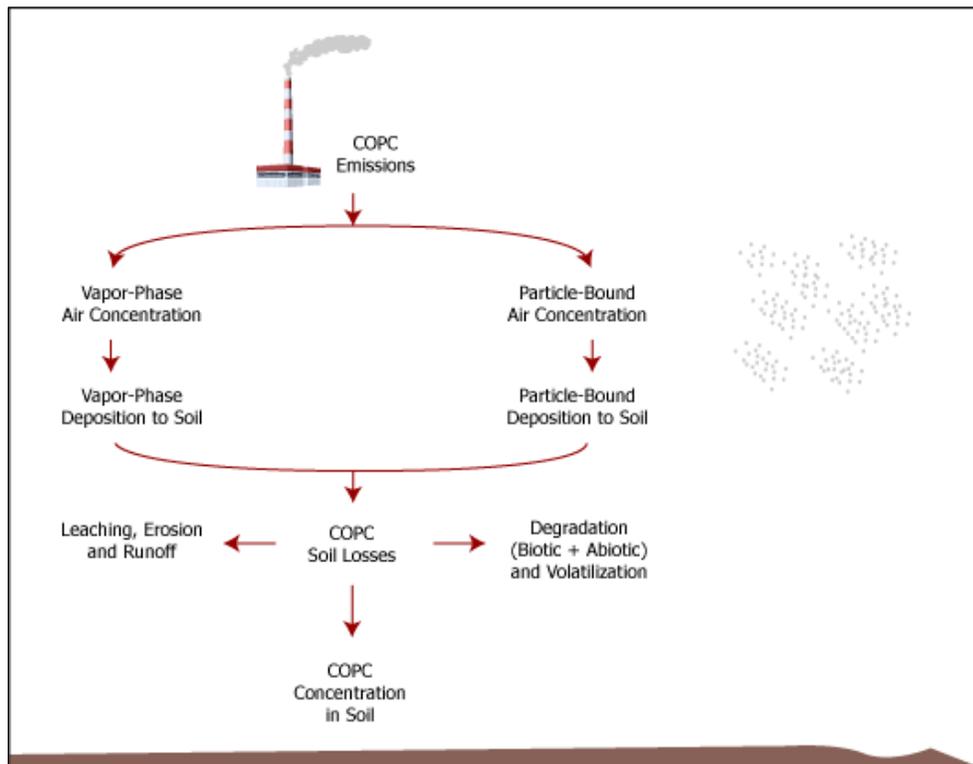


Figure 7. Air emissions pathways to soil. (EPA 2005)

The equations and mechanisms for estimating media concentrations are described in the HHRAP, Chapter 5 - *Estimating Media Concentrations* and is paraphrased below. The HHRAP recommended default values for each parameter are used unless otherwise noted.

The starting point for estimating media concentrations is the unitized AERMOD outputs of air concentrations and deposition. The first step is to select the appropriate model runs (vapor, particle, or particle-bound phase) to use for each pollutant. This depends on the pollutant-specific fraction in the vapor phase, F_v , as described in Section 4.3.

5.1 Air concentrations for direct inhalation

Total air concentrations are calculated by summing the vapor phase and particle phase concentrations. Air concentrations used in the evaluation of chronic exposure, via direct inhalation, are calculated using unitized yearly air parameters. Maximum one-hour average concentrations are calculated for comparison with acute health benchmarks.

5.2 Soil concentrations

Pollutant concentrations in soil are calculated by summing the vapor and particle phase deposition to the soil as described in Section 5.2 of HHRAP. In addition to the pollutant deposition to soil, the calculation of soil concentration accounts for pollutant loss via five mechanisms (shown in Fig. 7):

1. Leaching

2. Erosion
3. Runoff
4. Biotic and abiotic degradation of pollutant
5. Volatilization

The EPA recommends the following equations to calculate the cumulative soil concentration (C_s).

Carcinogens:

For $T_2 < tD$

$$C_s = \frac{D_s}{k_s \cdot (tD - T_1)} \cdot \left[\left(tD + \frac{\exp(-k_s \cdot tD)}{k_s} \right) - \left(T_1 + \frac{\exp(-k_s \cdot T_1)}{k_s} \right) \right]$$

For $T_1 < tD < T_2$

$$C_s = \frac{\left(\frac{D_s \cdot tD - C_{s,tD}}{k_s} \right) + \left(\frac{C_{s,tD}}{k_s} \right) \cdot (1 - \exp[-k_s \cdot (T_2 - tD)])}{(T_2 - T_1)}$$

where

| | | |
|------------|---|---|
| C_s | = | Average soil concentration over exposure duration (mg pollutant/kg soil) |
| D_s | = | Deposition term (mg pollutant/kg soil/yr) |
| T_1 | = | Time period at the beginning of combustion (yr) |
| k_s | = | Pollutant soil loss constant due to all processes (yr^{-1}) |
| tD | = | Time period over which deposition occurs (time period of combustion) (yr) |
| $C_{s,tD}$ | = | Soil concentration at time tD (mg/kg) |
| T_2 | = | Length of exposure duration (yr) |

The equations used to calculate the average soil concentration over the period of deposition are derived by integrating the instantaneous soil concentration equation over a default deposition time period of 30 years. The pollutant soil concentration (C_s) is then averaged over the lifetime of an individual for carcinogenic compounds. Hazard quotients are not averaged over a lifetime exposure duration. The highest annual average pollutant soil concentration occurring during the exposure duration period is used for non-carcinogenic pollutants to calculate hazard quotients.

The deposition term in the cumulative soil concentration (C_s) equation is expressed in two forms, one for mercury and one for all other chemicals.

The equation for pollutants other than mercury is:

$$D_s = \frac{100 \cdot Q}{Z_s \cdot BD} \cdot \left[F_v(Dy_{dv} + Dy_{wv}) + (1 - F_v)(Dy_{dp} + Dy_{wp}) \right]$$

The equation for the mercury deposition term in the cumulative soil concentration is:

$$D_s = \frac{100 \cdot 0.48Q_{(Total)}}{Z_s \cdot BD} \cdot \left[F_{v(HG^{++})}(Dy_{dv} + Dy_{wv}) + (1 - F_{v(HG^{++})})(Dy_{dp} + Dy_{wp}) \right]$$

The values $0.48Q$ for total mercury and $F_v = 0.85$ are used in the mercury modeling equation to calculate D_s . The calculated D_s value is then apportioned into the divalent mercury (Hg^{++}) and methyl mercury (MHg) forms based on the assumed 98% Hg^{++} and 2% MHg speciation split in soils. Elemental mercury (Hg^0) occurs in very small amounts in the vapor phase and does not exist in the particle or particle-bound phase. Therefore, elemental mercury deposition onto soils is assumed to be negligible or zero. It is recommended that elemental mercury be evaluated for the direct inhalation pathway only.

$$D_s (Hg^{++}) = 0.98 D_s (\text{Mercury})$$

$$D_s (\text{MHG}) = 0.02 D_s (\text{Mercury})$$

$$D_s (Hg^0) = 0.0$$

Divalent and methyl mercury are evaluated as individual pollutants. The C_s term is calculated for divalent and methyl mercury using the corresponding fate and transport parameters for mercuric chloride (divalent mercury, Hg^{2+}) and methyl mercury.

The soil loss constant (k_s) is determined using the following equations:

$$k_s = k_{sg} + k_{se} + k_{sr} + k_{sl} + k_{sv}$$

where

$$k_s = \text{Loss constant due to all processes (yr}^{-1}\text{)}$$

$$k_{sg} = \text{Loss constant due to biotic and abiotic degradation (yr}^{-1}\text{)}$$

$$k_{se} = \text{Loss constant due to soil erosion (yr}^{-1}\text{)}$$

$$k_{sr} = \text{Loss constant due to surface runoff (yr}^{-1}\text{)}$$

$$k_{sl} = \text{Loss constant due to leaching (yr}^{-1}\text{)}$$

$$k_{sv} = \text{Loss constant due to volatilization (yr}^{-1}\text{)}$$

The rate of biological degradation (k_{sg}) is pollutant-specific, depending on the complexity of the pollutant and the usefulness of the pollutant to microorganisms. The k_{sg} values used in this equation are the defaults recommended by HHRAP.

The following equation calculates the constant for the loss of soil resulting from surface runoff (k_{sr}) based on default values recommended in HHRAP.

$$k_{sr} = \frac{RO}{\theta_{sw} \cdot Z_s} \cdot \left(\frac{1}{1 + (Kd_s \cdot BD / \theta_{sw})} \right)$$

where

$$k_{sr} = \text{Pollutant loss constant due to runoff (yr}^{-1}\text{)}$$

$$RO = \text{Average annual surface runoff from pervious areas (cm/yr)}$$

$$\theta_{sw} = \text{Soil volumetric water content (mL water/cm}^3\text{ soil)}$$

$$Z_s = \text{Soil mixing zone depth (cm)}$$

$$Kd_s = \text{Soil-water partition coefficient (mL water/g soil)}$$

$$BD = \text{Soil bulk density (g soil/cm}^3\text{ soil)}$$

Soil losses due to leaching (k_{sl}) depend on the amount of water available to generate leachate and soil properties such as bulk density, soil moisture, soil porosity, and soil sorption properties. The following equation calculates a pollutant's soil loss constant due to leaching (k_{sl}).

$$k_{sl} = \frac{P + I - RO - E_v}{\theta_{sw} \cdot Z_s \cdot [1.0 + (BD \cdot Kd_s / \theta_{sw})]}$$

where

| | | |
|---------------|---|--|
| k_{sl} | = | Pollutant loss constant due to leaching (yr^{-1}) |
| P | = | Average annual precipitation (cm/yr) |
| I | = | Average annual irrigation (cm/yr) |
| RO | = | Average annual surface runoff from pervious areas (cm/yr) |
| E_v | = | Average annual evapotranspiration (cm/yr) |
| θ_{sw} | = | Soil volumetric water content (mL water/cm^3 soil) |
| Z_s | = | Soil mixing zone depth (cm) |
| Kd_s | = | Soil-water partition coefficient (cm^3 water/g soil) |
| BD | = | Soil bulk density (g soil/cm^3 soil) |

Semi-volatile and volatile pollutants emitted in high concentrations may become adsorbed to soil particles and exhibit volatilization losses from soil. The following equation computes the loss constant due to volatilization.

$$k_{sv} = \left(\frac{3.1536 \times 10^7 \cdot H}{Z_s \cdot Kd_s \cdot R \cdot T_a \cdot BD} \right) \cdot \left(\frac{D_a}{Z_s} \right) \cdot \left[1 - \left(\frac{BD}{\rho_{soil}} \right) \cdot \theta_{sw} \right]$$

where

| | | |
|----------------------|---|---|
| k_{sv} | = | Pollutant loss constant due to volatilization (yr^{-1}) |
| 3.1536×10^7 | = | Units conversion factor (s/yr) |
| H | = | Henry's Law constant ($\text{atm-m}^3/\text{mol}$) |
| Z_s | = | Soil mixing zone depth (cm) |
| Kd_s | = | Soil-water partition coefficient (mL/g) |
| R | = | Universal gas constant ($\text{atm-m}^3/\text{mol-K}$) |
| T_a | = | Ambient air temperature (K) = 298.1 K |
| BD | = | Soil bulk density (g soil/cm^3 soil) = 1.5 g/cm^3 |
| D_a | = | Diffusivity of pollutant in air (cm^2/s) |
| θ_{sw} | = | Soil volumetric water content (mL/cm^3 soil) = 0.2 mL/cm^3 |
| ρ_{soil} | = | Solids particle density (g/cm^3) = 2.7 g/cm^3 |

The universal soil loss equation (USLE) is used to calculate the unit soil loss (X_e). Default values from Appendix B of HHRAP are used in *MNRISKS* calculations of cumulative soil concentration. Calculating average soil concentration over the exposure duration (C_s) requires the use the following parameters:

1. Soil mixing zone depth (Z_s)
2. Soil bulk density (BD)
3. Available water ($P + I - RO - E_v$)
4. Soil volumetric water content (θ_{sw})

The default soil mixing zone depths (Z_s) in HHRAP are 2 cm for untilled soil and 20 cm for tilled soil. Soil dry bulk density (BD) is the ratio of the mass of soil to its total volume. The HHRAP recommended value of 1.5 g/cm^3 is used in *MNRISKS*.

The average annual volume of water available ($P + I - RO - E_v$) for generating leachate is the mass balance of all water inputs and outputs from the area under consideration. The average annual precipitation (P), irrigation (I), runoff (RO), and evapotranspiration (E_v) rates and other climatological data are obtained from the meteorological stations described in section 4.2 of this document.

The soil volumetric water content (θ_{sw}) depends on the available water and the soil structure. The recommended value of 0.2 ml/cm^3 is used in *MNRISKS*.

Based on EPA recommendations, the constant for the loss of soil resulting from erosion (k_{se}) is set equal to zero. This recommendation is based on the assumption that contaminated soil is eroding onto the specific receptor location at the same rate that soil is eroding off of it.

The soil bioavailability factor, B_s , is defined as the ratio between a pollutant's bioconcentration factors for soil and vegetation. For *MNRISKS* calculations, B_s is taken as 1.0.

5.3 Produce and vegetable concentrations

The calculations used to estimate concentrations of pollutants in produce are described in Chapter 5, section 5.3 of the HHRAP. The concentration of pollutants in plant material is necessary for two reasons: 1) humans may directly consume vegetables and fruits that are harvested from gardens located in the area impacted by air toxics, and 2) animals (e.g. cattle, chickens) may consume forage, silage, and grain grown in the area impacted by air toxics, and these animals are then consumed by humans. Because of general differences in produce contamination mechanisms, consideration of indirect exposure separates produce into two broad categories, aboveground produce and plant material, and belowground produce. In addition, aboveground produce is further subdivided into exposed and protected aboveground produce for consideration of contamination as a result of indirect exposure. Contamination of below ground produce is assumed to occur only through root uptake.

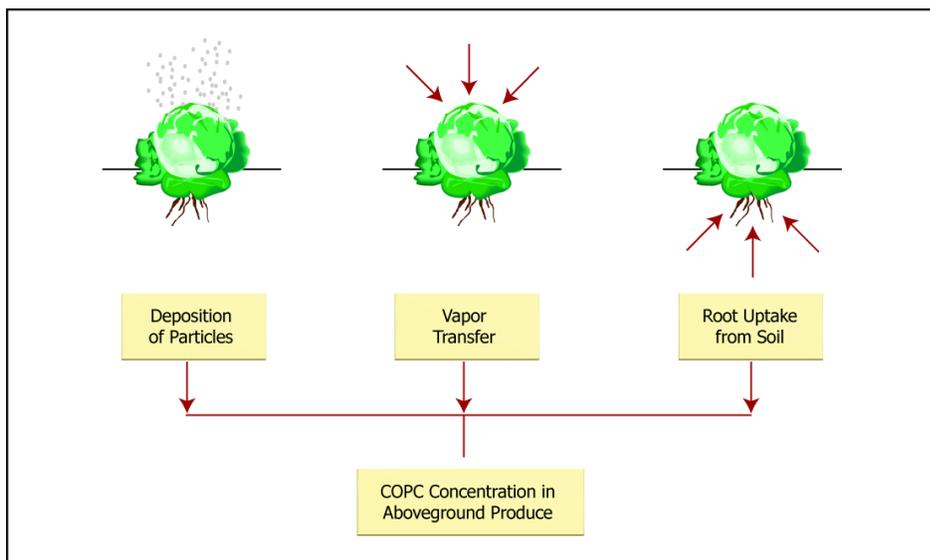


Figure 8. Above ground produce exposure pathways. (EPA 2005)

The total pollutant concentration in aboveground exposed produce is calculated as a sum of contamination occurring through all three of these mechanisms as illustrated in Figure 8. However, edible portions of aboveground produce (e.g., peas, corn) are protected by a covering; hence, they are protected from contamination through deposition and vapor transfer. Therefore, root uptake of

pollutants is the primary mechanism through which aboveground protected vegetation becomes contaminated.

Pollutant concentrations in aboveground vegetation resulting from wet and dry deposition onto plant surfaces of leafy plants and exposed produce (Pd) are calculated as:

$$Pd = \frac{1,000 \cdot Q \cdot (1 - F_v) \cdot [Dydp + (F_w \cdot Dywp)] \cdot Rp \cdot [1.0 - \exp(-kp \cdot Tp)]}{Yp \cdot kp}$$

where

- Pd = Plant (aboveground produce) concentration due to direct (wet and dry) deposition (mg pollutant/kg DW)
- 1,000 = Units conversion factor (mg/g)
- Q = Pollutant emission rate (g/s)
- F_v = Fraction of pollutant air concentration in vapor phase (unitless)
- $Dydp$ = Unitized yearly average dry deposition from particle phase (s/m²-yr)
- F_w = Fraction of pollutant wet deposition that adheres to plant surfaces (unitless)
- $Dywp$ = Unitized yearly wet deposition from particle phase (s/m²-yr)
- Rp = Interception fraction of the edible portion of plant (unitless)
- kp = Plant surface loss coefficient (yr⁻¹)
- Tp = Length of plant exposure to deposition per harvest of the edible portion of the i th plant group (yr)
- Yp = Yield or standing crop biomass of the edible portion of the plant (productivity) (kg DW/m²)

The default value of Rp is based on a weighted average of class-specific values. The produce classes are combined into two groups, exposed fruit and exposed vegetables. The exposed produce empirical constant (γ) is used to calculate Rp for leafy and fruiting vegetables. The exposed vegetable Rp is then determined by a weighted average based on productivity (Yp) of leafy and fruiting vegetables, respectively. The relative ingestion rates used to determine an average weighted Rp value are derived from the intake of homegrown produce discussion presented in the 1997 *Exposure Factors Handbook* (EPA 1997). The recommended Rp value is 0.39.

