15.0 Ecological Exposure Module

15.1 Purpose and Scope

The Ecological Exposure Module calculates the applied contaminant dose (in mg/kg-d) to ecological receptors that may be exposed via ingestion of contaminated plants, prey, and media (i.e., soil, sediment, and surface water). The Ecological Exposure Module uses various input contaminant concentrations from the Surface Impoundment, Surface Water, Terrestrial Food Web, and Aquatic Food Web Modules. Detailed information on the Ecological Exposure Module can be found in the background document (U.S. EPA, 2000). Figure 15-1 shows the relationship and information flow between the Ecological Exposure Module and the 3MRA modeling system.

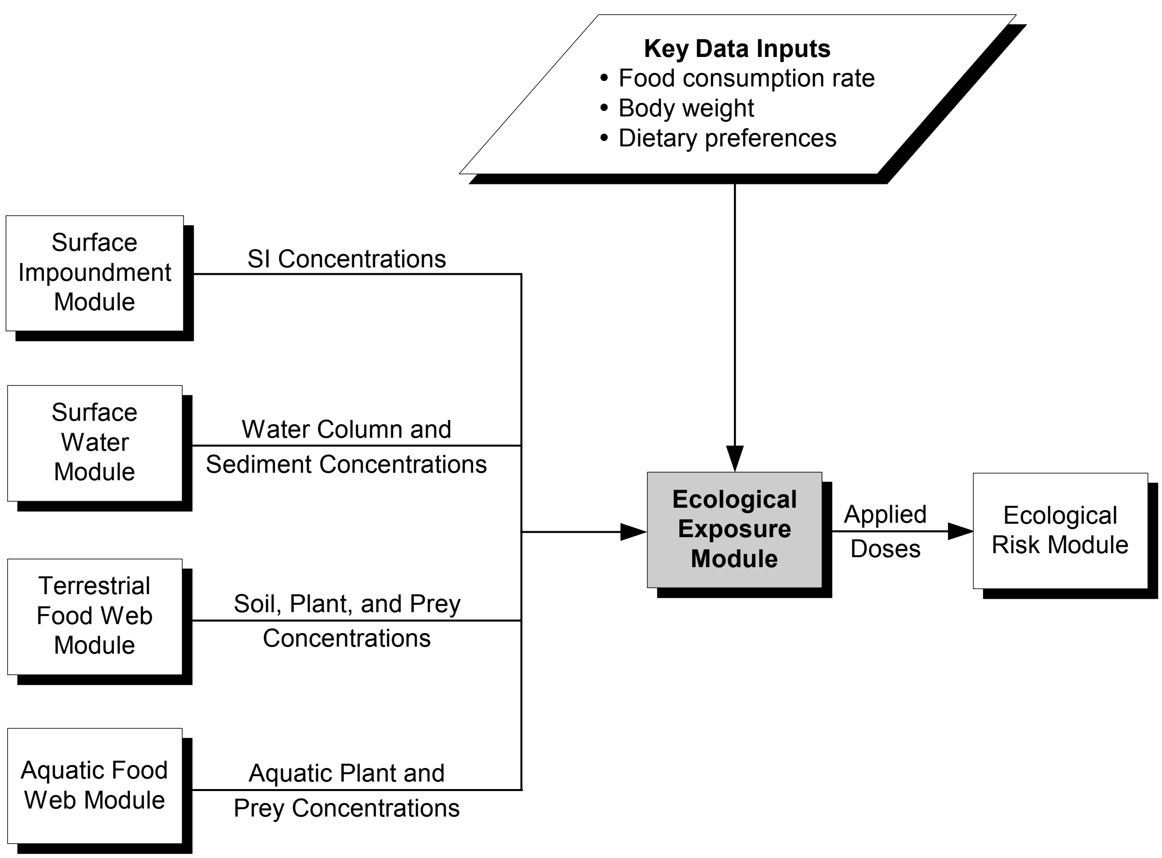

Figure 15-1. Information flow for the Ecological Exposure Module in the 3MRA modeling system.

The methodology and equations used to calculate the applied dose to mammals and birds assigned to habitats within the AOI are consistent with the principles and guidelines described in the *Guidelines for Ecological Risk Assessment* (U.S. EPA, 1998). The basic forms of these equations have been used by OSW and other EPA programs to predict applied doses in a variety of ecological risk analyses, and they are similar to the exposure equations recommended by other non-EPA risk assessors (see, for example, the *Methods and Tools for Estimation of the Exposure of Terrestrial Wildlife to Contaminants*, Sample et al., 1997). The Ecological Exposure Module performs the following three functions:

1. **Constructs a dietary matrix for each receptor for each habitat in the AOI.** The Ecological Exposure Module creates a diet for each ecological receptor based on dietary preferences.