Unweighted Rp and ingestion rates used for the weighting are:

| Aboveground Produce Class | Rp | Ingestion Rate (g DW/kg-day) |
|---------------------------|-------|------------------------------|
| Exposed fruits | 0.053 | 0.19 |
| Exposed vegetables | 0.982 | 0.11 |

The interception fractions for forage (0.5) and silage (0.46) are computed in a manner similar to produce.

Tp is treated as a constant for forage (0.12 yr) and silage (0.16 yr), based on the average period between successive harvests. The average period between hay harvests is assumed to be 60 days, and the average period between successive grazing is assumed to be 30 days. The average of 60 days and 30 days (i.e., 45 days) is assumed for foraging.

$$Tp = \frac{\text{days_between_harvests}}{365 \text{ days/yr}}$$

The HHRAP recommended value for standing crop biomass (Y_p) of 2.24 is used in *MNRISKS*.

The HHRAP recommended value for the plant surface loss coefficient (k_p) of 18 is used in *MNRISKS*.

Unweighted Y_p and ingestion rates used for the weighting are:

| Aboveground Produce Class | Y_p | Ingestion Rate (g DW/kg-day) |
|---------------------------|-------|------------------------------|
| Exposed fruits | 0.25 | 0.19 |
| Exposed vegetables | 5.66 | 0.11 |

For forage and silage, Y_p is calculated as a weighted average of the calculated pasture grass and hay Y_p values. Weightings are based on the fraction of a year that cattle are assumed to be pastured and eating grass (nine months per year) or not pastured and fed hay (three months per year). An unweighted pasture grass Y_p of 0.15 kg DW/m² is assumed. An unweighted hay Y_p of 0.5 kg DW/m² is adopted by the EPA. The unweighted pasture grass and hay Y_p values are multiplied by their weighting factors (0.75 and 0.25, respectively), and then added to calculate the weighted forage Y_p of 0.24 kg DW/m².

| Standing Crop Biomass (Productivity) (Y_p) |
|--|
| Forage = 0.24 kg DW/m ² |
| Silage = 0.8 kg DW/m ² |

The methodology used to estimate pollutant concentrations in aboveground produce due to air-to-plant transfer (P_v) considers a pollutant's resistance to moving from a plant's surface to the inner portions of the plant. This equation is used to calculate aboveground produce concentration due to air-to-plant transfer (P_v).

$$P_v = Q \cdot F_v \cdot \frac{C_{yv} \cdot B_{vag} \cdot VG_{ag}}{\rho_a}$$

where

- P_v = Concentration of pollutant in the plant resulting from air-to-plant transfer (µg pollutant/g DW)
- Q = Pollutant emission rate (g/s)
- F_v = Fraction of pollutant air concentration in vapor phase (unitless)
- C_{yv} = Unitized yearly average air concentration from vapor phase (µg-s/g-m³)
- B_{vag} = Pollutant air-to-plant biotransfer factor ([mg pollutant/g DW plant]/[mg pollutant/g air]) (unitless)
- VG_{ag} = Empirical correction factor for aboveground produce (unitless)
- ρ_a = Density of air (g/m³)

The parameter VG_{ag} is dependent on lipophilicity of the pollutant, and assigned a value of 0.001 for lipophilic pollutants (log K_{ow} greater than 4) or a value of 1.0 for pollutants with a log K_{ow} less than 4.

An empirical correction factor (*VG*) for lipophilic pollutants is incorporated to reduce estimated pollutant concentrations in vegetables. The empirical correction factors for above- and below-ground vegetables are:

Empirical Correction Factor for Belowground Produce (*VG_{rootveg}*)

$$VG_{rootveg} = \frac{M_{skin}}{M_{vegetable}}$$

where

- VG_{rootveg}* = Correction factor for belowground produce (g/g)
- M_{skin}* = Mass of a thin (skin) layer of belowground vegetable (g)
- M_{vegetable}* = Mass of the entire vegetable (g)

Empirical Correction Factor for Aboveground Produce (*VG_{ag}*)

- 0.01 for pollutants with a log *K_{ow}* greater than 4
- 1.0 for pollutants with a log *K_{ow}* less than 4

Empirical Correction Factor for Forage and Silage (*VG_{ag}*)

- Forage = 1
 - Silage = 0.5
-

The following equations are used to calculate root uptake of contaminants from soil for above ground and below ground produce due to root uptake (*Pr*).

Produce Concentration Due to Root Uptake (*Pr*)

Exposed and protected aboveground produce:

$$Pr = Cs \cdot Br$$

Belowground produce:

$$Pr = \frac{Cs \cdot RCF \cdot VG_{rootveg}}{Kd_s \cdot I \text{ kg/L}}$$

where

- Pr* = Concentration of pollutant in produce due to root uptake (mg/kg)
- Br* = Plant-soil bioconcentration factor for produce (unitless)
- VG_{rootveg}* = Empirical correction factor for belowground produce (unitless)
- Kd_s* = Soil-water partition coefficient (L/kg)
- Cs* = Average soil concentration over exposure duration (mg pollutant/kg soil)
- RCF* = Root concentration factor (unitless)

Empirical Correction Factor for Belowground Produce (*VG_{rootveg}*)

- 0.01 for pollutants with a log *K_{ow}* greater than 4
 - 1.0 for pollutants with a log *K_{ow}* less than 4
-

5.4 Beef and dairy product concentrations

The calculations used to estimate concentrations of pollutants in beef and dairy products are described in Chapter 5, Section 5.4 of the HHRAP. Cattle are assumed to consume forage, silage and grain that are contaminated with pollutants.

The following equation calculates pollutant concentrations in beef tissue (A_{beef}).

$$A_{beef} = \left(\sum (F_i \cdot Qp_i \cdot P_i) + Qs \cdot Cs \cdot Bs \right) \cdot Ba_{beef} \cdot MF$$

where

- A_{beef} = Concentration of pollutant in beef (mg pollutant/kg FW tissue)
- F_i = Fraction of plant type i grown on contaminated soil and ingested by the animal (cattle) (unitless)
- Qp_i = Quantity of plant type i eaten by the animal (cattle) per day (kg DW plant/day)
- P_i = Concentration of pollutant in each plant type i eaten by the animal (cattle) (mg/kg DW)
- Qs = Quantity of soil eaten by the animal (cattle) each day (kg/day)
- Cs = Average soil concentration over exposure duration (mg pollutant/kg soil)
- Bs = Soil bioavailability factor (unitless)
- Ba_{beef} = Pollutant biotransfer factor for beef (day/kg FW tissue)
- MF = Metabolism factor (unitless)

One hundred percent of the plant material eaten by cattle are assumed to have been grown on soil contaminated by the emission sources being evaluated, so F_i is taken as 1.0.

The daily quantity of plants eaten by cattle are estimated (kg DW/day) for forage, silage, and grain feeds are included in this estimate.

The following beef cattle ingestion rates for forage, silage, and grains are based on the total daily intake rate of about 12 kg DW/day.

Quantity of Plant Type i Eaten by the Animal (Cattle) Each Day (Qp_i)

Forage = 8.8 kg DW/day Beef; 13.2 kg DW/day Dairy
 Silage = 2.5 kg DW/day, 4.1 kg DW/day Dairy
 Grain = 0.47 kg DW/day, 3.0 kg DW/day Dairy

The following equation calculates pollutant concentration in forage, silage, and grain.

Concentration of pollutant in Plant Type i Eaten by the Animal (Cattle) (P_i)

$$P_i = \sum_i (Pd + Pv + Pr)$$

where

- P_i = Concentration of pollutant in each plant type i eaten by the animal (mg pollutant/kg DW)
- Pd = Plant concentration due to direct deposition (mg pollutant/kg DW)
- Pv = Plant concentration due to air-to-plant transfer (mg pollutant/kg DW)
- Pr = Plant concentration due to root uptake (mg pollutant/kg DW)

Additional cattle contamination occurs through ingestion of soil.

Quantity of Soil Ingested by the Animal (Cattle) Per Day (Qs)

0.5 kg/day – Beef Cattle
 0.4 kg/day – Dairy Cattle

The equation for concentrations in beef cattle (A_{beef}) can be modified to calculate pollutant milk concentrations (A_{milk}):

$$A_{milk} = \left(\sum (F_i \cdot Qp_i \cdot P_i) + Qs \cdot Cs \cdot Bs \right) \cdot Ba_{milk} \cdot MF$$

where

- A_{milk} = Concentration of pollutant in milk (mg pollutant/kg milk)
- F_i = Fraction of plant type i grown on contaminated soil and ingested by the animal (dairy cattle) (unitless)
- Qp_i = Quantity of plant type i eaten by the animal (dairy cattle) each day (kg DW plant/day)
- P_i = Concentration of pollutant in plant type i eaten by the animal (dairy cattle) (mg/kg DW)
- Qs = Quantity of soil eaten by the animal (dairy cattle) each day (kg soil/day)
- Cs = Average soil concentration over exposure duration (mg pollutant/kg soil)
- Bs = Soil bioavailability factor (unitless)
- Ba_{milk} = Pollutant biotransfer factor for milk (day/kg WW tissue)
- MF = Metabolism factor (unitless)

5.5 Pork concentrations

The calculations for pollutant concentrations in pork are described in Chapter 5, Section 5.5 of the HHRAP. Pollutant concentrations in pork tissue are estimated on the basis of the amount of pollutants that swine are assumed to consume through their diet of silage and grain. Additional pollutant contamination of pork tissue may occur through the ingestion of soil by swine.

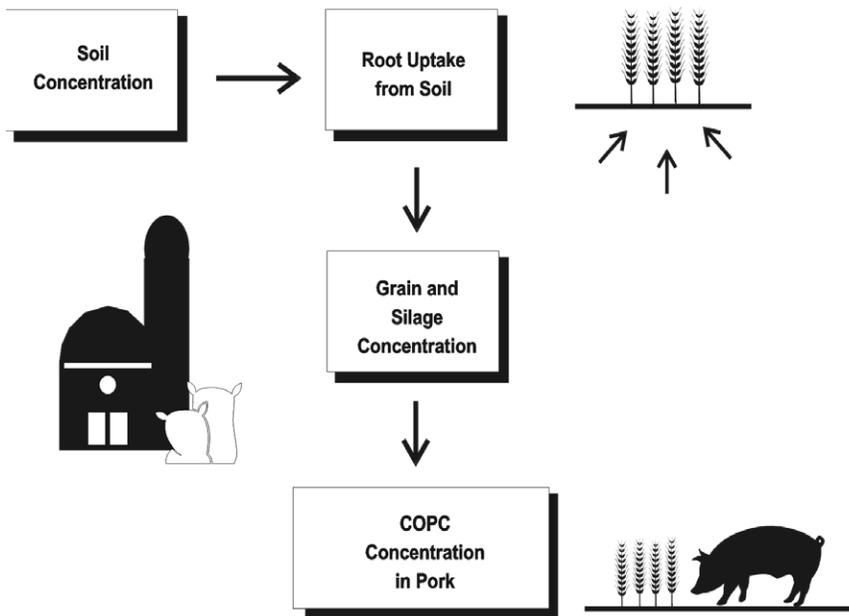


Figure 9. Pork consumption pathway (EPA 2005).

The following equation calculates pollutant concentrations in swine (A_{pork}).

$$A_{pork} = \left(\sum (F_i \cdot Qp_i \cdot P_i) + Qs \cdot Cs \cdot Bs \right) \cdot Ba_{pork} \cdot MF$$

where

| | | |
|-------------|---|--|
| A_{pork} | = | Concentration of pollutant in pork (mg pollutant/kg FW tissue) |
| F_i | = | Fraction of plant type i grown on contaminated soil and ingested by the animal (swine)(unitless) |
| Qp_i | = | Quantity of plant type i eaten by the animal (swine) each day (kg DW plant/day) |
| P_i | = | Concentration of pollutant in plant type i eaten by the animal (swine) (mg/kg DW) |
| Qs | = | Quantity of soil eaten by the animal (swine) (kg/day) |
| Cs | = | Average soil concentration over exposure duration (mg pollutant/kg soil) |
| Bs | = | Soil bioavailability factor (unitless) |
| Ba_{pork} | = | Pollutant biotransfer factor for pork (day/kg FW tissue) |
| MF | = | Metabolism factor (unitless) |

Because swine are not grazing animals, they are assumed not to eat forage. The daily quantity of plant feeds (kilograms of DW) consumed by swine is estimated for each category of plant feed.

Quantity of Plant Type i Eaten by the Animal (Swine) Each Day (Qp_i)

Grain = 3.3 kg DW/day

Silage = 1.4 kg DW/day

- The calculation of P_i for pork is identical to that for beef cattle.
- Additional contamination of swine from soil ingestion (Qs) is taken as 0.37 kg DW/day.
- The calculation of Cs for pork is the same as for beef cattle.
- The calculation of Bs for pork is the same as for beef cattle.
- The recommended values for MF are identical to those recommended for beef cattle.
- The calculation of F_i for pork is identical to that for beef cattle.

5.6 Chicken and egg concentrations

Estimates of the pollutant concentrations in chicken and eggs are based on the amount of pollutants that chickens consume through ingestion of grain and soil. The uptake of pollutants via inhalation and via ingestion of water is assumed to be insignificant. Chickens are assumed to be free-range animals that have contact with soil; and therefore, are assumed to consume part of their diet as soil. The remainder of the diet is assumed to consist of grain. Grain ingested by chickens is assumed to have originated from the exposure scenario location; therefore, 100% of the grain consumed is assumed to be contaminated.

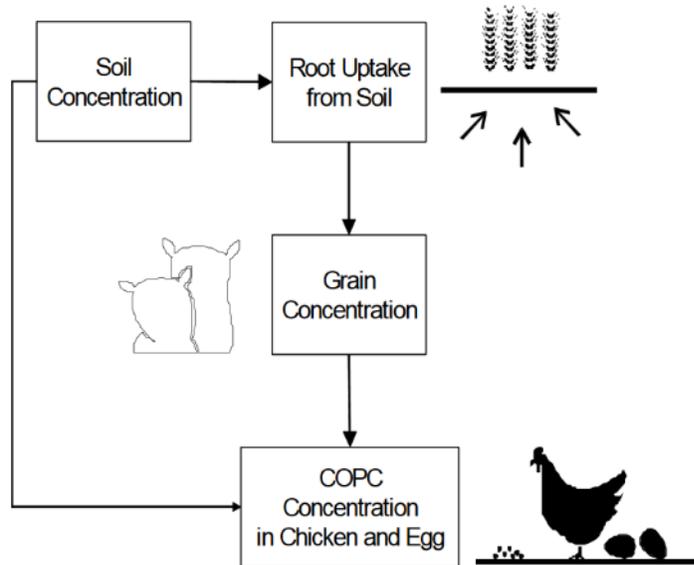


Figure 10. Chicken and egg exposure pathways (EPA 2005).

Grain is considered to be a feed item that is protected from deposition of particles and vapor transfer. As a result, only contamination due to root uptake of pollutants is considered in the calculation of pollutant concentration in grain.

The following equation calculates pollutant concentrations in chicken and eggs.

$$A_{chicken} \text{ or } A_{egg} = (\sum [F_i \cdot Qp_i \cdot P_i] + Qs \cdot Cs \cdot Bs) \cdot (Ba_{egg} \text{ or } Ba_{chicken})$$

where

- $A_{chicken}$ = Concentration of pollutant in chicken (mg pollutant/kg FW tissue)
- A_{egg} = Concentration of pollutant in eggs (mg pollutant/kg FW tissue)
- F_i = Fraction of plant type i (grain) grown on contaminated soil and ingested by the animal (chicken)(unitless)
- Qp_i = Quantity of plant type i (grain) eaten by the animal (chicken) each day (kg DW plant/day)
- P_i = Concentration of pollutant in plant type i (grain) eaten by the animal (chicken) (mg/kg DW)
- Qs = Quantity of soil eaten by the animal (chicken) (kg/day)
- Cs = Average soil concentration over exposure duration (mg pollutant/kg soil)
- Bs = Soil bioavailability factor (unitless)
- $Ba_{chicken}$ = Pollutant biotransfer factor for chicken (day/kg FW tissue)
- Ba_{egg} = Pollutant biotransfer factor for eggs (day/kg FW tissue)

The pollutant concentration in grain is calculated using the following equation.

Concentration of pollutant in Plant Type i Eaten by the Animal (Chicken) (P_i)

$$P_i = \sum_i (Pr)$$

where

- P_i = Concentration of pollutant in each plant type i eaten by the animal (mg pollutant/kg DW)
- Pr = Plant concentration due to root uptake (mg pollutant/kg DW)

Pollutant concentrations in chickens also depend on the intake of soil. Chickens are assumed to consume 10% of their total diet as soil. The value of 0.022 kg-DW/Day is used.