2. **Calculates applied doses for animals in terrestrial habitats.** Using the dietary matrix and the media,[1] plant, and prey concentrations calculated by the Terrestrial Food Web Module, the Ecological Exposure Module calculates applied doses for each avian and mammalian receptor species assigned to terrestrial habitats in the AOI.

3. **Calculates applied doses for animals in margin habitats (wetland or waterbody).** Using the dietary matrix and the media,[1] plant, and prey concentrations calculated by the Aquatic Food Web and Terrestrial Food Web Modules, the Ecological Exposure Module calculates applied doses for each avian and mammalian receptor species assigned to margin habitats in the AOI.

15.2 Conceptual Approach

The conceptual approach to predicting ecological exposures in the 3MRA modeling system addresses several major sources of variability in ecological exposures, such as environmental characteristics of different ecosystems, spatial resolution of contaminant concentrations, dietary composition, and receptor-specific exposure factors. Specifically, the approach addresses variability through (1) the development of representative habitats; (2) selection of receptors based on ecological region; (3) the recognition of opportunistic feeding and foraging behavior using probabilistic methods; (4) the creation of a dietary scheme specific to region, habitat, and receptor; and (5) the application of appropriate graphical tools to capture spatial variability in exposure.

The Ecological Exposure Module simulates exposures for birds and mammals assigned to 11 types of habitats representing waterbody margin habitats for streams/rivers, lakes, and ponds; terrestrial habitats; and wetland margin habitats. The 3MRA modeling system exposure factor database contains data on 57 species, including mammals (23), birds (22), and selected herpetofauna (12). This suite of receptors covers a wide range of feeding strategies from obligate herbivores to opportunistic feeders. Because toxicological data were considered

[1] Constituent concentrations in surface impoundments may also be used to calculate exposure if the receptor's home range overlaps the impoundment.

insufficient to develop ingestion benchmarks for herpetofauna for the contaminants included in this version of the 3MRA modeling system, the Ecological Exposure Module does not predict applied doses to these receptors. However, the module was developed to calculate exposures to herpetofauna as toxicological data become available.

For each year in the simulation, the Ecological Exposure Module predicts the applied dose to mammals and birds assigned to waterbody margin, wetland, and terrestrial habitats delineated within the area of interest (AOI). The model is flexible enough to be applied to any habitat, allows a unique home range to be defined for each receptor in the AOI, and constructs a receptor-specific diet based on information in the ecological exposure factor database. Simple food webs, constructed to represent each type of habitat, provide the framework for creating a matrix of dietary preferences for each simulation. That is, the diet of avian and mammalian receptors is constructed based on the food web specific to each habitat, and the dietary preferences can be varied with each simulation. Data on dietary preferences are used to determine which of the 17 possible categories of food are eaten by each receptor and how much of each food category is eaten.

The ecological exposure framework is largely based on the desire to provide an appropriate level of resolution for national-scale analyses. The Ecological Exposure Module performs the necessary calculations to predict contaminant exposures for birds and mammals; the underlying framework defines the spatial scale for the exposure modeling, as well as the habitats and receptors that are assigned to the AOI.

15.2.1 Criteria for the Ecological Exposure Module

The Ecological Exposure Module was designed to satisfy three important criteria that respond to reviews of the earlier efforts to conduct a national-level ecological risk assessment. Those criteria are as follows:

- The module must capture the wide variability in ecological systems in a manner that is appropriate given the availability of data to characterize and evaluate ecological exposure and risk.

- The module must define spatial boundaries for ecological exposures at a scale that takes full advantage of the spatial resolution offered by the 3MRA modeling system and is meaningful with respect to predicting ecological risks.

- The module must allow for the site-based assignment of ecological receptors that reflect the major trophic elements and feeding strategies relevant to exposure, as well as regional characteristics that influence the composition of ecological communities.

To satisfy these criteria, the Ecological Exposure Module contains the following three critical elements:

- A representative habitat scheme,
- Habitat-specific food webs, and

- Appropriate receptor species for each habitat and food web.

Within the context of these criteria, the Ecological Exposure Module selects the media, plant, and prey contaminant concentrations to which each receptor is exposed and calculates the applied dose to chemical stressors across space and time. The Ecological Exposure Module was developed to allow for flexibility in calculating exposures in habitats, home ranges, and receptors that can be defined at virtually any scale desired by the user. For instance, a home range can be defined as a spatially unique area for each receptor, or many receptors can share the same home range. Regardless of how the spatial extent of exposure is defined, the module will calculate a "spatially consistent" applied dose, allowing each receptor to ingest plants, prey, or environmental media within its home range. Similarly, the representative habitats can be delineated for virtually an unlimited number of sizes and shapes provided that the geographical coordinates can be identified. Although a receptor species can be assigned to multiple habitats within an AOI, the Ecological Exposure Module calculates a time series of applied doses to each receptor within each habitat once and only once. That is, a given receptor may not be assigned to multiple home ranges within a habitat.

Representative Habitat Scheme. The representative habitats shown in Table 15-1 were designed to be general enough to encompass a broad range of ecological systems in the conterminous 48 states and can be used to define the spatial boundaries of exposure for any site in the 3MRA modeling system. The representative habitats capture important characteristics of a variety of environmental settings that determine what plants and animals are likely to be present and what exposure pathways are likely to be of interest. The representative habitat scheme supports a level of detail commensurate with the data and models available to predict exposures to chemical stressors. For example, there are many important ecological distinctions between coniferous and deciduous forests; however, the fate and transport models in the 3MRA modeling

Table 15-1. Representative Habitats for 3MRA

Terrestrial Habitats
Grassland
Shrub/scrub
Forest
Crops/pasture
Residential
Waterbody Margin Habitats
River/stream
Lake
Pond
Wetland Margin Habitats
Permanently Flooded Grassland
Permanently Flooded Shrub/scrub
Permanently Flooded Forest

system are not capable of producing forest-specific simulations, and data on potential forest receptors are insufficient to generate a meaningful distinction in predicted exposures and risks to receptors found in these two types of forest habitats. Consequently, the forest habitat represents both deciduous and coniferous forests in the 3MRA modeling system.

The type of habitat determines which species are present at a site because the habitat provides essential resources such as food; shelter; nesting sites or materials; and appropriate sites for behaviors such as courtship, mating, roosting, or hibernation. The criteria used to develop the representative habitats were based on a survey of existing ecological classifications and reflect the importance of the physical setting in terms of essential resources (Bailey, 1996; Bourgeron and Engelking, 1994; Cowardin et al., 1979; Davis and Simon, 1995; Demarchi, 1996; Drake and Faber-Langendoen, 1997; Federal Geographic Data Committee, 1997; Küchler, 1964; Omernik, 1987; Sawyer and Keeler-Wolf, 1995; Shafale and Weakley, 1990; USDA Forest Service, 1994; U.S. FWS, 1998; Viereck and Elbert, 1991; Weakley et al., 1998; and Whitney, 1985). The following subsections provide a very brief summary of the criteria and resulting habitats that were defined to represent the wide variability in ecological systems; additional detail is provided in U.S. EPA (1999b).

Criteria for Terrestrial and Wetland Habitats. The primary criteria for defining terrestrial and wetland habitats are soil moisture and vegetation structure. Soil moisture, or degree of saturation, affects soil chemistry, general vegetation structure, and habitat suitability. Soil moisture is differentiated based on the following three categories:

- Terrestrial—well-aerated, nonsaturated soils;
- Intermittently flooded—periodically saturated or inundated but aerated for some periods during the growing season; and
- Permanently flooded—saturated or inundated throughout most years.

These characteristics are quite general and do not include many of the abiotic parameters often associated with ecological classification systems, such as latitude, climate, topography, elevation, or soil type. Nevertheless, vegetation type is directly affected by these abiotic parameters and is, therefore, often used as a general indicator of many abiotic characteristics. Vegetation structure refers to the stature, spacing, and relative stem size of the dominant vegetation. It describes the primary producers and indicates the appropriateness of the habitat for use by major trophic levels. Generally accepted categories of vegetation structure include grasses, herbs, shrub/scrub, forest, and cropland. Each category has dominant vegetation with distinct height and density that, in turn, supports a distinct suite of fauna.

In addition to the general classifications cited in U.S. EPA (1999b), primary sources for defining wetland habitats include Christensen et al. (1988), Damman and French (1987), Glaser (1987), Gosselink and Turner (1978), Kadlec and Knight (1996), Larsen (1982), Mitsch and Gosselink (1993), Niering (1985), Norquist (1984), Sharitz and Gibbons (1982), Verry (1997), Windell et al. (1986), and Winter (1989).