Average Soil Concentration Over Exposure Duration (C_s):

- The calculation of C_s for chicken is the same as for beef cattle.
- The calculation of B_s for chicken is the same as for beef cattle.
- The calculation of F_i for chicken is identical to that for beef cattle.
- Q_{pi} is set to 0.2 kg DW/day. Chickens are assumed not to eat forage (EPA 2005). The daily quantity of plant feeds (kilograms of DW) consumed by chickens is estimated for grain feed.

5.7 Water and fish concentrations

The calculations for pollutant concentrations in surface water and fish are described in Chapter 5, Section 5.7 of the HHRAP.

5.7.1 Waterbody pollutant calculations

Waterbody pollutant concentrations are calculated for the evaluation of the surface water media concentrations and the fish ingestion exposure pathway for all receptors with the assumption that a waterbody is present at that location. The area extent of a watershed is defined by the topography that drains into a waterbody. The watershed is important in determining the overall pollutant loading to a waterbody since runoff from pervious and impervious areas of the watershed contribute to a waterbody's pollutant concentration.

The program, MINLEAP (MPCA, accessed 2017), is used to compute annual volumetric flow rates and residence times using three factors:

- Waterbody surface area
- Average waterbody depth
- Watershed total area

The factors are estimated for *MNRISKS* using four ecological areas:

1. Central Hardwood Forests (CHF)
2. Northern Lakes and Forests (NLF)
3. Western Corn-belt Plains (WCB)
4. Northern Glaciated Plains (NGP)

Waterbody current velocities and volumetric flow rates are annual average values. Volumetric flow rates for smaller streams or lakes (volumetric flow rates smaller than 10,000m³ / year) are calculated as the product of the watershed area and one-half of the local average annual surface runoff. This calculation is completed because MINLEAP reports these volumetric flow rates as zero.

To work around this problem, this study adopted the lake "residence time", which MINLEAP reports consistently. The following procedure is used to convert the residence time in years to the required Volumetric Flow Rate (m³ / year):

1. Lakes Volume (m³) = Lakes Surface Area (m²) * Lakes Average Depth (m)
2. Volumetric Flow Rate (m³ / year) = Lake Volume (m³) / Residence Time (Years)

The Lake Volume (m³) is obtained by multiplying the waterbody's surface area and the average depth of lakes in Minnesota (15.5 ft = 4.72 m). Table 4 summarizes the Residence Time correlations, which are calculated from representative data points for each ecological region.

Table 4. Residence time correlation summary by ecological region.

| Region | Y = Residence Time (years) and X = Watershed / Waterbody Surface Area Ratio | Evaluation X = 1 | Evaluation X = 10 |
|--------|---|------------------|-------------------|
| 1. NLF | $Y = 15.641 * X^{-0.8973}$ | Y = 15.641 | Y = 1.981 |
| 2. CHF | $Y = 31.077 * X^{-0.9255}$ | Y = 31.077 | Y = 3.689 |
| 3. WCP | $Y = 28.454 * X^{-0.8952}$ | Y = 28.454 | Y = 3.622 |
| 4. NGP | $Y = 316.25 * X^{-1.3254}$ | Y = 316.25 | Y = 14.9496 |

The equation for the Annual Volumetric Flow Rate is provided below.

$$\text{Annual Volumetric Flow Rate} = \text{Surface Area (m}^2\text{)} * \text{Depth (m)} / \text{Residence Time (years)}$$

Figure 11 presents the complete calculation procedure for waterbody input data. Current velocities for streams are calculated as the volumetric flow rate divided by the cross-sectional area.

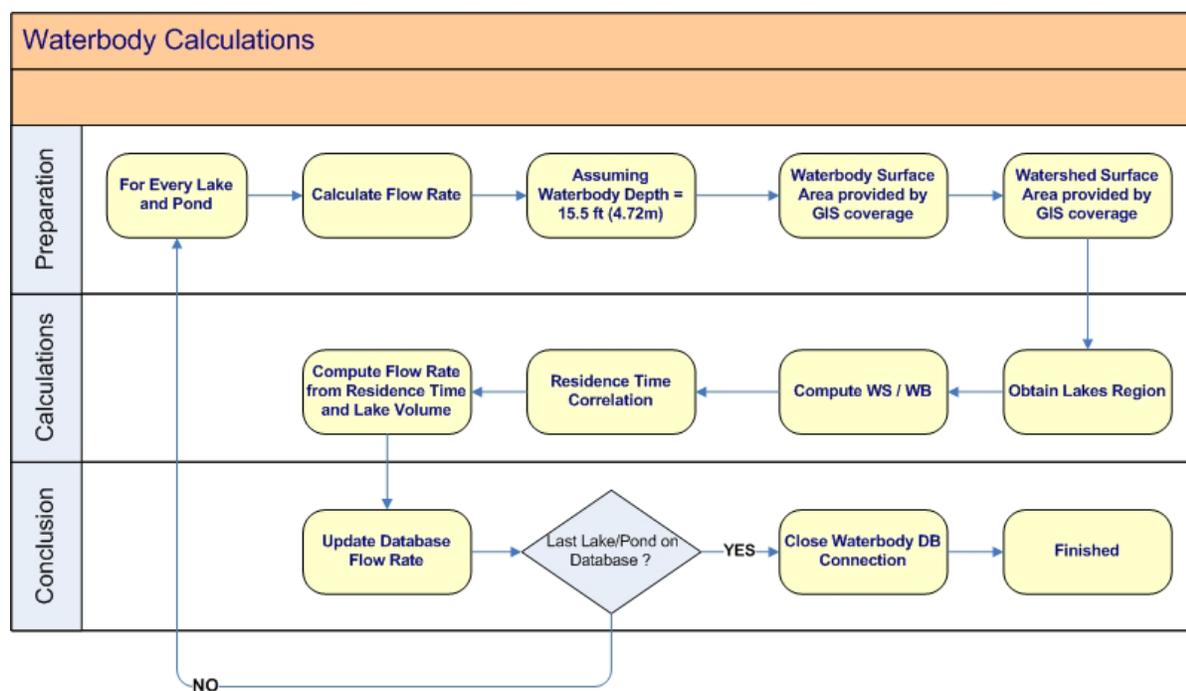


Figure 11. Waterbody calculation process in MNRISKS.

Waterbody pollutant concentrations are calculated using the following loading mechanisms:

- Direct deposition onto the watershed and waterbody
- Runoff from impervious surfaces within the watershed
- Runoff from pervious surfaces within the watershed
- Soil erosion over the total watershed

- Direct diffusion of vapor phase pollutants into the surface water
- Internal transformation of compounds chemically or biologically

Soil erosion from the watershed, which is carried to the waterbody, is calculated by using the Universal Soil Loss Equation (USLE) and a sediment delivery ratio.

Surface water concentration algorithms include:

- A sediment mass balance
- Assumption that Total Suspended Sediments (TSS) do not change over time

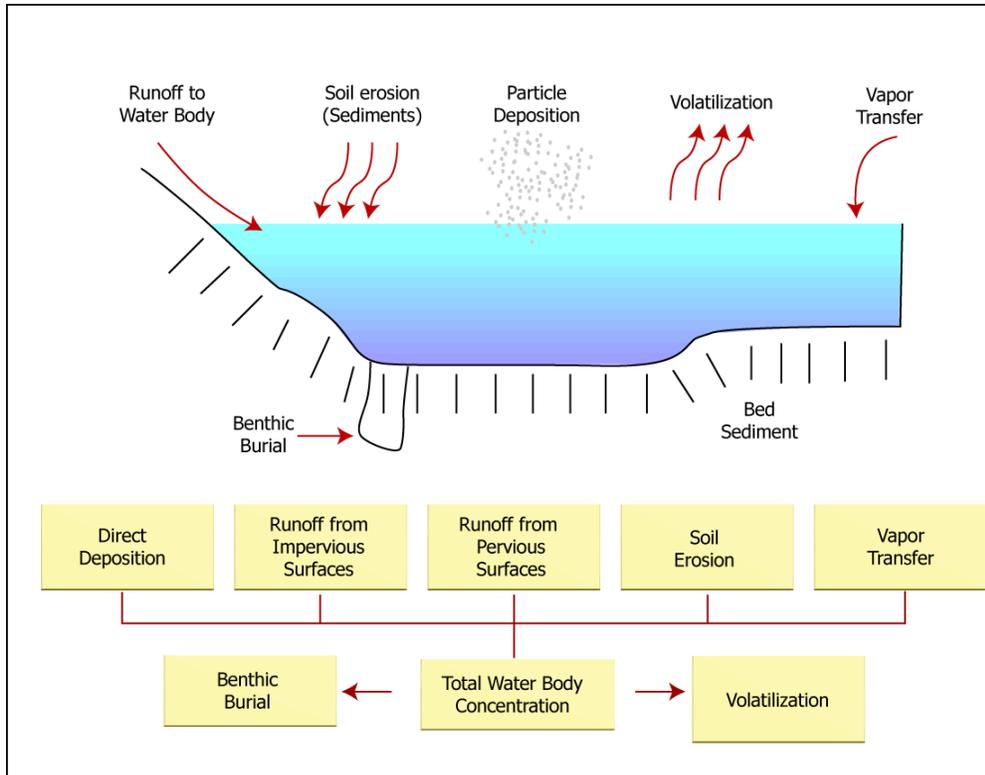


Figure 12. Transport processes in a waterbody (EPA 2005).

The USLE and a sediment delivery ratio are used to estimate the rate of soil erosion from the watershed. Surface water concentration algorithms include a sediment mass balance, in which the amount of sediment assumed to be buried and lost from the waterbody is equal to the difference between the amount of soil introduced to the waterbody by erosion and the amount of suspended solids lost in downstream flow. The total water column pollutant concentration is the sum of the pollutant concentration dissolved in water and the pollutant concentration associated with suspended solids. Partitioning between water and sediment varies with the pollutant. The total concentration of each pollutant is partitioned between the sediment and the water column. To evaluate the pollutant loading to a waterbody from its associated watershed, the pollutant concentration in watershed soils is calculated. The equation for pollutant concentration in soil includes a loss term that considers the loss of contaminants from the soil after deposition. These loss mechanisms lower the soil concentration associated with a specific deposition rate.

The following equation calculates the total pollutant load to a waterbody (L_T).

Total Pollutant Load to the Waterbody (L_T)

$$L_T = L_{DEP} + L_{dif} + L_{RI} + L_R + L_E + L_I$$

where

- L_T = Total pollutant load to the waterbody (including deposition, runoff, and erosion) (g/yr)
- L_{DEP} = Total (wet and dry) particle phase and vapor phase pollutant direct deposition load to waterbody (g/yr)
- L_{dif} = Vapor phase pollutant diffusion load to waterbody (g/yr)
- L_{RI} = Runoff load from impervious surfaces (g/yr)
- L_R = Runoff load from pervious surfaces (g/yr)
- L_E = Soil erosion load (g/yr)
- L_I = Internal transfer (g/yr)

Due to the limited data and uncertainty associated with the chemical or biological internal transfer, L_I , of compounds into daughter products, a default value of zero is used for this variable.

The following equation calculates the load to the waterbody from the direct deposition of wet and dry particles and vapors onto the surface of the waterbody (L_{DEP}).

$$L_{DEP} = Q \cdot [F_v \cdot Dytwv + (1 - F_v) \cdot Dytwp] \cdot A_w$$

where

- L_{DEP} = Total (wet and dry) particle phase and vapor phase pollutant direct deposition load to waterbody (g/yr)
- Q = Pollutant emission rate (g/s)
- F_v = Fraction of pollutant air concentration in vapor phase (unitless)
- $Dytwv$ = Unitized yearly (waterbody or watershed) average total (wet and dry) deposition from vapor phase (s/m²-yr)
- $Dytwp$ = Unitized yearly (waterbody or watershed) average total (wet and dry) deposition from particle phase (s/m²-yr)
- A_w = Waterbody surface area (m²)

The following equation calculates the vapor phase pollutant diffusion load to the waterbody (L_{dif}).

$$L_{dif} = \frac{K_v \cdot Q \cdot F_v \cdot Cywv \cdot A_w \cdot 1 \times 10^{-6}}{H \cdot T_{wk}}$$

where

- L_{dif} = Vapor phase pollutant diffusion load to waterbody (g/yr)
- K_v = Overall pollutant transfer rate coefficient (m/yr)
- Q = Pollutant emission rate (g/s)
- F_v = Fraction of pollutant air concentration in vapor phase (unitless)
- $Cywv$ = Unitized yearly (waterbody or watershed) average air concentration from vapor phase (µg-s/g-m³)
- A_w = Waterbody surface area (m²)
- 10^{-6} = Units conversion factor (g/µg)

- H = Henrys Law constant (atm-m³/mol)
 R = Universal gas constant (atm-m³/mol-K)
 T_{wk} = Waterbody temperature (K)

In some watershed soils, a fraction of the total (wet and dry) deposition in the watershed will fall on impervious surfaces. This deposition may accumulate and be washed off during rain events. The following equation calculates impervious runoff load to a waterbody (L_{RI}).

$$L_{RI} = Q \cdot [F_v \cdot Dytwv + (1.0 - F_v) \cdot Dytwp] \cdot A_I$$

where

- L_{RI} = Runoff load from impervious surfaces (g/yr)
 Q = Pollutant emission rate (g/s)
 F_v = Fraction of pollutant air concentration in vapor phase (unitless)
 $Dytwv$ = Unitized yearly (waterbody or watershed) average total (wet and dry) deposition from vapor phase (s/m²-yr)
 $Dytwp$ = Unitized yearly (waterbody or watershed) average total (wet and dry) deposition from particle phase (s/m²-yr)
 A_I = Impervious watershed area receiving pollutant deposition (m²)

Impervious watershed area receiving pollutant deposition (A_I) is the portion of the total effective watershed area that is impervious to rainfall (such as roofs, driveways, streets, and parking lots) and drains to the waterbody. The following equation calculates the pollutant load to the waterbody from pervious soil surfaces in the watershed (L_R).

$$L_R = RO \cdot (A_L - A_I) \cdot \frac{C_s \cdot BD}{\theta_{sw} + Kd_s \cdot BD} \cdot 0.01$$

where

- L_R = Runoff load from pervious surfaces (g/yr)
 RO = Average annual surface runoff from pervious areas (cm/yr)
 A_L = Total watershed area receiving pollutant deposition (m²)
 A_I = Impervious watershed area receiving pollutant deposition (m²)
 C_s = Average soil concentration over exposure duration (in watershed soils) (mg pollutant/kg soil)
 BD = Soil bulk density (g soil/cm³ soil)
 θ_{sw} = Soil volumetric water content (mL water/cm³ soil)
 Kd_s = Soil-water partition coefficient (cm³ water/g soil)
 0.01 = Units conversion factor (kg-cm²/mg-m²)

The following equation is used to calculate soil erosion load (L_E).

$$L_E = X_e \cdot (A_L - A_I) \cdot SD \cdot ER \cdot \frac{C_s \cdot Kd_s \cdot BD}{\theta_{sw} + Kd_s \cdot BD} \cdot 0.001$$

where

| | | |
|------------------|---|---|
| L_E | = | Soil erosion load (g/yr) |
| X_e | = | Unit soil loss (kg/m ² -yr) |
| A_L | = | Total watershed area (evaluated) receiving pollutant deposition (m ²) |
| A_I | = | Impervious watershed area receiving pollutant deposition (m ²) |
| SD | = | Sediment delivery ratio (watershed) (unitless) |
| ER | = | Soil enrichment ratio (unitless) |
| C_s | = | Average soil concentration over exposure duration (in watershed soils) (mg pollutant/kg soil) |
| BD | = | Soil bulk density (g soil/cm ³ soil) |
| ϑ_{sw} | = | Soil volumetric water content (mL water/cm ³ soil) |
| Kd_s | = | Soil-water partition coefficient (mL water/g soil) |
| 0.001 | = | Units conversion factor (mg pollutant/g pollutant) |

The USLE is used to calculate the unit soil loss (X_e) specific to each watershed.

$$X_e = RF \cdot K \cdot LS \cdot C \cdot PF \cdot \frac{907.18}{4047}$$

where

| | | |
|--------|---|---|
| X_e | = | Unit soil loss (kg/m ² -yr) |
| RF | = | USLE rainfall (or erosivity) factor (yr ⁻¹) |
| K | = | USLE erodibility factor (ton/acre) |
| LS | = | USLE length-slope factor (unitless) |
| C | = | USLE cover management factor (unitless) |
| PF | = | USLE supporting practice factor (unitless) |
| 907.18 | = | Units conversion factor (kg/ton) |
| 4047 | = | Units conversion factor (m ² /acre) |

The USLE RF variable, which represents the influence of precipitation on erosion, is derived from data on the frequency and intensity of storms. This value is typically derived on a storm-by-storm basis, but average annual values have been compiled (EPA 2005). The following equation calculates sediment delivery ratio (SD).

$$SD = a \cdot (A_L)^b$$

where

| | | |
|-------|---|---|
| SD | = | Sediment delivery ratio (watershed) (unitless) |
| a | = | Empirical intercept coefficient (unitless) |
| b | = | Empirical slope coefficient (unitless) |
| A_L | = | Total watershed area receiving pollutant deposition (m ²) |

The sediment delivery ratio (*SD*) for a large land area, a watershed or part of a watershed, can be calculated, on the basis of the area of the watershed. The empirical intercept coefficient (*a*) varies based on watershed surface area as cited in HHRAP:

| Watershed Area (sq. miles) | "a" Coefficient (unitless) |
|----------------------------|----------------------------|
| ≤0.1 | 2.1 |
| 1 (>0.1 but ≤1.0) | 1.9 |
| 10 (>1.0 but ≤10) | 1.4 |
| 100 (>10 but ≤100) | 1.2 |
| 1000 (>100) | 0.6 |

According to Vanoni (1975), sediment delivery ratios vary approximately with the -0.125 power of the drainage area. Therefore, the empirical slope coefficient is assumed to be 0.125. A_L is the total watershed surface area evaluated that is affected by deposition and drains to the body of water.