Criteria for Freshwater Margin Habitats. Using waterbody margin habitats in the exposure assessment allows for the inclusion of freshwater aquatic plants and prey that are integral parts of the food web for terrestrial receptors in habitats that include fishable waterbodies. A brief review of the literature supports the use of two criteria, energy/flow and size, as a simple but effective classification approach. Although aquatic classifications consist of more complex divisions, they fundamentally include these two criteria. The energy/flow criterion distinguishes between still water and flowing water, and the size criterion addresses the intrinsic differences between large and small systems, such as net primary production, diversity of habitat, and length and complexity of food webs. No commonly used size cutoffs were found in the literature. For lakes versus ponds, the waterbody margin habitats use EPA's Environmental Monitoring and Assessment Program (EMAP) 10-hectare cutoff for small versus large lakes; thus, surface waterbodies with a surface area greater than 10 hectares were classified as lakes, and those below 10 hectares were classified as ponds. For streams versus rivers, the generally accepted stream order concept was considered, and stream order 5[2] was initially proposed as a cutoff between streams (small flowing waterbodies) and rivers (large flowing waterbodies). Based on simple mass balance calculations of probable contaminant loadings to surface waterbodies, it was readily apparent that the predicted contaminant concentrations in streams larger than stream order 5 would effectively be diluted below detectable levels. Therefore, streams and rivers of order 5 and below were represented as a single habitat, and those of order 6 and above are not included in the ecological exposure assessment. References consulted for the development of the waterbody margin habitats include the habitat classifications cited in U.S. EPA (1999), as well as in Davis and Simon (1995), USDA (1998), and Caduto (1990).

Habitat-Specific Food Webs. The representative habitats are used not only to define the spatial boundaries for site-based exposures, but also to provide the ecological basis for development of food webs that reflect important exposure pathways to chemical stressors. The habitat-specific food webs were designed to be simple enough to allow for parameterization in the model, but flexible enough to capture a full range of feeding strategies and exposure pathways. The food webs were developed based on generally accepted concepts about food webs and natural community dynamics (Anderson, 1997; Begon and Mortimer, 1981; Caduto, 1990; Davis and Simon, 1995; Kadlec and Knight, 1996; Sample et al., 1997; Schoener, 1989; Schoenly and Cohen, 1991; Suter, 1993; Tanner, 1978; U.S. EPA, 1993, 1994). In describing the predator-prey interactions in the representative habitats, a number of sources were consulted for general habitat information on receptor species, including a wide variety of field guides, nature guides, wildlife encyclopedias, and species-specific monographs that describe the habitats known to be frequented or used by the species. All dietary items reported as commonly eaten were considered in constructing the food webs and, of course, in developing the ecological exposure factors described in Volume II on data collection.

Terrestrial Habitat Food Webs. As suggested in Figure 15-2, the receptors assigned to the terrestrial food web include primary producers (vascular plants); soil biota; and birds; mammals, and herpetofauna across three trophic levels. Trophic level 1 (TL1) consists of species that consume only plants (i.e., the herbivores) and that are potential prey for higher

[2] The Strahler (1957) stream ordering system is used throughout this document.

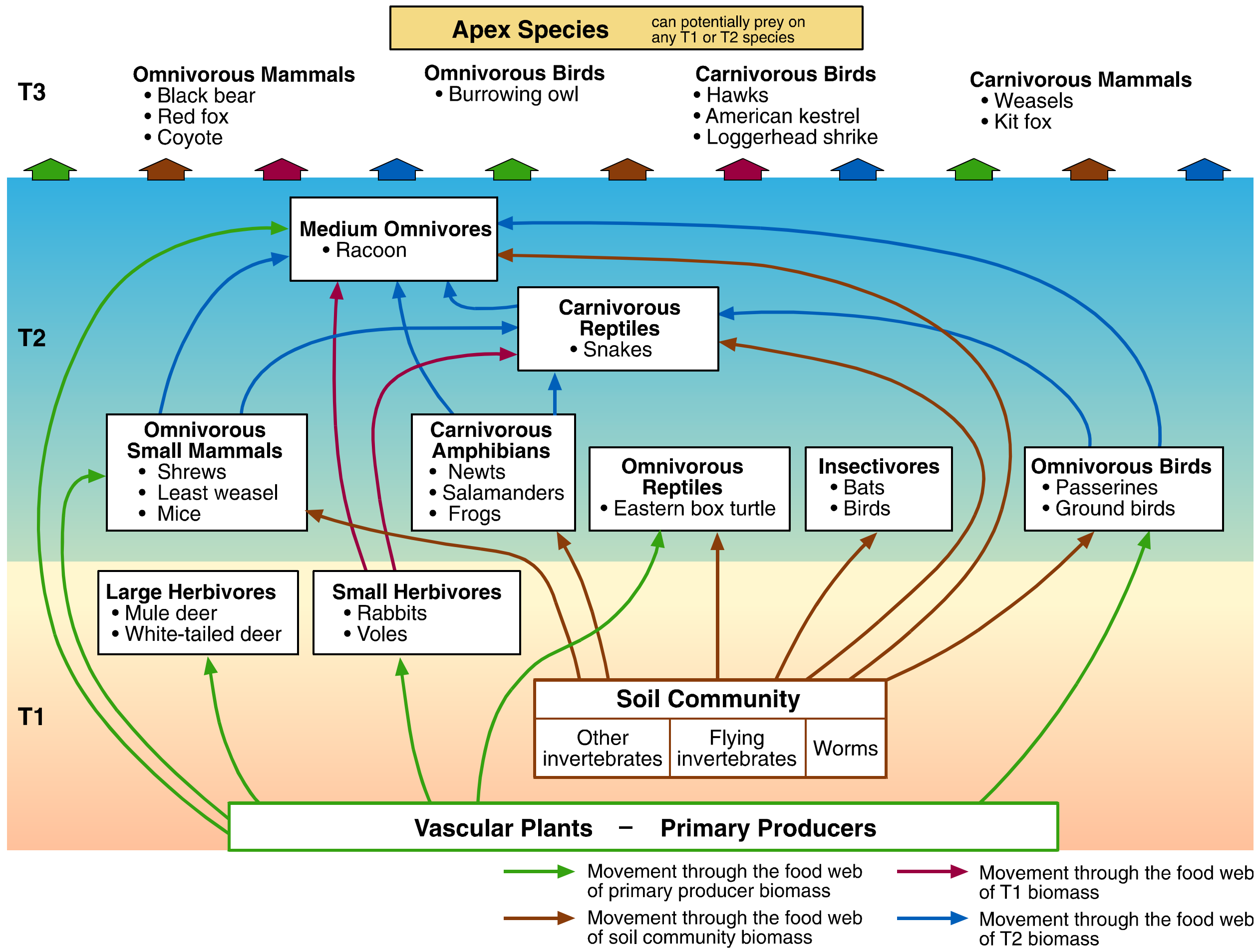

Figure 15-2. Simple terrestrial food web showing example receptors.

trophic level species. TL1 species include small and large mammals and invertebrates. The soil community is a unique subset within TL1 and includes invertebrate soil organisms that live in direct contact with soil, thus reflecting a unique exposure pathway. Within this conceptual framework, the soil community is both a source of food for certain receptors and a receptor group evaluated by the Ecological Risk Module. The dynamics within soil communities are, in fact, very complex and include herbivores, omnivores, and carnivores at several trophic levels within the soil community. However, modeling this complexity within the 3MRA modeling system is well beyond the level of resolution that can be used in a national assessment strategy.

Trophic level 2 (TL2) includes species that consume plants and/or animals (omnivores and carnivores) and are themselves eaten by larger predators. The TL2 species include a wide array of small- to medium-sized mammals, birds, and herpetofauna. For example, the TL2 carnivores include species of reptiles and amphibians that eat soil invertebrates, as well as specialized feeding guilds such as insectivores. The species included in TL2 represent several faunal classes, functional groups, and size ranges. Opportunistic feeders in TL2, such as raccoons, increase the complexity of the web by feeding on virtually any TL1 or TL2 prey. Trophic level 3 (T3) consists of apex species, or those that do not have any predators (other than humans) in the habitat. Apex species include several faunal classes of receptors, such as large mammals (black bears) and raptors (Cooper's hawks), and tend to be among the widest ranging receptors in the habitat.

Waterbody/Wetland Margin Habitat Food Webs. As suggested by Figure 15-3, the margin habitats for surface waterbodies (e.g., streams, lakes) include elements of both aquatic systems and terrestrial systems. As with the terrestrial habitats, the receptors assigned to the aquatic and wetland food webs include primary producers (vascular aquatic plants and algae); sediment and surface water biota; and birds, mammals, and herpetofauna across three trophic levels. These receptors may be exposed through the ingestion of aquatic biota (e.g., fish, benthic invertebrates, and aquatic plants) and surface water, as well as through the incidental ingestion of sediment. In addition, receptors assigned to margin habitats may be exposed through the ingestion of soil, terrestrial plants, and prey items described in the terrestrial habitat food web section (e.g., raccoons). For receptors in these habitats that feed strictly on aquatic food items (e.g., muskrats and mink), the food web is assumed to be relatively simple, consisting of the four-compartment aquatic food web directly linked to the receptor. For example, the osprey eats fish almost exclusively and, therefore, is an apex predator at the top of this simplified aquatic food web.