The following equation calculates total waterbody pollutant concentration (C_{wtot}). The total waterbody concentration includes both the water column and the bed sediment.

$$C_{wtot} = \frac{L_T}{Vf_x \cdot f_{wc} + k_{wt} \cdot A_W \cdot (d_{wc} + d_{bs})}$$

where

- C_{wtot} = Total waterbody pollutant concentration (including water column and bed sediment) (g pollutant/m³ waterbody)
- L_T = Total pollutant load to the waterbody (deposition, runoff, and erosion) (g/yr)
- Vf_x = Average volumetric flow rate through waterbody (m³/yr)
- f_{wc} = Fraction of total waterbody pollutant concentration in the water column (unitless)
- k_{wt} = Overall total waterbody pollutant dissipation rate constant (yr⁻¹)
- A_W = Waterbody surface area (m²)
- d_{wc} = Depth of water column (m)
- d_{bs} = Depth of upper benthic sediment layer (m)

- A default value of 0.03 is use in *MNRISKS* for d_{bs} and represents the midpoint of the specified range (i.e., 0.01 – 0.05).

The following equation calculates the fraction of total waterbody pollutant concentration in the water column (f_{wc}), and the subsequent equation to calculate total waterbody contaminant concentration in benthic sediment (f_{bs}).

Fraction of Total Waterbody Pollutant Concentration in the Water Column (f_{wc}) and Benthic Sediment (f_{bs})

$$f_{bs} = 1 - f_{wc}$$

$$f_{wc} = \frac{(1 + Kd_{sw} \cdot TSS \cdot 10^{-6}) \cdot d_{wc} / d_z}{(1 + Kd_{sw} \cdot TSS \cdot 10^{-6}) \cdot d_{wc} / d_z + (\theta_{bs} + Kd_{bs} \cdot C_{BS}) \cdot d_{bs} / d_z}$$

where

- f_{wc} = Fraction of total waterbody pollutant concentration in the water column (unitless)
- f_{bs} = Fraction of total waterbody pollutant concentration in benthic sediment (unitless)

- Kd_{sw} = Suspended sediments/surface water partition coefficient (L water/kg suspended sediment)
- TSS = Total suspended solids concentration (mg/L)
- 10^{-6} = Units conversion factor (kg/mg)
- d_z = Total waterbody depth (m)
- ϑ_{bs} = Bed sediment porosity ($L_{water}/L_{sediment}$)
- Kd_{bs} = Bed sediment/sediment pore water partition coefficient (L water/kg bottom sediment)
- C_{BS} = Bed sediment concentration (g/cm^3 [equivalent to kg/L])
- d_{wc} = Depth of water column (m)
- d_{bs} = Depth of upper benthic sediment layer (m)

An average annual value for TSS of 10 mg/L is used in *MNRISKS* in lieu of site specific information. The default value of 1,825 m/yr provided for D_{ss} is characteristic of Stoke's settling velocity for an intermediate (fine to medium) silt.

The following default value for bed sediment porosity (ϑ_{bs}) is used in *MNRISKS* in lieu of site specific information:

$$\vartheta_{bs} = 0.6 \frac{L_{water}}{L_{sediment}}$$

(assuming $\rho_s = 2.65$ kg/L [bed sediment density] and $C_{BS} = 1$ kg/L [bed sediment concentration])

A default value of 0.1 kg/L is used as a default bed sediment (C_{BS}) and 0.03 meter is the default depth of the upper benthic layer (d_{bs}).

The following equation is calculates the overall dissipation rate of pollutants in surface water due to volatilization and benthic burial.

$$k_{wt} = f_{wc} \cdot k_v + f_{bs} \cdot k_b$$

where

- k_{wt} = Overall total waterbody dissipation rate constant (yr^{-1})
- f_{wc} = Fraction of total waterbody pollutant concentration in the water column (unitless)
- k_v = Water column volatilization rate constant (yr^{-1})
- f_{bs} = Fraction of total waterbody pollutant concentration in benthic sediment (unitless)
- k_b = Benthic burial rate constant (yr^{-1})

The following equation calculates water column volatilization rate constant.

$$k_v = \frac{K_v}{d_z \cdot (1 + Kd_{sw} \cdot TSS \cdot 10^{-6})}$$

where

- k_v = Water column volatilization rate constant (yr^{-1})
- K_v = Overall pollutant transfer rate coefficient (m/yr)
- d_z = Total waterbody depth (m)
- Kd_{sw} = Suspended sediments/surface water partition coefficient (L water/kg suspended sediments)
- TSS = Total suspended solids concentration (mg/L)
- 1×10^{-6} = Units conversion factor (kg/mg)

Volatile organic chemicals can move between the water column and the overlying air. The overall transfer rate K_v , or conductivity, is determined by a two-layer resistance model that assumes that two stagnant films are bounded on either side by well-mixed compartments. Concentration differences serve as the driving force for the water layer diffusion. Pressure differences drive the diffusion for the air layer. From balance considerations, the same mass must pass through both films; the two resistances thereby combine in series, so that the conductivity is the reciprocal of the total resistance.

The following equation calculates the overall transfer rate coefficient (K_v).

Overall Pollutant Transfer Rate Coefficient (K_v)

$$K_v = \left(K_L^{-1} + \left(K_G \cdot \frac{H}{R \cdot T_{wk}} \right)^{-1} \right)^{-1} \cdot \theta^{T_{wk} - 293}$$

where

- K_v = Overall pollutant transfer rate coefficient (m/yr)
- K_L = Liquid phase transfer coefficient (m/yr)
- K_G = Gas phase transfer coefficient (m/yr)
- H = Henry's Law constant (atm-m³/mol)
- R = Universal gas constant (atm-m³/mol-K)
- T_{wk} = Waterbody temperature (K)
- θ = Temperature correction factor (unitless)

The value of the conductivity K_v depends on the intensity of turbulence in the waterbody and the overlying atmosphere. As Henry's Law constant increases, the conductivity tends to be increasingly influenced by the intensity of turbulence in water. Conversely, as Henry's Law constant decreases, the value of the conductivity tends to be increasingly influenced by the intensity of atmospheric turbulence. The liquid and gas phase transfer coefficients, K_L and K_G , respectively, vary with the type of waterbody.

Henry's Law constants generally increase with increasing vapor pressure of a pollutant and generally decrease with increasing solubility of a pollutant. Henry's Law constants used in *MNRISKS* are documented in the pollutant spreadsheet available at [Pollutant Chemical and Physical Properties-MNRISK: Pollutants](#). The universal ideal gas constant, R , is 8.205e10⁻⁵ atm-m³/mol-K, at 20 C and the temperature correction factor (θ) (1.026) is used to adjust for the actual water temperature.

The following equation calculates the liquid phase transfer coefficient. (K_L).

For quiescent lakes or ponds:

$$K_L = (C_d^{0.5} \cdot W) \cdot \left(\frac{\rho_a}{\rho_w} \right)^{0.5} \cdot \frac{k^{0.33}}{\lambda_z} \cdot \left(\frac{\mu_w}{\rho_w \cdot D_w} \right)^{-0.67} \cdot 3.1536 \times 10^7$$

where

- K_L = Liquid phase transfer coefficient (m/yr)
- D_w = Diffusivity of pollutant in water (cm²/s)
- u = Current velocity (m/s)
- 1e10⁻⁴ = Units conversion factor (m²/cm²)
- d_z = Total waterbody depth (m)
- C_d = Drag coefficient (unitless)
- W = Average annual wind speed (m/s)
- ρ_a = Density of air (g/cm³)
- ρ_w = Density of water (g/cm³)
- k = von Karman constant (unitless)

- λ_z = Dimensionless viscous sublayer thickness (unitless)
- μ_w = Viscosity of water corresponding to water temperature (g/cm-s)
- 3.1536×10^7 = Units conversion factor (s/yr)

For a stagnant system (quiescent lake or pond), the transfer coefficient is controlled by wind-induced turbulence.

MNRISKS uses the following default values:

1. Diffusivity of chemical in water ranging (D_w) from 1.0×10^{-5} to 8.5×10^{-2} cm²/s
2. Dimensionless viscous sublayer thickness (λ_z) of 4
3. Von Karman constant (k) of 0.4
4. Drag coefficient (C_d) of 0.0011
5. Density of air (ρ_a) of 0.0012 g/cm³ at standard conditions (temperature = 20 C or 293 K, pressure = 1 atm or 760 millimeters of mercury)
6. A density of water (ρ_w) of 1 g/cm³,
7. A viscosity of water (μ_w) of a 0.0169 g/cm-s corresponding to water temperature

The following equation calculates gas phase transfer coefficient (K_G).

Gas Phase Transfer Coefficient (K_G)

For quiescent lakes or ponds:

$$K_G = (C_d^{0.5} \cdot W) \cdot \frac{k^{0.33}}{\lambda_z} \cdot \left(\frac{\mu_a}{\rho_a \cdot D_a} \right)^{-0.67} \cdot 3.1536 \times 10^7$$

where

- K_G = Gas phase transfer coefficient (m/yr)
- C_d = Drag coefficient (unitless)
- W = Average annual wind speed (m/s)
- k = von Karman constant (unitless)
- λ_z = Dimensionless viscous sublayer thickness (unitless)
- μ_a = Viscosity of air corresponding to air temperature (g/cm-s)
- ρ_a = Density of air corresponding to water temperature (g/cm³)
- D_a = Diffusivity of pollutant in air (cm²/s)
- 3.1536×10^7 = Units conversion factor (s/yr)

For a stagnant system (quiescent lake or pond), the transfer coefficients are controlled by wind-induced turbulence. For quiescent lakes or ponds, the gas phase transfer coefficient of 1.81×10^{-4} g/cm-s is used for the viscosity of air corresponding to air temperature.

The following equation calculates benthic burial rate (k_b).

$$k_b = \left(\frac{X_e \cdot A_L \cdot SD \cdot 1 \times 10^3 - V f_x \cdot TSS}{A_w \cdot TSS} \right) \cdot \left(\frac{TSS \cdot 1 \times 10^6}{C_{BS} \cdot d_{bs}} \right)$$

where

- k_b = Benthic burial rate constant (yr⁻¹)
- X_e = Unit soil loss (kg/m²-yr)
- A_L = Total watershed area (evaluated) receiving deposition (m²)
- SD = Sediment delivery ratio (watershed) (unitless)

| | | |
|--------------------|---|---|
| Vf_x | = | Average volumetric flow rate through waterbody (m ³ /yr) |
| TSS | = | Total suspended solids concentration (mg/L) |
| A_w | = | Waterbody surface area (m ²) |
| C_{BS} | = | Bed sediment concentration (g/cm ³) |
| d_{bs} | = | Depth of upper benthic sediment layer (m) |
| 1×10^{16} | = | Units conversion factor (kg/mg) |
| 1×10^3 | = | Units conversion factor (g/kg) |

The benthic burial rate constant (k_b) can be expressed in terms of the rate of burial (Wb):

$$Wb = k_b \cdot d_{bs}$$

where

| | | |
|----------|---|--|
| Wb | = | Rate of burial (m/yr) |
| k_b | = | Benthic burial rate constant (yr ⁻¹) |
| d_{bs} | = | Depth of upper benthic sediment layer (m) |

The default value of 1.0 kg/L is used for bed sediment concentration (C_{BS}).

The calculated value for k_b should range from 0 to 1.0. Low k_b values are expected for water bodies with no or limited sedimentation (rivers and fast flowing streams), and k_b values closer to 1.0 expected for water bodies with higher sedimentation (lakes).

The following equation calculates total pollutant concentration in water column (C_{wctot}).

$$C_{wctot} = f_{wc} \cdot C_{wtot} \cdot \frac{d_{wc} + d_{bs}}{d_{wc}}$$

where

| | | |
|-------------|---|---|
| C_{wctot} | = | Total pollutant concentration in water column (mg pollutant/L water column) |
| f_{wc} | = | Fraction of total waterbody pollutant concentration in the water column (unitless) |
| C_{wtot} | = | Total waterbody pollutant concentration, including water column and bed sediment (mg pollutant/L waterbody) |
| d_{wc} | = | Depth of water column (m) |
| d_{bs} | = | Depth of upper benthic sediment layer (m) |

The following equation calculates the concentration of pollutant dissolved in the water column (C_{dw}).

$$C_{dw} = \frac{C_{wctot}}{1 + Kd_{sw} \cdot TSS \cdot 1 \times 10^{-6}}$$

where

| | | |
|--------------------|---|---|
| C_{dw} | = | Dissolved phase water concentration (mg pollutant/L water) |
| C_{wctot} | = | Total pollutant concentration in water column (mg pollutant/L water column) |
| Kd_{sw} | = | Suspended sediments/surface water partition coefficient (L water/kg suspended sediment) |
| TSS | = | Total suspended solids concentration (mg/L) |
| 1×10^{-6} | = | Units conversion factor (kg/mg) |

The following equation calculates pollutant concentration sorbed to bed sediment (C_{sb}).

$$C_{sb} = f_{bs} \cdot C_{wtot} \cdot \left(\frac{Kd_{bs}}{\theta_{bs} + Kd_{bs} \cdot C_{BS}} \right) \cdot \left(\frac{d_{wc} + d_{bs}}{d_{bs}} \right)$$

where

| | | |
|---------------|---|---|
| C_{sb} | = | Pollutant concentration sorbed to bed sediment (mg pollutant/kg sediment) |
| f_{bs} | = | Fraction of total waterbody pollutant concentration in benthic sediment (unitless) |
| C_{wtot} | = | Total waterbody pollutant concentration, including water column and bed sediment (mg pollutant/L waterbody) |
| Kd_{bs} | = | Bed sediment/sediment pore water partition coefficient (L water/kg bed sediment) |
| θ_{bs} | = | Bed sediment porosity ($L_{pore\ water}/L_{sediment}$) unitless |
| C_{BS} | = | Bed sediment concentration (g/cm^3) |
| d_{wc} | = | Depth of water column (m) |
| d_{bs} | = | Depth of upper benthic sediment layer (m) |

5.7.2 Fish concentration calculations

Details of how the concentration of pollutants in fish are calculated are included in Chapter 5, Section 5.7.5 of HHRAP. The pollutant concentration in fish is calculated using either a pollutant-specific bioconcentration factor (BCF), a pollutant-specific bioaccumulation factor (BAF), or a pollutant-specific biota-sediment accumulation factor ($BSAF$). *MNRISKS* uses $BCFs$ for organic pollutants with log Kow less than 4.0 and $BAFs$ (rather than $BCFs$) for organic pollutants with log Kow of 4.0 or greater. These biological accumulation and biological concentration factors are included in the online pollutant [spreadsheet](#).

The following equation calculates pollutant concentrations in fish tissue from bioconcentration factors:

$$C_{fish} = C_{dw} \cdot BCF_{fish}$$

where

| | | |
|--------------|---|--|
| C_{fish} | = | Concentration of pollutant in fish (mg pollutant/kg FW tissue) |
| C_{dw} | = | Dissolved phase water concentration (mg pollutant/L) |
| BCF_{fish} | = | Bioconcentration factor for pollutant in fish (L/kg) |

The following equation calculates pollutant concentrations in fish tissue from bioaccumulation factors:

$$C_{fish} = C_{dw} \cdot BAF_{fish}$$

where

| | | |
|--------------|---|--|
| C_{fish} | = | Concentration of pollutant in fish (mg pollutant/kg FW tissue) |
| C_{dw} | = | Dissolved phase water concentration (mg pollutant/L) |
| BAF_{fish} | = | Bioaccumulation factor for pollutant in fish ([mg pollutant/kg FW tissue]/[mg pollutant/kg feed]) (unitless) |

The following equation calculates pollutant concentrations in fish tissue from biota-to-sediment accumulation factors using pollutant sorbed to bed sediment:

$$C_{fish} = \frac{C_{sb} \cdot f_{lipid} \cdot BSAF}{OC_{sed}}$$

where

- C_{fish} = Concentration of pollutant in fish (mg pollutant/kg FW tissue)
 C_{sb} = Concentration of pollutant sorbed to bed sediment (mg pollutant/kg bed sediment)
 f_{lipid} = Fish lipid content (unitless)
 $BSAF$ = Biota-to-sediment accumulation factor ([mg pollutant/kg lipid tissue]/[m g pollutant/kg sediment]) (unitless)
 OC_{sed} = Fraction of organic carbon in bottom sediment (unitless)

Values for the fraction of organic carbon in bottom sediment (OC_{sed}) range from 0.03 to 0.05, a default value of 0.04 is used in *MNRISKS*. Values for fish lipid content range from 0.03 – 0.07. The default value of 0.07 is used as the fish lipid content (f_{lipid}) in *MNRISKS*.

5.8 Metabolism factor

The metabolism factor (MF) represents the estimated amount of pollutant that remains in fat and muscle. An MF of 0.01 for bis(2-ethylhexyl)phthalate (BEHP), and 1.0 for all other pollutants is used. MF does not relate to metabolism in produce, chicken, or fish. Use of a MF does not apply for direct exposures to air, soil, or water, or to ingestion of produce, chicken, or fish.

5.9 Chemical and physical properties

Table 5 shows the chemical and physical properties used in *MNRISKS* calculations. The chemical and physical properties for each pollutant is available at: [Pollutant Chemical and Physical Properties-MNRISK](#). The assigned values align with the HHRAP database when available.

Table 5. Chemical and physical properties used to calculate a pollutant’s movement between the air, soil and water.

| Parameter Name | Parameter Abbreviation | Units | Brief Description | Equation |
|--------------------|------------------------|--------------------------|---|-----------------------------|
| Molecular Weight | MW | grams/mol | The ratio of the average mass of one molecule of an element or compound to one twelfth of the mass of an atom of carbon-12. | |
| Melting Point | Tm | degrees K | The temperature at which a given material changes from a solid to a liquid. | |
| Vapor Pressure | Vp | atmospheres | The <i>pressure</i> exerted by a <i>vapor</i> in thermodynamic equilibrium with its condensed phases (solid or liquid) at a given temperature in a closed system. | |
| Aqueous Solubility | S | mg/L | The property of a solid, liquid, or gaseous chemical substance called solute to dissolve in water. | |
| Henry’s Law | H | atm-m ³ /mole | The ratio of the partial pressure of a compound in air to the concentration of the compound in water at a given temperature under equilibrium conditions. | $H = \frac{Vp \cdot MW}{S}$ |

| Parameter Name | Parameter Abbreviation | Units | Brief Description | Equation |
|--|------------------------|--------------------|---|---|
| Diffusivity in Air* | D_a | cm ² /s | The gas phase transfer of a pollutant through air. | $D_{a,i} = \frac{1.9}{(MW_i)^{2/3}}$ |
| Diffusivity in Water* | D_w | cm ² /s | The liquid phase transfer of a pollutant through water. | $D_{w,i} = \frac{22 \cdot 10^{-5}}{(MW_i)^{2/3}}$ |
| *Diffusivity for TCDD | | | Diffusivity for TCDD congeners. | $\frac{D_x}{D_y} = \left(\frac{MW_y}{MW_x} \right)^{0.5}$ |
| Octanol Water Partitioning Coefficient | K_{ow} | Unitless | The ratio of the solute concentration in the water-saturated <i>n</i> -octanol phase to the solute concentration in the <i>n</i> -octanol-saturated water phase. | |
| Soil Organic Carbon-Water Partition Coefficient | K_{oc} | mL/g | The ratio of adsorbed compound per unit weight of organic carbon to the aqueous solute concentration. | Equation depends on ionizing, non-ionizing, and the volatility of the compound. |
| Soil-Water Partition Coefficient | Kd_s | cm ³ *g | The partitioning of a compound between soil pore-water and soil particles. | $Kd_s = f_{oc,s} \cdot K_{oc}$ |
| Suspended Sediment-Surface Water Partition Coefficient | Kd_{sw} | L*kg | The partitioning of a compound between surface water and suspended solids or sediments. | $Kd_{sw} = f_{oc,sw} \cdot K_{oc}$ |
| Bed Sediment-Sediment Pore-Water Partition Coefficient | Kd_{bs} | cm ³ *g | The partitioning of a compound between the bed sediments and bed sediment pore-water. | $Kd_{bs} = f_{oc,bs} \cdot K_{oc}$ |
| Soil Loss Constant Due to Degradation | ksg | yr | The loss of a compound from the soil by processes other than leaching | $ksg = \frac{0.693}{t_{1/2}}$ |
| Fraction of Pollutant Air Concentration in the Vapor Phase | F_v | unitless | Calculation depends on presence in environment in solid (1) vs liquid phase (2). Methyl mercury is assumed not to exist in the gas phase and, therefore, assigned an F_v of zero. | $F_v = 1 - \frac{c S_T}{p_L^- + c S_T}$ $\ln\left(\frac{p_L^-}{p_s^-}\right) = \frac{\Delta S_f}{R} \frac{(T_m - T)}{T}$ |
| Root Concentration Factor | RCF | unitless | The belowground transfer of contaminants from soil to a root vegetable. K_{ow} values of 2.0 and higher (1), log K_{ow} values less than 2.0 (2). | $\log(RCF) = 0.77 \log K_{ow} - 1.52,$ $\log(RCF - 82) = 0.77 \log K_{ow} - 1.52$ |
| Plant-Soil Bioconcentration Factor | $Br_{rootveg}$ | unitless | The uptake from soil to the belowground root vegetables or produce. | $Br_{rootveg} = \frac{RCF}{Kd_s}$ |

| Parameter Name | Parameter Abbreviation | Units | Brief Description | Equation |
|---|------------------------------|-----------------------|--|---|
| Plant-Soil Bioconcentration Factor | Br_{forage} Br_{ag} | unitless | The uptake from soil and the subsequent transport of pollutants through the roots to the aboveground plant parts. | $\log Br_{forage} = 1.588 - 0.578 (\log K_{ow})$ $\log Br_{ag} = 1.588 - 0.578 (\log K_{ow})$ |
| Air-to-Plant Biotransfer Factor | Bv | unitless | The ratio of pollutant concentration in aboveground plant parts to the pollutant concentration in air. | $\log B_{vol} = 1.065 \log K_{ow} - \log \left(\frac{H}{RT} \right) - 1.654$ $Bv = \frac{\rho_{air} \bullet B_{vol}}{(1 - f_{water}) \bullet \rho_{forage}}$ |
| Biotransfer Factors for Beef and Milk | Ba_{beef} Ba_{milk} | Day*kg (fresh weight) | The ratio of pollutant concentration in fresh weight animal tissue to the daily intake of pollutant by the animal (Ba). Calculation differs if organic, ionizable, metal, or mercury. USEPA recommends Ba values of zero for elemental mercury. | $\log Ba_{fat} = -0.099 (\log K_{ow})^2 + 1.07 \log K_{ow} - 3.56$ $Ba_{milk} = 10^{\log Ba_{fat} \times 0.04}$ $Ba_{beef} = 10^{\log Ba_{fat} \times 0.19}$ $K_{ow} = K_{own} \times (FracNeutral) + K_{owi} \times (1 - FracNeutral)$ $FracNeutral = 1 + 10^{pH - pKa}$ |
| Biotransfer Factors for Pork | Ba_{pork} | unitless | Ba_{pork} values are derived from Ba_{beef} values, assuming that pork is 23% fat and beef is 19% fat. | |
| Biotransfer Factors for Chicken and Poultry Eggs | $Ba_{chicken}$ Ba_{egg} | unitless | The pollutant concentration in the fresh weight tissue to the pollutant intake from the feed. Biotransfer factors are calculated from bioconcentration factors for chicken and poultry eggs. | Biotransfer factors for chicken are derived $Ba_{chicken}$ using the same method used to estimate Ba_{beef} values, modified to reflect an assumed fat content of chicken of 14%, and eggs of 8%. |
| Bioconcentration Factor for Fish | BCF_{fish} | unitless | The ratio of the pollutant concentration in fish to the pollutant concentration in the water column where the fish is exposed, used for organics (except PCDDs, PCDFs, and PCBs) with a $\log K_{ow}$ value less than 4.0, and for metals (except lead and mercury). | |
| Bioaccumulation Factor for Fish | BAF_{fish} | unitless | The ratio of the pollutant concentration in fish to the pollutant concentration in the waterbody where the fish are exposed, used for organics (except PCDDs, PCDFs, and PCBs) with a $\log K_{ow}$ value greater than 4.0, lead, and mercuric compounds. | |
| Biota-Sediment Accumulation Factors for Fish | $BSAF_{fish}$ | unitless | The transfer of pollutants from the bottom sediment to the lipid in fish, are used for PCDDs, PCDFs, and PCBs. | |

The list of chemicals included in *MNRISKS* is derived from the MPCA air toxics emission inventory that is produced every three years. The following hierarchy is used to populate the physical/chemical parameters required for the HHRAP equations.

1. Recent measurements from Minnesota with adequate power from high quality studies

2. More recent values from the scientific literature (than from databases below), especially for emerging pollutants.
3. The EPA CompTox chemicals dashboard, <https://comptox.epa.gov/dashboard/>.
4. The EpiWin software from EPA (EPA 2016).
5. The MPCA air toxics emission inventory also chemical mixtures and general chemical groupings such as “PAHs” and “arsenic compounds”. The HHRAP parameters for specific chemical compounds are used as “surrogate” physical/chemical & fate properties for mixtures of chemicals of the same chemical group (e.g., chrysene fate properties from HHRAP are used for “PAHs”). Similarly, where HHRAP contained these properties for an element (e.g., nickel) the properties are assigned to “nickel compounds”.
6. The available physical chemical properties adopted for HHRAP.

6. Quantifying exposure

6.1 Exposure scenarios

An exposure scenario is a combination of “exposure pathways” to which a single “receptor” may be subjected. Human receptors may be exposed to air toxics emitted to the atmosphere from two primary exposure routes, either directly—via inhalation; or indirectly—via subsequent ingestion of water, soil, vegetation, and animals that are exposed to chemicals through the food chain.

Each exposure pathway consists of four fundamental components:

- A source of the pollutant and a mechanism of release (e.g., from a car’s tailpipe).
- An environmental medium (e.g., air, water, soil) in which the pollutant is retained and available for exposure (retention medium), or a transport mechanism and subsequent retention medium in cases involving media transfer of pollutants.
- A potential human contact with the contaminated medium—this is referred to as the exposure point and consists of a specific receptor exposed at a specific geographic location.
- An exposure route (breathing, drinking, eating, contact with skin).

Humans, plants, and animals in the assessment area may take up pollutants directly from the air or indirectly via a media receiving deposition (e.g., soil, vegetation, or water). Some pollutants may also bioaccumulate as described in Section 5.

The EPA HHRAP recommends the following hypothetical exposure scenarios:

- Farmer adult
- Farmer child
- Resident adult
- Resident child
- Fisher adult
- Fisher child
- Short term inhalation

Exposure scenarios are not referred to as “subsistence” since the actual mass per day amounts of food are less than daily-recommended caloric intakes. *MNRISKS* can flexibly accommodate combinations of

exposure pathways. For example, many cities allow residents to raise chickens for meat and eggs within municipal boundaries. This pathway can be added to the resident scenario (which includes inhalation, soil exposure, and consumption of above ground vegetables) to account for this exposure.

Note that the following exposure scenarios are not very important for air toxics risk assessment:

Ingestion of groundwater – EPA (EPA 1998) found that groundwater is an insignificant exposure pathway for air toxics emissions risk assessment.

Inhalation of re-suspended dust – EPA (EPA 1998) found that inhalation of re-suspended dust was insignificant, for air toxics emissions risk assessment.

Dermal exposure to surface water, soil, or air – Available data indicate that the contribution of dermal exposure to soils to overall risk is typically small (EPA 1996, 1995). The risk resulting from soil ingestion and dermal contact was 50-fold less than the risk from any other exposure pathway and 300-fold less than the total estimated risk (EPA 1996, 1995).

Inhalation of pollutants and ingestion of water by Animals – These exposure pathways have not been included in the recommended exposure scenarios because the contribution of these pathways to total risk is anticipated to be negligible in comparison with that of the exposure pathways being evaluated. However, these exposure pathways may need to be evaluated on a case-by-case basis considering site-specific exposure setting characteristics.

In addition, although the pathways described below may include exposure through drinking surface water, that pathway is excluded by default in *MNRISKS*. The drinking water pathway assumes surface water is the sole source of drinking water. This assumption is unwarranted because most Minnesotans drink well water or treated surface water (MDH 2017).

Table 6. Recommended exposure pathways for a human health risk assessment.

| Exposure Pathways | Recommended Exposure Scenarios ^a | | | | | | |
|--|---|--------------|----------|----------------|--------|--------------|-----------------------------|
| | Farmer | Farmer Child | Resident | Resident Child | Fisher | Fisher Child | Acute Receptor ^b |
| Inhalation of Vapors and Particulates | • | • | • | • | • | • | • |
| Incidental Ingestion of Soil | • | • | • | • | • | • | -- |
| Ingestion of Drinking Water from Surface Water Sources | • | • | • | • | • | • | -- |
| Ingestion of Homegrown Produce | • | • | • | • | • | • | -- |
| Ingestion of Homegrown Beef | • | • | -- | -- | -- | -- | -- |
| Ingestion of Milk from Homegrown Cows | • | • | -- | -- | -- | -- | -- |
| Ingestion of Homegrown Chicken | • | • | d | d | d | d | -- |
| Ingestion of Eggs from Homegrown Chickens | • | • | d | d | d | d | -- |
| Ingestion of Homegrown Pork | • | • | -- | -- | -- | -- | -- |
| Ingestion of Fish | d | d | d | d | • | • | -- |
| Ingestion of Breast Milk | c | -- | c | -- | c | -- | -- |

Notes:

- Pathway is included in exposure scenario.
- Pathway is not included in exposure scenario.
- ^a Exposure scenarios are defined as a combination of exposure pathways evaluated for a receptor at a specific location.
- ^b The acute receptor scenario evaluates short-term 1-hour maximum COPC air concentrations (see Chapter 3) at any land use area that would support the other recommended exposure scenarios, as well as commercial and industrial land use areas (excluding workers at the facility being directly evaluated in the risk assessment).
- ^c Infant exposure to PCDDs, PCDFs, and dioxin-like PCBs via the ingestion of their mother’s breast milk is evaluated as an additional exposure pathway, separately from the recommended exposure scenarios identified in this table (see Chapter 2).
- ^d Site-specific exposure setting characteristics (e.g., presence of ponds on farms, or presence of ponds or small livestock within semi-rural residential areas) may warrant the permitting authority consider adding this exposure pathway to the scenario (see Section 4.2).

6.1.1 Inhalation exposure and single pathway exposures

Air pollution impacts are often evaluated by looking only at the inhalation pathway. This approach is available in *MNRISKS*, as well as additional capabilities for evaluating indirect exposure from other media. By evaluating individual pathways separately, it is possible to determine the pathway contributing the most to the total risk at a given location.

6.1.2 Adult resident scenario receptor

The adult resident exposure scenario is evaluated to account for the combination of exposure pathways to which a receptor may be exposed in an urban or rural (non-farm) setting. The adult resident is assumed to be exposed to pollutants from the emission source through the following exposure pathways:

- Direct inhalation of vapors and particles
- Incidental ingestion of soil
- Ingestion of homegrown produce

6.1.3 Farmer scenario receptor

The farmer exposure scenario is evaluated to account for the combination of exposure pathways to which a receptor may be exposed in a farm or ranch exposure setting. The farmer is assumed to be exposed to pollutants emitted from the facility through the following exposure pathways:

- Direct inhalation of vapors and particles
- Incidental ingestion of soil
- Ingestion of homegrown produce
- Ingestion of homegrown beef
- Ingestion of milk from homegrown cows
- Ingestion of homegrown chicken
- Ingestion of eggs from homegrown chickens
- Ingestion of homegrown pork

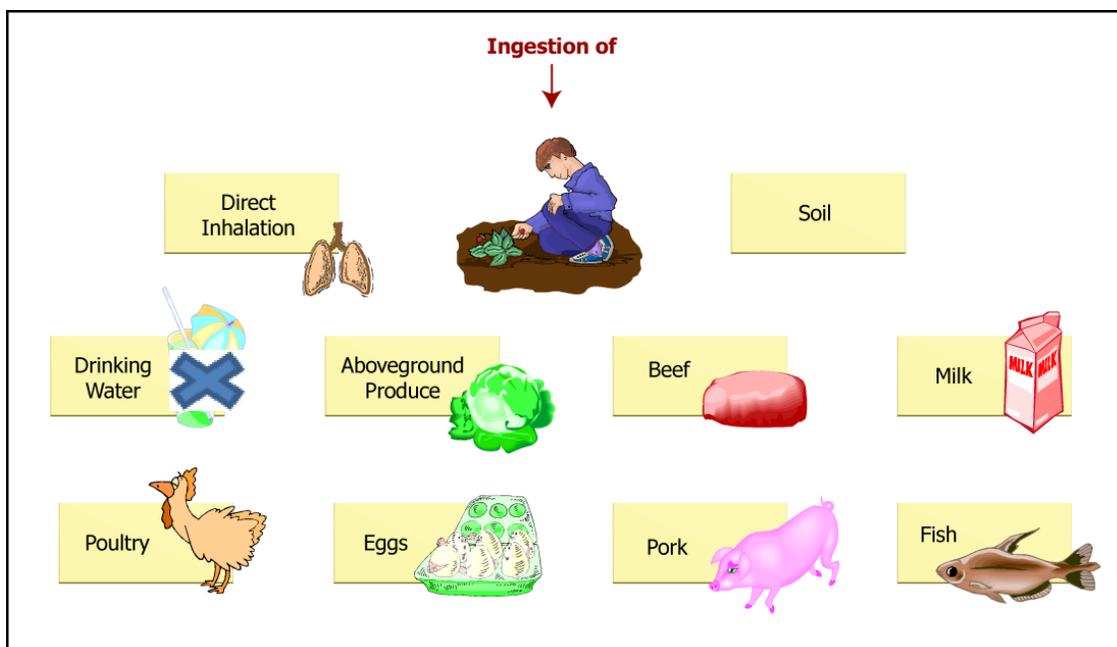


Figure 13. Farmer scenario exposure pathways (EPA 2005).