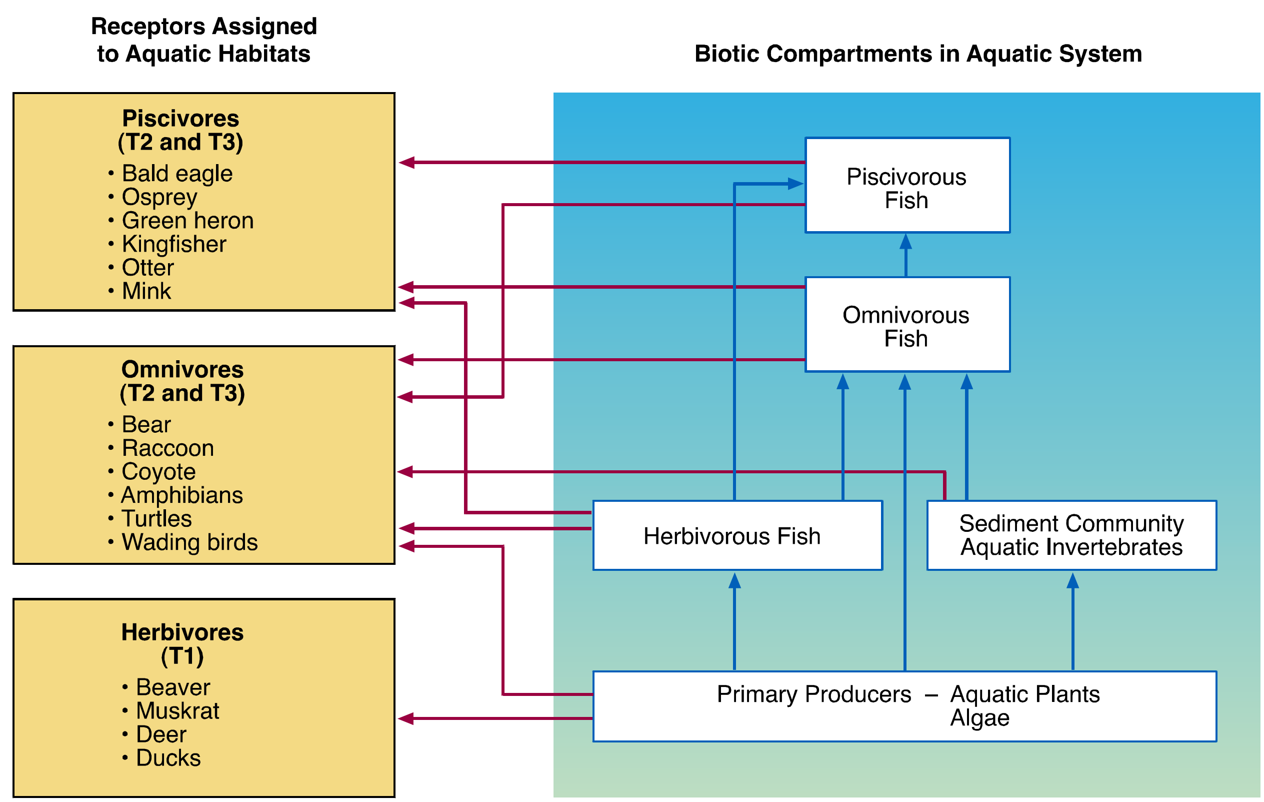

Figure 15-3. Simple margin food web showing both aquatic and terrestrial components.

For omnivores and more opportunistic species in the waterbody margin habitats, the food web is essentially the same as that for strictly terrestrial species, with aquatic prey available as additional potential food items. Many of these species (e.g., raccoon or black bear) are equally successful whether or not aquatic prey are available; however, these species are opportunistic and will take advantage of any prey that are readily available.