6.1.4 Fisher scenario receptor

The fisher exposure scenario is evaluated to account for the combination of exposure pathways to which a receptor may be exposed in an urban or rural setting where fish consumption is the main source of protein in the receptor diet. The fisher is exposed to pollutants emitted from the facility through the following pathways:

- Direct inhalation of vapors and particles
- Incidental ingestion of soil
- Ingestion of homegrown produce
- Ingestion of fish

6.1.5 Child scenarios

Each of the adult scenarios has a corresponding child scenario. The exposure pathways for children are the same as for adults, but in the child scenarios there are differences in breathing, consumption rates, and exposure duration.

6.1.6 Acute risk scenario

The acute exposure scenario is evaluated to account for short-term effects of exposure to maximum 1-hour concentrations of pollutants in emissions from the facility through direct inhalation of vapors and particles.

6.1.7 Exposure scenario locations

A receptor's designated exposure scenario depends on the urban or rural setting where human activity or land use supports any of the recommended exposure pathways. Exposure scenario locations are the modeled receptor grid nodes. Concentrations, deposition, exposure, and risks from each pathway and scenario are calculated at each receptor point for each emission point that is within specified distances. For point sources these calculations are made at every receptor point within 50 kilometers of the source. For nonpoint sources the calculations are made at every receptor within 20 kilometers. The choice of results to be extracted for any location depend on the land use at the receptor and whether a particular pathway is reasonable at that location.

6.2 Generic exposure rate equation

The calculation of pollutant-specific exposure rates for each exposure pathway evaluated involves:

- Estimated pollutant media concentrations
- Consumption rate
- Receptor body weight
- Frequency and duration of exposure

This calculation is repeated for each pollutant and for each exposure pathway included in an exposure scenario. The following sections describe a general exposure rate calculation and the exposure pathway-specific variables that may affect this calculation. Acute exposure resulting from direct inhalation is also evaluated separately.

Exposure can occur over a period of time. In the calculation of an average exposure per unit of time, the total exposure can be divided by the time period. An average exposure can be expressed in terms of body weight. All exposures quantified in the risk assessment are:

- Unitized for time and body weight
- Presented in units of milligrams per kilogram of body weight per day

The generic exposure equation used to calculate chemical intake (EPA 1989) is:

$$I = [(C_{gen} \times CR) / BW] * [EF * ED / AT]$$

where

I = Intake—the amount of pollutant at the exchange boundary (mg/kg/day); for evaluating exposure to non-carcinogenic pollutants, the intake is referred to as average daily dose (*ADD*); for evaluating exposure to carcinogenic compounds, the intake is referred to as lifetime average daily dose (*LADD*)

| | | |
|------------------|---|--|
| C_{gen} | = | Generic pollutant concentration in media of concern (e.g., mg/kg for soil or mg/L for surface water) |
| CR | = | Consumption rate—the amount of contaminated medium consumed per unit of time or event (e.g., kg/day for soil and L/day for water) |
| EF | = | Exposure frequency (days/year) |
| ED | = | Exposure duration (years) |
| BW | = | Average body weight of the receptor over the exposure period (kg) |
| AT | = | Averaging time—the period over which exposure is averaged (days); for carcinogens, the averaging time is 25,550 days, based on a lifetime exposure of 70 years; for non-carcinogens, averaging time equals ED (years) multiplied by 365 days per year. |
| $[EF * ED / AT]$ | = | Temporal adjustment to account for exposure duration and frequency. |

The EPA recommends using the maximum for the following exposure values: (1) the highest modeled air parameter values at current and reasonable potential future exposure scenario locations, (2) the exposure frequency, and (3) the exposure duration. Body weight is typically set at average values.

6.3 Exposure calculations

Exposure occurs through direct inhalation of vapors and particles and through indirect exposures when foods or soils have pollutants deposited onto them, and they are then ingested.

6.3.1 Air exposure pathways

Direct inhalation of vapors and particulate emissions is a potential exposure pathway. Receptors in the assessment area are directly exposed to pollutants in vapor, particulate, and particle-bound phases. The factors that affect exposure from vapor and particulate inhalation include vapor and particulate pollutant concentrations, respiration rate during the period of exposure, and length of exposure. HHRAP default inhalation rates for children and adults are used in *MNRISKS*.

Inhalation of vapors and particulates will be influenced by the relative amount of time that a receptor spends indoors. Although vapors entering buildings and residences as a result of air exchange are likely to remain airborne and, therefore, may be inhaled, particulates entering these same buildings are more likely to settle out and not be inhaled. However, air toxics risk assessments commonly include both vapor phase and particle phase pollutants and assumes they are inhaled throughout the day, both indoors and outdoors.

6.3.2 Food exposure pathways

Plants and animals may take up emitted pollutants from the air or from pollutants deposited to the soil. Humans are exposed to pollutants via the food chain when they consume these contaminated plants and animals as a food source. Human intake of pollutants is determined on the basis of:

1. The types of foods consumed.
2. The amount of food consumed per day.
3. The concentration of pollutants in the food.
4. The percentage of the diet contaminated by pollutants.

Other variables may also significantly affect the estimation of exposure. For example, the types of foods consumed will affect exposure, because different plants and animal tissues will take up pollutants at different rates. Furthermore, the types of foods consumed vary with age, geographical region, and socio-cultural factors.

The amount of daily food consumption varies with age, sex, body weight, and geographic region and varies within these categories. The exposure parameters used in *MNRISKS* are taken from the Exposure Factors Handbook from 2011; specifically, the section regarding food items produced at home.

The percentage of home grown food consumed by the individual will affect exposure, because not all of an individual's dietary intake may be contaminated. Receptors, located in a rural or suburban area, which can raise animals and grow food in gardens, will have a larger percentage of their food produced locally than people living in the city.

The EPA HHRAP recommends the following assumptions regarding the percentage of contaminated food:

- With regard to aboveground and belowground produce, it is assumed that 100% of the contaminated produce is consumed.
- With regard to beef, milk, pork, chicken, and eggs, it is assumed that 100% of these animal tissues consumed by the farmer adult or farmer child are contaminated. No other receptors are assumed to consume these animal tissues.
- With regard to fish, it is assumed that 100% of the fish consumed by the fisher adult or fisher child are contaminated. No other receptors are assumed to consume fish.

6.3.3 Soil exposure pathways

Soil ingestion, dermal exposure to soil, and inhalation of re-suspended dust are potential soil exposure pathways. The EPA recommends that soil ingestion be considered in all risk assessments. However, dermal exposure to soil and inhalation of re-suspended dust are currently recommended for evaluation only if site-specific exposure setting characteristics require that these exposure pathways be evaluated. Based on air dispersion modeling and deposition of pollutants, emission concentrations in soil will vary with distance from the source. Soil used for farming or recreation will be involved in pathways of human exposure that differ from those of soil on roadways or in urban areas.

Children and adults are exposed to pollutants in soil when they consume soil that has adhered to their hands. Factors that influence exposure by soil ingestion include soil concentration, the rate of soil ingestion during the time of exposure, and the length of time spent in the vicinity of contaminated soil. Soil ingestion rates in children are based on studies that measure the quantities of non-absorbable tracer minerals in the feces of young children. Ingestion rates for adults are based on assumptions about exposed surface area and frequency of hand-to-mouth consumption.

6.3.4 Drinking water pathway

The drinking water pathway is used to determine exposure to pollutants in drinking water obtained from surface water or precipitation (e.g., cisterns). For the evaluation of a surface waterbody as a drinking water source, exposure is affected by the concentration of the pollutant in the water, the daily amount of water ingested, and the percentage of time an individual spends in the area serviced by that water supply system. The pollutant concentration in a surface waterbody includes the contribution of pollutant loading from the surrounding watershed via runoff. Drinking water exposure is excluded by default in *MNRISKS*, but can be included when appropriate. Because the drinking water pathway assumes surface water is an individual's sole source of drinking water, the pathway will overestimate risk for most Minnesotans that receive their drinking water from wells or treated surface water.

6.3.5 Fish consumption pathway

The consumption of fish from surface water bodies that receive deposition (directly or via runoff) from emission sources are potential routes of exposure. Factors that affect human exposure by ingestion of fish from surface waters include:

1. Sediment and water pollutant concentrations
2. Types of fish consumed
3. Ingestion rates for the various fish
4. Percent of dietary fish caught in the surface waterbody affected by the combustion unit

The types of fish consumed will affect exposure because different types of fish take up pollutants at different rates. For example, fatty fish tend to accumulate organic pollutants more readily than lean fish. The amount of fish consumed also affects exposure, because people who eat large amounts of fish will tend to have higher exposures. Fish consumption rates vary greatly, depending on geographic region and social or cultural factors. Because 100% of a receptor's dietary fish may not originate from the surface waterbody near emission sources, the percentage of locally caught fish is also a variable for exposure. The Fisher scenario incorporates RME fish consumption rates from the nearest fishable waterbody.

6.4 Exposure parameters

Exposures calculated in a risk assessment are intended to represent reasonable maximum exposure conditions (RME). The EPA recommended values for exposure parameters are used in *MNRISKS*. Consumption rate is the amount of contaminated medium consumed per unit of time or event. Consumption rates for subsistence food types (e.g., beef for the subsistence farmer; fish for the subsistence fisher) is assumed to be 100% from the assessment area being evaluated (e.g., farm; waterbody). Consumption rates for non-subsistence food types (e.g., homegrown vegetables) are assumed to be a fraction of the total dietary intake.

The receptors in each recommended exposure scenario are assumed to be exposed to all of the exposure scenario-specific exposure pathways 350 days per year (EPA 1989, 1991). This assumption is based on the assumption that all receptors spend a minimum of two weeks at a location other than the exposure scenario location.

Exposure duration is the length of time that a receptor is exposed via a specific exposure pathway. Although a receptor is no longer exposed to pollutants via the direct inhalation exposure pathway after an emission source ceases operation, a receptor is exposed via the indirect exposure pathways for as long as the receptor and pollutants remain in the assessment area. Therefore, the EPA recommends in the HHRAP using default values to estimate the maximum exposure.

Although an emissions source may remain in the same location for over 100 years—and a person may have a lifetime of exposure to emissions from that source—data from the U.S. Census Bureau on population mobility indicate that most Americans do not remain in the same area for their entire lifetime (Census 2008). The exposure duration values recommended by the EPA are presented in the following table.

Table 7. Exposure duration values for the scenario receptors.

| Recommended Exposure Scenario Receptor | Value | Source |
|---|--------------|----------------------------|
| Child Resident | 6 years | <i>EPA 2005</i> |
| Adult Resident | 30 years | <i>EPA 2005</i> |
| Subsistence Fisher | 30 years | <i>EPA 2005</i> |
| Subsistence Fisher Child | 6 years | Same as the Child Resident |
| Subsistence Farmer | 40 years | <i>EPA 2005</i> |
| Subsistence Farmer Child | 6 years | Same as the Child Resident |

For non-carcinogenic pollutants, EPA uses the years of exposure multiplied by 365 days per year for the exposure averaging time (EPA 2005). However, for carcinogenic pollutants the duration of exposure will vary by the receptor’s age, in that the scenario’s exposure duration is determined by the hypothetical age of the child or adult in question. The EPA recommends that carcinogenic exposures for different receptor ages be evaluated separately, because the daily activities of these receptors vary. For some exposure pathways, such as soil ingestion, children may have greater exposure and be at greater risk compared to adults.

7. Human health risk calculations

The final step of a risk assessment is the calculation of the excess lifetime cancer risks and non-carcinogenic hazards for each of the pathways and receptors. Cancer risks and non-cancer hazards are then summed for specific exposure scenarios, across all applicable exposure pathways, to obtain an estimate of total individual risk and hazard at each receptor.

Risk from exposure to emissions of carcinogenic substances can be quantified as the probability that an individual would develop cancer, based on a unique set of exposure, model, and toxicity assumptions. Cancer risk estimates represent the incremental probability that an individual will develop cancer over a lifetime as a result of specific exposures to carcinogenic chemicals. For example, a risk of 1×10^{-5} is interpreted to mean that an individual has no more than, a one in 100,000 chance of developing cancer from the exposure being evaluated. Regulatory risk target levels are discussed in section 7.4.

In contrast, hazard is quantified as the potential for developing non-carcinogenic health effects as a result of exposure to pollutants, averaged over an exposure period. A hazard is not a probability but, rather, a measure (calculated as a ratio) of the magnitude of an individual's potential exposure relative to a standard exposure level (*RfD* or *RfC*). The standard exposure level is calculated over a similar exposure period and is estimated to pose no appreciable likelihood of adverse health effects to individuals, including special populations (EPA 1989). Risks and hazards are typically characterized for a single recipient and are referred to as individual risks and hazards (EPA 1989, NC DEHNR 1997).

7.1 Cancer risk

Cancer risks are estimated in the form of potential additional cases of cancer in a population of 100,000.

Cancer risks are calculated using the following equations:

$$\text{Cancer Risk} = \text{LADD} \times \text{CSF}$$

where

$$\begin{aligned} \text{LADD} &= \text{Lifetime average daily dose (mg/kg-day)} \\ \text{CSF} &= \text{Cancer slope factor (mg/kg-day)}^{-1} \end{aligned}$$

Within a specific exposure pathway, individuals may be exposed to more than one pollutant. The total risk associated with exposure to all pollutants through a single exposure pathway is estimated as (EPA 1989):

$$\begin{aligned} \text{Cancer Risk}_T &= \sum_i \text{Cancer Risk}_i \\ \text{Cancer Risk}_T &= \text{Total cancer risk for a specific exposure pathway} \\ \text{Cancer Risk}_i &= \text{Cancer risk for pollutant } i \text{ for a specific exposure pathway} \end{aligned}$$

Inhalation cancer risk is calculated as:

$$\text{Cancer Risk}_{inh(i)} = EC \times URF_{(i)}$$

$\text{Cancer Risk}_{inh(i)}$ = Individual lifetime cancer risk from direct inhalation of pollutant *i* (unitless)

$$\begin{aligned} EC &= \text{Exposure concentration } (\mu\text{g}/\text{m}^3) \\ URF_{(i)} &= \text{Inhalation Unit Risk Factor } (\mu\text{g}/\text{m}^3)^{-1} \end{aligned}$$

$$EC = \frac{C_a \times EF \times ED}{AT \times 365 \text{ days/year}}$$

| | |
|----------------|--|
| AT | = Averaging Time (yr) |
| C _a | = Pollutant air concentration (µg/m ³) |
| ED | = Exposure duration (yr) |
| EF | = Exposure frequency (days/year) |

Indirect exposure pathway cancer risk is calculated as:

$$\text{Cancer Risk}_i = \frac{I \times ED \times EF \times CSF}{AT \times 365}$$

Cancer Risk_i = Individual lifetime cancer risk through indirect exposure to pollutant carcinogen i (unitless)

| | |
|-----|---|
| I | = Daily intake of pollutant from plant and animal tissue (mg pollutant/kg By-day) |
| ED | = Exposure duration (yr) |
| EF | = Exposure frequency (days/yr) |
| CSF | = Cancer Slope factor (mg/kg-day) ⁻¹ |
| AT | = Averaging time (yr) |
| 365 | = Unit conversion factor (day/yr) |

At particular exposure scenario locations, receptors may be exposed through a number of exposure pathways. Risks from multiple exposure pathways may be summed for a given receptor.

7.2 Noncancer risks (hazard quotients)

Standard risk assessment models include the assumption that non-carcinogenic effects, exhibit a threshold; that is, there is a level of exposure below which no adverse effects will be observed (EPA 1989). The potential for non-carcinogenic health effects resulting from exposure to a chemical is generally assessed by:

1. Comparing an exposure estimate to an *RfD* for oral exposures
2. Comparing an estimated chemical air concentration to the *RfC* for inhalation exposures

Chronic *RfDs* and *RfCs* are used to evaluate all exposure pathways. The comparisons of exposure estimates and pollutant-specific air concentrations to *RfD* and *RfC* values, described above, are known as hazard quotients (*HQ*), which are calculated as:

$$HQ = ADD / RfD \text{ or } HQ = EC / RfC$$

where

| | |
|------------|--|
| <i>HQ</i> | = Hazard quotient (unitless) |
| <i>ADD</i> | = Average daily dose (mg/kg-day) |
| <i>EC</i> | = Total pollutant air concentration (mg/m ³) |
| <i>RfD</i> | = Reference dose (mg/kg-day) |
| <i>RfC</i> | = Reference concentration (mg/m ³) |

As with carcinogenic chemicals in a specific exposure pathway, a receptor may be exposed to multiple chemicals associated with non-carcinogenic health effects. The total non-carcinogenic hazard attributable to exposure to all pollutants through a single exposure pathway is known as a hazard index (*HI*). Consistent with the procedure for addressing carcinogenic risks, the non-carcinogenic hazards from all sources of air toxics emissions can be summed for each receptor.