The receptor assignments for wetland habitats raised some unique questions with respect to flooding regimes and the implications on habitat classification and receptors. Habitat information for wetland species rarely indicates the degree or frequency of flooding when describing wetland habitats. Therefore, it was difficult to differentiate between species using intermittently flooded as opposed to permanently flooded wetland habitats. In many cases, the food or prey items attributed to a species were used as an indicator. For example, if a source reported that a species fishes in wetland habitats, that species was assigned to the appropriate permanently flooded wetland habitat, which, as defined in this framework, supports fish and other aquatic life. Because of the predominant use in the source literature of terms such as swamps and marshes, which imply a relatively long flood duration, fewer species were assigned to the intermittently flooded wetland habitats. Indeed, intermittently flooded wetlands are generally less discernible from surrounding uplands than are permanently flooded wetlands and, thus, are reported less frequently in general wildlife habitat literature. These differences are reflected in the smaller receptor groups associated with the intermittently flooded wetlands. Intermittently flooded wetlands are not delineated as independent habitats in the 3MRA modeling system. Consequently, receptors assigned to intermittently flooded wetlands are simply added to the list of receptors assigned to the terrestrial habitat if the intermittently flooded wetland is located within the spatial boundaries of the terrestrial habitat.

Ecological Receptors. Within the framework of habitats and food webs, receptor species were selected using a weight-of-evidence approach intended to support analyses of various habitats across the conterminous 48 states. Most importantly, receptor species were chosen to reflect a full range of exposures and, as a group, represent all of the faunal classes, trophic levels, and feeding strategies that are typical of terrestrial and aquatic margin habitats. The simple food webs created for the terrestrial and aquatic margin habitats provided the context for receptor selection and are used to define the relationships between predators and prey. The receptors selected to populate the food webs may be both predator and prey in a given habitat. For example, small omnivores, such as mice or shrews, may consume a variety of plants and animal prey items in lower trophic levels. Given their position in the food web, mice or shrews might also be eaten by apex predators, such as the coyote or red-tailed hawk. Key determinants for receptor selection are summarized as follows:

- **Geographic distribution.** National applicability was achieved primarily by selecting species that are widely distributed throughout the conterminous 48 states and then adding species to cover as many ecological regions as possible. Section level data from Bailey's ecoregions (Bailey, 1996) were digitized and included in the 3MRA geographic information system (GIS). Only those species documented to occur in the section where a site was located were included in the exposure assessment.

- **Availability of wildlife exposure factors.** The majority of the receptors selected for the representative national data set included species for which wildlife exposure factors were readily available. The main sources for ecological exposure factor data were the *Wildlife Exposure Factors Handbook* (U.S. EPA, 1993), *Methods and Tools for Estimation of the Exposure of Terrestrial Wildlife to Contaminants* (Sample et al., 1997), and the U.S. Army Corps of Engineers' *Species Profile Series* (various dates and authors, e.g., Lane and Mitchell, 1997).

- **Faunal class.** Major faunal classes—mammals, birds, reptiles, and amphibians—generally occur throughout all trophic levels. Faunal class distinctions are useful in selecting receptors because species within similar groups are known to respond similarly to environmental disturbance. Although the 3MRA modeling system contains redundancy within each faunal class, exposure factors were not available for species in all classes at all trophic levels. As a result, certain species are underrepresented.

- **Functional niche.** Receptors experience different exposures based on dietary composition. To ensure that all potential exposure pathways were reflected in each habitat, receptors were selected to cover the full spectrum of dietary preferences and feeding strategies (e.g., herbivores, carnivores, omnivores, and insectivores).

To summarize, receptor species were chosen to reflect a full range of exposures and, as a group, represent all of the faunal classes, trophic levels, and feeding strategies that are typical of terrestrial and aquatic margin habitats, respectively. Table 15-2 provides a complete list of receptor species cross-referenced by representative habitat.

Table 15-2. Representative Habitats for Receptor Species

	Representative Habitats										
	Terrestrial					Waterbody Margin			Wetland Margin		
Species	Grasslands	Shrub/Scrub	Forest	Cropland	Residential	River/Stream	Lake	Pond	PF Grasslands	PF Shrub/Scrub	PF Forest
Alligator snapping turtle						✔	✔	✔			✔
American kestrel	✔		✔	✔	✔						
American robin	✔	✔	✔	✔	✔						
American woodcock	✔	✔	✔	✔		✔			✔	✔	✔
Bald Eagle						✔	✔	✔	✔	✔	✔
Beaver						✔	✔	✔	✔	✔	✔
Belted kingfisher						✔	✔	✔	✔	✔	✔
Black bear		✔	✔			✔	✔	✔			✔
Black-tailed jackrabbit	✔	✔		✔							
Bullfrog						✔	✔	✔	✔		✔
Burrowing owl	✔			✔							
Canada goose							✔	✔			
Cerulean warbler			✔								✔