The *HI* is calculated as:

$$HI = \sum HQ_i$$

where

HI = Total hazard for a specific exposure pathway
HQ_i = Hazard quotient for pollutant (*i*)

A receptor may be exposed to pollutants associated with non-carcinogenic health effects through more than one exposure pathway. For the purposes of the risk assessment, it is reasonable to estimate a receptor's total hazard as the sum of the *HI*s for each of the exposure pathways. Specifically, a receptor's total hazard is the sum of hazards from each individual exposure pathway, expressed as:

$$\text{Cumulative HI} = \sum HI$$

where

Cumulative HI = Total hazard index from multiple exposure pathways
HI = Total hazard index for a specific exposure pathway

The following equation calculates Hazard Quotients (HQ) for the direct inhalation exposure pathway to non-carcinogenic pollutants.

$$HQ_{inh(i)} = \frac{EC \times 0.001}{RfC}$$

$HQ_{inh(i)}$ = Hazard quotient for direct inhalation of pollutant *i*

EC = Exposure concentration $\mu\text{g}/\text{m}^3$
 0.001 = Units conversion factor $\text{mg}/\mu\text{g}$
 RfC = Reference concentration (mg/m^3)

where

$$EC = \frac{C_a \times EF \times ED}{AT \times 365 \text{ days/year}}$$

EC = Exposure concentration ($\mu\text{g}/\text{m}^3$)

C_a = Total pollutant air concentration ($\mu\text{g}/\text{m}^3$)
 EF = Exposure frequency (days/yr)
 ED = Exposure duration (yr)
 AT = Averaging time (yr)
 365 = Units adjustment factor (days per year)

The following equation calculates Hazard Quotients (HQ) for indirect exposure to non-carcinogenic pollutants:

$$HQ = \frac{I \times ED \times EF}{RfD \times AT \times 365}$$

HQ = Hazard Quotient

| | |
|-----|---|
| I | = Daily intake of pollutant i from animal tissue j (mg pollutant/ kg-day) |
| ED | = Exposure duration (yr) |
| EF | = Exposure frequency (days/yr) |
| R/D | = Reference Dose (mg/kg-day) |
| AT | = Averaging time (yr) |
| 365 | = Units conversion factor (day/yr) |

7.3 Acute inhalation exposure

In addition to long-term chronic effects, short-term or acute effects are considered from direct inhalation of vapor phase and particle phase pollutants. It is assumed that short-term emissions will not have a significant impact through the indirect exposure pathways (as compared to impacts from long-term emissions). Therefore, acute effects are only evaluated through the short-term (maximum one-hour) inhalation of vapors and particulates exposure pathway.

7.4 Risk modeling

Risk modeling in *MNRISKS* is based on the EPA HHRAP as implemented in the human health risk assessment software IRAP View™. This software implements the EPA HHRAP guidance to estimate potential human health cancer and non-cancer health effects resulting from the selected pathways and exposure scenarios.

MNRISKS uses the following approach:

1. Import the AERMOD modeled unitized air dispersion modeling results for all the sources. For point sources each emission release point is modeled separately. For allocated point sources, high traffic onroad mobile sources, and gas stations each emission point is modeled as a separate source. Other nonpoint, non-road, and on-road sources are allocated to census block groups, so each block group is modeled once as a polygon area source in AERMOD.
2. Import all LULC maps, census block groups (in shapefile format), base maps of the assessment area and other desired features to support identification of land use characteristics.
3. Import the emission rates from the Emissions Inventory database
4. Import the updated chemical fate and transport parameters table
5. Use the IRAP-*h* View™ calculation engine to calculate potential human health cancer risks and hazard quotients for each source at each receptor point.

7.4.1 Risk modeling inputs

The specific inputs to risk modeling include the following:

- Speciated emission rates specific to each emission source and emission release point.
- Fate and transport parameter values evaluated at each exposure location.
- Exposure parameter values specific to each exposure pathway evaluated.
- Chemical and physical properties specific to each pollutant evaluated.

Speciated emission rates are input to the risk modeling and allocated to the unitized air parameter values obtained as output from air modeling. Speciated emission rates are entered on a gram per second basis and verified using CAS numbers or MPCA assigned ID numbers for chemical mixtures. Contaminant-specific emission rates are required since toxicity values in risk modeling are also contaminant specific.

7.4.3 Exposure scenario parameters

Before modeled concentrations are used for exposure estimation a series of assumptions must be made as to how, when, and where the exposure takes place. This set of assumptions is called the exposure scenario parameters.

Table 8. Exposure parameter values for the resident scenario. (EPA 2005).

| Parameter Description | Units | Resident Adult | Resident Child |
|--|--------------------|----------------|----------------|
| Averaging time for carcinogens | yr | 70 | 70 |
| Averaging time for non-carcinogens | yr | 30 | 6 |
| Body weight | kg | 70 | 15 |
| Exposure duration | yr | 30 | 6 |
| exposure frequency | day/yr | 350 | 350 |
| Inhalation exposure duration | yr | 30 | 6 |
| Inhalation exposure frequency | day/yr | 350 | 350 |
| Inhalation exposure time | hr/day | 24 | 24 |
| Inhalation rate | m ³ /hr | 0.63 | 0.30 |
| Length of exposure duration | yr | 30 | 6 |
| Time period over which release of emissions occurs | yr | 30 | 30 |

Note: The EPA published an update to the Exposure Factors Handbook in 2011 that included recommended body weights and inhalation rates.

For the air inhalation pathway, the factors that affect exposure include air contaminant (vapor and particulate) concentrations at each exposure location, respiration rate during the period of exposure, length of exposure, and time period over which the release of emissions occurs. Respiration rates of 0.63 cubic meters per hour (m³/hr) for the adult and 0.30 m³/hr for the child are used to represent normal or non-working average inhalation rates (EPA 2005). These values are consistent with the *Exposure Factors Handbook* (EPA 1997 & 2011), and about 25% less than inhalation rates specified in EPA's risk assessment guidance for superfund sites (EPA 1989, 1991).

Values used for length of exposure are consistent with HHRAP. A value of 30 years is used to represent the time period over which the release of emissions from a source occurs. Specific values for this parameter are not available for emission sources evaluated, and therefore, the value of 30 years is an assumed value based on the intended life expectancy of industrial facilities and other emission sources considered.

Exposure via inhalation of contaminants is influenced by daily activities (e.g., resting, playing, working) and where those activities occur (e.g., indoors, outdoors, driving, occupation) (EPA 1987). The numerical influence of these daily exposure elements is also expected to be receptor and exposure location specific. For example, a scenario receptor (e.g., Resident Adult) may spend more time indoors, which may tend to decrease exposure to some contaminants and increase exposures to others, but work at a location that has significantly higher exposure concentrations compared to the residence exposure location evaluated. *MNRISKS* calculates the exposure at the receptor location based upon the assumption of continuous exposure to the outdoor air concentration.

7.4.4 Risk modeling outputs

Estimates of media concentrations, cancer risks and noncancer risks (hazard quotients and hazard indices) are produced for each source and contaminant modeled, and at each receptor point affected by

the source. These estimates can be viewed in tabular format or visualized using the GIS interface for any desired geographic extents in Minnesota. Outputs can be selected for an individual source or a group of sources, an individual exposure pathway, or for a single pollutant or group of pollutants.

7.5 Human health benchmarks

The following sections discuss carcinogenic and non-carcinogenic toxicity benchmarks of compounds. Toxicity benchmarks and slope factors may change as additional toxicity research is conducted. The toxicity values table is periodically updated to reflect the most current health benchmark values. Table 10 lists the categories of toxicity benchmarks along with the definition and method of calculation.

A complete list of the toxicity values used for each pollutant is available at: [AERA | Air toxicity values: Air toxicity values - Tableau Server \(state.mn.us\)](#).

Table 9. Terminology and equations used in human health risk calculations. (EPA 2005).

| Term | Definition | Calculation |
|---|---|---|
| Oral Reference Dose (RfD) | Is the amount of a chemical that one can ingest every day for a lifetime that is not anticipated to cause harmful non cancer health effects. The RfD can be compared to an estimate of exposure in mg/kg-day. | $Oral\ RfD = \frac{RfC \cdot 20\ m^3/d}{70\ kg\ BW}$ |
| Inhalation Reference Concentration (RfC) | Is the concentration of a chemical that one can breathe every day for a lifetime that is not anticipated to cause harmful noncancer health effects. The RfC can be compared to an estimate of exposure concentration in mg/m ³ . | |
| Oral Slope factor (OSF) (Inhalation or Oral) | Is an estimate of the increased cancer risk from oral exposure to a dose of 1 mg/kg-day for a lifetime. The OSF can be multiplied by an estimate of lifetime exposure (in mg/kg-day) to estimate the lifetime cancer risk. | $Inhal.\ CSF = \frac{Inhal.\ URF \cdot 70\ kg}{20\ m^3/d} \cdot 1000\ \mu g/mg$ |
| Inhalation Unit risk (IUR) | Is an estimate of the increased cancer risk from oral exposure to a dose of 1 mg/kg-day for a lifetime. The OSF can be multiplied by an estimate of lifetime exposure (in mg/kg-day) to estimate the lifetime cancer risk. | $Inhal.\ URF = \frac{Oral\ CSF \cdot 20\ m^3/d}{70\ kg \times 1000\ \mu g/mg}$ |

7.5.1 Inhalation health benchmarks

Inhalation health benchmark (IHB) concentrations are available from various toxicity data sources to assess each chemical with respect to these exposure duration-health effect measures: non-cancer acute, chronic reference concentrations and cancer risk-based air concentrations considered protective at a 10⁻⁵ additional cancer risk level for lifetime exposures.

The MPCA/MDH hierarchy of toxicity data sources for assessing air toxics inhalation risks is summarized below.

1. Specific MDH guidance
2. EPA IRIS
3. California EPA (CALEPA)
4. Provisional Peer Reviewed Toxicity Values
5. Agency for Toxic Substances and Disease Registry (ATSDR)

This hierarchy is described in MPCA's Air Emissions Risk Analysis (AERA) guidance manual ([Air Emission Risk Analysis \(AERA\) Guidance \(state.mn.us\)](#)). MPCA's hierarchy of screening inhalation health benchmarks is maintained in the Risk Analysis Screening Spreadsheet (RASS) associated with the AERA process.

For PCBs and dioxin/furans, MDH recommends using the World Health Organization's Toxic Equivalent Factors scheme (Van den Berg, et al. 2006) to weight each compound according to its relative toxicity for cancer risk evaluations. The MDH also recommends using the dioxin cancer slope factor proposed by the EPA in its draft dioxin reassessment. In collaboration with MDH, the MPCA derived a dioxin inhalation unit risk based on this slope factor [Dioxins - Guidance for Air \(state.mn.us\)](#)

To evaluate carcinogenic PAHs (cPAHs), MDH recommends using relative potency factors in conjunction with EPA's benzo(a)pyrene toxicity values. More information on this can be found at [Guidance for Evaluating the Cancer Potency of Polycyclic Aromatic Hydrocarbon \(PAH\) Mixtures in Environmental Samples \(state.mn.us\)](#).

7.5.2 Use of surrogate inhalation and oral health benchmarks

Toxicity information is not typically available for entire mixtures or groups of many chemicals, such as aldehydes, but an IHB may be available for one or more of the individual chemicals contained in the mixture. As a rough screening measure, surrogate toxicity values for chemical mixtures or groups are derived from the most toxic chemical with an available IHB contained in the mixture or group. Where surrogates are used to represent chemical groups or mixtures, they are identified on the *ToxValues* page of the RASS. The same principles are used to assign surrogate values for appropriate chemicals included in the emission inventory but not listed in the RASS.

Oral surrogate toxicity values are assigned to chemical mixtures or groups based on the most relevant chemical within the mixture or group. In circumstances where no other information is available, the most toxic chemical is used for the surrogate. A specific list of surrogates is available in Appendix C of this document.

7.5.3 Ingestion toxicity values – reference doses (RfDs) and oral slope factors

Current ingestion toxicity values are obtained from the Risk Assessment Information System (RAIS) managed by Oak Ridge National Laboratory (https://rais.ornl.gov/cgi-bin/tools/TOX_search?select=chemtox). For dioxin/furans and PCBs the MDH recommends using the World Health Organization's Toxic Equivalent Factors scheme (Van den Berg, et al. 2006) to weight each compound according to its relative toxicity for cancer risk evaluations. The MPCA uses this approach for ingestion and for inhalation risk estimates. The MPCA also uses EPA's draft dioxin reassessment cancer slope factor that is detailed online at [Dioxins - Guidance for Air \(state.mn.us\)](#)

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Appendix A – Abbreviations and terminology

Fugitive emissions: The EPA defines fugitive emissions in the regulations promulgated under title V of the Clean Air Act as “*those emissions which could not reasonably pass through a stack, chimney, vent, or other functionally-equivalent opening*” (title 40 of the Code of Federal Regulations, sections 70.2 and 71.2). Fugitive emissions are typically modeled as area or volume sources in the AERMOD model.

IRIS: The EPA Integrated Risk Information System

Land use land cover (LULC) maps: LULC data files describe the vegetation, water, natural surface, and cultural features on the land surface. The USGS provides these data sets and associated maps as a part of its National Mapping Program. The LULC mapping program is designed so that standard topographic maps of a scale of 1:250,000 can be used for compilation and organization of the land use and land cover data. LULC maps are available in digital formats.

MDH: Minnesota Department of Health

Mobile: Mobile sources include on-road vehicles, off-road vehicles, and other transportation equipment. For modeling, mobile sources are broken down into on-road vehicles, aircraft, locomotives and off-road sources.

Examples of on-road vehicles:

- Automobiles
- Trucks
- Buses

Examples of off-road sources:

- Agricultural equipment, such as farm tractors
- Construction equipment
- Lawn mowers
- Recreational vehicles
 - Snowmobiles
 - All-terrain vehicles
 - Boats and personal watercraft

Other types of transportation vehicles:

- Aircraft
- Railroad locomotives
- Marine vessels

Nonpoint source: Nonpoint sources are defined as any emissions source not required to submit criteria pollutant inventories. They are also called area sources. Examples of these types of emission sources include vehicles, residential fires, snowmobiles, and portable fuel tanks. A list of the nonpoint sources included in *MNRISKS* is given in Table 1 and Appendix B.

Point source: Stationary source of fixed size that is designed to vent vapors and/or particulates into ambient air and from which emissions may result in the release of contaminants into ambient air while the source is operated as intended (vents, flares, etc.). Stack sources are characterized for air modeling based on physical stack parameters (stack height, stack diameter, etc.) and operational conditions (stack temperature, stack exit velocity, etc.).

Receptor: A location where concentration and risk calculations are estimated.

RME: Reasonable maximum exposure.

SRV: MPCA Tier 1 Soil Reference Value.

Surrogate: When the precise location of a nonpoint or mobile source is not included in the inventory, a surrogate or alternative measurement is used to distribute county emissions to block groups using land use maps and activity data that capture the ways a given category occurs in space across a county. For example, county emissions from restaurants are distributed to block groups according to the density of restaurants operating within its boundaries.

Topographic maps: Topographic maps are readily available in both hard copy and electronic format directly from USGS or numerous other vendors. These maps are commonly at a scale of 1:24,000, and in a tagged information file format (TIFF) with TIFF World File included for geo-referencing.

VKT: Vehicle Kilometers Traveled. The traffic data provided by MNDOT are in metric units.

Appendix B – Surrogates for apportioning county emissions to block groups

Table 10. Surrogates for apportioning county emissions to Census Block Groups.

| SCC category | Surrogate description | Data source for apportioning | Surrogate ID |
|--------------------------|---|---|----------------------|
| A_ResWoodIndoorHeat | Single family households | ACS | frx_sfhh |
| A_ResWoodOutdoorHeat | Single family households in low intensity developed and undeveloped land | ACS, LULC | frx_sfhh_undev |
| NR_Agriculture | Land in agricultural use | LULC | frx_ag |
| NR_Construction | Developed in metro and medium_high development outstate | LULC | frx_cnstrx_medhidev |
| NR_LawnGardenRes | Single family households | ACS | frx_sfhh |
| NR_LawnGardenComm | Open_low_medium_intensity development | LULC | frx_dev |
| NR_Recreation | Developed_low intensity, developed open space, and water surface area | LULC | frx_owtl |
| NR_Rail | Railroad shapefile | Rail network spatial dataset | frx_rail |
| NR_CommercialIndustrial | Commercial_institutional_industrial in metro and medium_high outstate | LULC | frx_comminstindmedhi |
| NR_Logging | Forests | LULC | frx_for |
| A_ResidentialActivities | Single family households | ACS | frx_sfhh |
| A_Compost_Decomposition | Land area | LULC | frx_land |
| A_UncontrolledCombustion | Single family residences where structures fires and yard waste burning would be allowable and developed areas where structure fires may occur agricultural areas where crop burning would occur | ACS, zoning, LULC | frx_agsfdev |
| A_Boilers | Commercial_institutional_industrial in metro and medium_high outstate | LULC | frx_comminstindmedhi |
| NR_CMV | Major waterways and port shapefile | World waterway infrastructure shapefile | frx_wwports |
| A_Agriculture | Land in agricultural use | | frx_ag |
| A_PetrolStorTrans | Single family households, commercial in metro - outstate high intensity developed, gas stations, pipelines, diesel VKT | ACS, MPCA Tanks data, LULC, National Pipeline database, MNDOT VKT | frx_diespl_pgc_gs |
| A_CommResCooking | Single family households and commercial in metro - outstate LU categories 23,24 (med & high intensity developed) | ACS, LULC | frx_sfhhcommehi |
| A_SurfaceCoat | Commercial_institutional_industrial in metro and medium_high outstate | LULC | frx_comminstindmedhi |
| OR_Gasoline | VKT | VKT with gasoline fraction from EPAMOVES | frx_gasvktOR |
| OR_Diesel | VKT | VKT with diesel fraction from EPAMOVES | frx_diesvktOR |
| A_Biogenic | Undeveloped land | LULC | frx_undev |
| A_SelectMercury | Commercial_institutional_industrial in metro and medium_high outstate | LULC | frx_comminstindmedhi |

| SCC category | Surrogate description | Data source for apportioning | Surrogate ID |
|--------------|---|---|----------------------|
| NR_Airports | Number of airports in each county | Airports information in Minnesota shapefile | frx_airports |
| NR_Portables | VKT | VKT | frx_portvkt |
| A_Industrial | Commercial_institutional_industrial in metro and medium_high outstate | LULC | frx_comminstindmedhi |

Algorithm for each pollutant in each block group:

$$\text{block group emissions} = \text{county emissions} * \frac{\text{surrogate value in block group}}{\sum(\text{surrogate block group values in county})}$$

$$\sum \left(\frac{\text{surrogate value in block group}}{\sum(\text{surrogate blockgroup values in county})} \right) \text{summed over all BGs in a county will usually} = 1$$

Appendix C – Pollutant groups for emissions processing and risk characterization

Table 11. Pollutant groups for emissions processing and risk characterization.

| CAS_NO | group_cas | POLLUTANT CATEGORYNAME | COPC_DESC | Group |
|------------|------------|---------------------------|--------------------------------------|--------------|
| 7783-70-2 | 7440-36-0 | Antimony Compounds | ANTIM PENTA FL | ANTIMONY |
| 10025-91-9 | 7440-36-0 | Antimony Compounds | ANTIM TRICL | ANTIMONY |
| 7440-36-0 | 7440-36-0 | Antimony Compounds | ANTIMONY | ANTIMONY |
| 1327-33-9 | 7440-36-0 | Antimony Compounds | ANTIMONY OXIDE | ANTIMONY |
| 1309-64-4 | 7440-36-0 | Antimony Compounds | ANTIMONY TRIOXIDE | ANTIMONY |
| 7440-38-2 | 7440-38-2 | Arsenic Compounds | ARSENIC | ARSENIC |
| 1327-53-3 | 7440-38-2 | Arsenic Compounds | ARSENIC TRIOXIDE | ARSENIC |
| 7784-42-1 | 7440-38-2 | Arsenic Compounds | ARSINE | ARSENIC |
| 7440-41-7 | 7440-41-7 | Beryllium Compounds | BERYLLIUM | BERYLLIUM |
| 1304-56-9 | 7440-41-7 | Beryllium Compounds | BERYLLIUM OXIDE | BERYLLIUM |
| 7795-91-7 | 111-76-2 | Glycol Ethers | Diethylene Glycol Monoethyl Ether | BUT CELLOSOL |
| 7440-43-9 | 1306-23-6 | Cadmium Compounds | CADMIUM | CADMIUM |
| 1306-19-0 | 1306-23-6 | Cadmium Compounds | CADMIUM OXIDE | CADMIUM |
| 1306-23-6 | 1306-23-6 | Cadmium Compounds | CADMIUM SULFIDE | CADMIUM |
| 12018-01-8 | 16065-83-1 | Chromium Compounds | CHROMIUM DIOXIDE | CHROMIUM III |
| 12018-19-8 | 16065-83-1 | Chromium Compounds | CHROMIUM ZINC OXIDE | CHROMIUM III |
| 16065-83-1 | 16065-83-1 | Chromium Compounds | CHROMIUM (III) | CHROMIUM III |
| 1308-14-1 | 16065-83-1 | Chromium Compounds | CHROMIUM HYDROXIDE | CHROMIUM III |
| 1308-38-9 | 16065-83-1 | Chromium Compounds | CHROMIUM (III) OXIDE | CHROMIUM III |
| 10294-40-3 | 18540-29-9 | Chromium Compounds | BARIUM CHROMATE | CHROMIUM VI |
| 13765-19-0 | 18540-29-9 | Chromium Compounds | CALCIUM CHROMATE | CHROMIUM VI |
| 7738-94-8 | 18540-29-9 | Chromium Compounds | CHROMIC ACID | CHROMIUM VI |
| 18540-29-9 | 18540-29-9 | Chromium Compounds | CHROMIUM (VI) | CHROMIUM VI |
| 14977-61-8 | 18540-29-9 | Chromium Compounds | CHROMYL CHLORIDE | CHROMIUM VI |
| 1333-82-0 | 18540-29-9 | Chromium Compounds | CHROMIUM (VI) OXIDE (1:3) | CHROMIUM VI |
| 7778-50-9 | 18540-29-9 | Chromium Compounds | K+ Dichromate | CHROMIUM VI |
| 7758-97-6 | 18540-29-9 | Lead Compounds | LEAD CHROMATE | CHROMIUM VI |
| 7789-00-6 | 18540-29-9 | Chromium Compounds | POTASSIUM CHROMATE | CHROMIUM VI |
| 10034-82-9 | 18540-29-9 | Chromium Compounds | SODIUM CHROMATE (VI) | CHROMIUM VI |
| 10588-01-9 | 18540-29-9 | Chromium Compounds | SODIUM DICHROMATE | CHROMIUM VI |
| 7789-06-2 | 18540-29-9 | Chromium Compounds | STRONTIUM CHROMATE | CHROMIUM VI |

| CAS_NO | group_cas | POLLUTANT CATEGORYNAME | COPC_DESC | Group |
|------------|------------|--------------------------------------|---|---------------------|
| 13530-65-9 | 18540-29-9 | Chromium Compounds | ZINC CHROMATE | CHROMIUM VI |
| 50922-29-7 | 16065-83-1 | Chromium Compounds | Zinc Chromite | CHROMIUM III |
| 11103-86-9 | 18540-29-9 | Chromium Compounds | Zinc K+ Chromate | CHROMIUM VI |
| 1345-16-0 | 7440-48-4 | Cobalt Compounds | COBALT ALUMINATE | COBALT |
| 7440-48-4 | 7440-48-4 | Cobalt Compounds | COBALT | COBALT |
| 13586-82-8 | 7440-48-4 | Cobalt Compounds | COBALT 2-ETHYLHEXANOATE | COBALT |
| 61789-51-3 | 7440-48-4 | Cobalt Compounds | COBALT NAPHTHA | COBALT |
| 1307-96-6 | 7440-48-4 | Cobalt Compounds | COBALT OXIDE | COBALT |
| 10124-43-3 | 7440-48-4 | Cobalt Compounds | COBALT SULFATE | COBALT |
| 136-52-7 | 7440-48-4 | Cobalt Compounds | COBALT 2-ETHYLHEXANOATE (KNOWN STOICHIOMETRY) | COBALT |
| 544-92-3 | 7440-50-8 | Copper Compounds | COPPER CYANIDE | COPPER |
| 1319-77-3 | 1319-77-3 | Cresol/Cresylic Acid (Mixed Isomers) | CRESOL MX IS | CRESOL MX IS |
| 108-39-4 | 1319-77-3 | Cresol/Cresylic Acid (Mixed Isomers) | M-CRESOL | CRESOL MX IS |
| 95-48-7 | 1319-77-3 | Cresol/Cresylic Acid (Mixed Isomers) | O-CRESOL | CRESOL MX IS |
| 106-44-5 | 1319-77-3 | Cresol/Cresylic Acid (Mixed Isomers) | P-CRESOL | CRESOL MX IS |
| 544-92-3 | 57-12-5 | Cyanide Compounds | COPPER CYANIDE | CYANIDE |
| 57-12-5 | 57-12-5 | Cyanide Compounds | CYANIDE | CYANIDE |
| 74-90-8 | 57-12-5 | Cyanide Compounds | HYDROGEN CYANIDE | CYANIDE |
| 151-50-8 | 57-12-5 | Cyanide Compounds | POTASSIUM CYANIDE | CYANIDE |
| 506-64-9 | 57-12-5 | Cyanide Compounds | SILVER CYANIDE | CYANIDE |
| 143-33-9 | 57-12-5 | Cyanide Compounds | SODIUM CYANIDE | CYANIDE |
| 557-21-1 | 57-12-5 | Cyanide Compounds | ZINC CYANIDE | CYANIDE |
| 13967-50-5 | 57-12-5 | Cyanide Compounds | GOLD POTASSIUM CYANIDE | CYANIDE |
| 25321-22-6 | 25321-22-6 | Dichlorobenzenes | DICHLOROBENZENES | DICHLOROBENZENES |
| 541-73-1 | 25321-22-6 | Dichlorobenzenes | M-DICHLOROBENZENE | DICHLOROBENZENES |
| 95-50-1 | 25321-22-6 | Dichlorobenzenes | O-DICHLOROBENZENE | DICHLOROBENZENES |
| 106-46-7 | 25321-22-6 | Dichlorobenzenes | P-DICHLOROBENZENE | DICHLOROBENZENES |
| 10061-01-5 | 542-75-6 | Dichloropropenes, 13 | C-DICHLOROPROPENE | DICHLOROPROPENE, 13 |
| 542-75-6 | 542-75-6 | Dichloropropenes, 13 | DICHLOROPROPENE, 13 | DICHLOROPROPENE, 13 |
| 10061-02-6 | 542-75-6 | Dichloropropenes, 13 | T-DICHLOROPROPENE | DICHLOROPROPENE, 13 |
| 431-89-0 | HFCs | Hydrofluorocarbons | HFC-227ea | Hydrofluorocarbons |

| CAS_NO | group_cas | POLLUTANT CATEGORYNAME | COPC_DESC | Group |
|--------------|-----------|---------------------------|--------------------------------|---------------------------|
| 593-53-3 | HFCs | Hydrofluorocarbons | HFC-41 | Hydrofluorocarbons |
| 75-46-7 | HFCs | Hydrofluorocarbons | HFC-23 | Hydrofluorocarbons |
| 7439-92-1 | 7439-92-1 | Lead Compounds | LEAD | LEAD |
| 1317-36-8 | 7439-92-1 | Lead Compounds | LEAD (II) OXIDE | LEAD |
| 598-63-0 | 7439-92-1 | Lead Compounds | LEAD CARBONATE | LEAD |
| 7758-97-6 | 7439-92-1 | Lead Compounds | LEAD CHROMATE | LEAD |
| 7446-27-7 | 7439-92-1 | Lead Compounds | LEAD PHOSPHATE | LEAD |
| 7446-14-2 | 7439-92-1 | Lead Compounds | LEAD SULFATE | LEAD |
| 78-00-2 | 7439-92-1 | Lead Compounds | TETRAETHYL LEAD | LEAD |
| 10377-66-9 | 7439-96-5 | Manganese Compounds | MANGAN NITRATE | MANGANESE |
| 7785-87-7 | 7439-96-5 | Manganese Compounds | MANGAN SULFATE | MANGANESE |
| 7439-96-5 | 7439-96-5 | Manganese Compounds | MANGANESE | MANGANESE |
| 1313-13-9 | 7439-96-5 | Manganese Compounds | MANGANESE DIOXIDE | MANGANESE |
| 8030-70-4 | 7439-96-5 | Manganese Compounds | MANGANESE TALLATE | MANGANESE |
| 1317-34-6 | 7439-96-5 | Manganese Compounds | MANGANESE TRIOXIDE | MANGANESE |
| 7439-97-6 | 7439-97-6 | Mercury Compounds | MERCURY | MERCURY |
| 22967-92-6 | 7439-97-6 | Mercury Compounds | MERCURY (ORGANIC) | MERCURY |
| 7440-02-0 | 7440-02-0 | Nickel Compounds | NICKEL | NICKEL |
| 6018-89-9 | 7440-02-0 | Nickel Compounds | NICKEL ACETATE TETRAHYDRATE | NICKEL |
| 12054-48-7 | 7440-02-0 | Nickel Compounds | NICKEL HYDROXIDE | NICKEL |
| NICKEL REFIN | 7440-02-0 | Nickel Compounds | NICKEL REFINING DUST | NICKEL |
| 7786-81-4 | 7440-02-0 | Nickel Compounds | NICKEL SULFATE | NICKEL |
| 13462-88-9 | 7440-02-0 | Nickel Compounds | NICKEL BROMIDE | NICKEL |
| 7718-54-9 | 7440-02-0 | Nickel Compounds | NICKEL CHLORIDE | NICKEL |
| 13138-45-9 | 7440-02-0 | Nickel Compounds | NICKEL NITRATE | NICKEL |
| 1313-99-1 | 7440-02-0 | Nickel Compounds | NICKEL(II) OXIDE (1:1) | NICKEL |
| 1314-06-3 | 7440-02-0 | Nickel Compounds | NICKEL (III) OXIDE | NICKEL |
| 13770-89-3 | 7440-02-0 | Nickel Compounds | NICKEL SULFAMATE | NICKEL |
| PFC | PFAS | Perfluoroalkyl substances | Perfluorocarbons | Perfluoroalkyl substances |
| 115-25-3 | PFAS | Perfluoroalkyl substances | PFC-318 | Perfluoroalkyl substances |
| 76-19-7 | PFAS | Perfluoroalkyl substances | PFC-218 | Perfluoroalkyl substances |
| 7488-56-4 | 7782-49-2 | SELENIUM Compounds | SELENIUM DISULFIDE | SELENIUM |
| 12640-89-0 | 7782-49-2 | SELENIUM Compounds | SELENIUM OXIDE | SELENIUM |
| 108-38-3 | 1330-20-7 | Xylenes (Mixed Isomers) | M-XYLENE | XYLENES ISO |
| 95-47-6 | 1330-20-7 | Xylenes (Mixed Isomers) | O-XYLENE | XYLENES ISO |
| 106-42-3 | 1330-20-7 | Xylenes (Mixed Isomers) | P-XYLENE | XYLENES ISO |
| 1330-20-7 | 1330-20-7 | Xylenes ISO | XYLENES ISO | XYLENES ISO |

| CAS_NO | group_cas | POLLUTANT CATEGORYNAME | COPC_DESC | Group |
|------------|------------|---------------------------|---------------------------------------|------------------------------|
| 12018-19-8 | 7440-66-6 | Zinc Compounds | CHROMIUM ZINC OXIDE | ZINC |
| 13530-65-9 | 7440-66-6 | Zinc Compounds | ZINC CHROMATE | ZINC |
| 50922-29-7 | 7440-66-6 | Zinc Compounds | Zinc Chromite | ZINC |
| 557-21-1 | 7440-66-6 | Zinc Compounds | ZINC CYANIDE | ZINC |
| 11103-86-9 | 7440-66-6 | Zinc Compounds | Zinc K+ Chromate | ZINC |
| 75-89-8 | HFC-ols | Fluoroalcohols | Trifluoroethanol | Fluoroalcohols |
| 359-13-7 | HFC-ols | Fluoroalcohols | Difluoroethanol | Fluoroalcohols |
| 371-62-0 | HFC-ols | Fluoroalcohols | 2-Fluoroethanol | Fluoroalcohols |
| 375-01-9 | PFAS | Perfluoroalkyl substances | Perfluoropropyl carbinol | Perfluoroalkyl substances |
| 422-05-9 | PFAS | Perfluoroalkyl substances | 2,2,3,3,3-Pentafluoro-1- propanol | Perfluoroalkyl substances |
| 76-37-9 | PFAS | Perfluoroalkyl substances | 2,2,3,3-Tetrafluoro-1- propanol | Perfluoroalkyl substances |
| 76-14-2 | PFAS | Perfluoroalkyl substances | 1,2- Dichlorotetrafluoroetha ne | Perfluoroalkyl substances |
| 140-29-4 | 57-12-5 | Cyanide Compounds | BENZYL CYANIDE | CYANIDE |
| 156-62-7 | 57-12-5 | Cyanide Compounds | Calcium cyanamide | CYANIDE |
| 14307-35-8 | 18540-29-9 | Chromium Compounds | Lithium Chromate | CHROMIUM VI |
| 13943-58-3 | 57-12-5 | Cyanide Compounds | Potassium ferrocyanide | CYANIDE |