(continued)

Table 15-2. Representative Habitats for Receptor Species (continued)

Species	Representative Habitats										
	Terrestrial					Waterbody Margin			Wetland Margin		
	Grasslands	Shrub/Scrub	Forest	Cropland	Residential	River/Stream	Lake	Pond	PF Grasslands	PF Shrub/Scrub	PF Forest
Cooper's hawk			✔	✔	✔						
Coyote	✔	✔	✔	✔						✔	✔
Deer mouse	✔	✔	✔	✔							
Eastern newt			✔				✔		✔	✔	✔
Eastern cottontail rabbit	✔	✔	✔	✔	✔						
Eastern box turtle	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Flatwoods salamander					✔			✔	✔	✔	✔
Gopher frog	✔	✔	✔					✔			
Great blue heron						✔	✔	✔	✔	✔	✔
Great Basin pocket mouse	✔	✔									
Green heron						✔	✔	✔	✔	✔	✔
Green frog						✔	✔	✔	✔	✔	✔
Herring gull						✔	✔	✔	✔	✔	
Kit fox	✔	✔									
Least weasel	✔		✔	✔							
Lesser scaup							✔	✔	✔		✔
Little brown bat				✔	✔		✔	✔			
Loggerhead shrike	✔	✔	✔	✔							
Long-tailed weasel	✔		✔	✔							
Mallard						✔	✔	✔	✔	✔	✔
Marsh wren									✔	✔	
Meadow vole	✔			✔	✔						
Mink						✔	✔	✔	✔		
Mule deer	✔	✔	✔						✔	✔	✔
Muskrat						✔	✔	✔			
Northern water snake						✔	✔	✔	✔	✔	✔
Northern bobwhite	✔	✔	✔	✔							
Osprey						✔	✔	✔	✔	✔	

(continued)

Table 15-2. Representative Habitats for Receptor Species (continued)

Species	Representative Habitats										
	Terrestrial					Waterbody Margin			Wetland Margin		
	Grasslands	Shrub/Scrub	Forest	Cropland	Residential	River/Stream	Lake	Pond	PF Grasslands	PF Shrub/Scrub	PF Forest
Painted turtle						✔	✔	✔			
Pine vole	✔		✔								
Prairie vole	✔			✔							
Raccoon	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Racer	✔	✔									
Red fox	✔	✔	✔	✔					✔	✔	✔
Red-tailed hawk	✔	✔		✔	✔						
River otter						✔			✔	✔	
Short-tailed shrew	✔		✔	✔	✔						
Short-tailed weasel	✔		✔	✔							
Snapping turtle							✔	✔			
Southern hognose snake			✔	✔							
Spotted sandpiper						✔	✔	✔			✔
Tree swallow	✔	✔		✔	✔						
Western meadowlark	✔	✔		✔							
White-tailed deer	✔	✔	✔			✔	✔	✔			

Within the framework of representative habitats, food webs, and receptors, the Ecological Exposure Module constructs dietary matrices and calculates exposures. These functions are described in the following sections.

15.2.2 Construct a Dietary Matrix

To predict a time series of applied doses for wildlife, the Ecological Exposure Module must first construct a dietary matrix for each receptor based on the dietary preferences contained in the ecological exposure database. The database contains each receptor's minimum and maximum preference values for each of the dietary items shown in Table 15-3. These categories are sampled to generate a percentage of the diet within the range of the minimum and maximum preference values in the database for a particular receptor and dietary item.

Table 15-3. Categories of Dietary Items for Ecological Exposure Assessment

Category	Dietary Item
Terrestrial Prey	Earthworms
	Other soil invertebrates
	Small mammals
	Small birds
	Small herpetofauna
	Medium omnivores
	Herbivores
Aquatic Prey	Benthic filter feeders
	TL3 fish
	TL4 fish
Vegetation	Aquatic plants
	Fruits, fruit/seeds (single item)
	Fern(s), fungi, dicot & monocot shoots
	Forbs, grasses, shrubs
	Roots
	Crops, corn
	Seeds/nuts
Environmental Media	Soil
	Sediment
	Surface water

The Ecological Exposure Module rank orders categories of dietary items from most preferred to least preferred (based the maximum preference values), and the categories are sampled starting with the most preferred category first and continuing through the ranked categories in order until the diet is complete. The sampling approach was designed to address the wide variability in animal diets indicated by available data and, at the same time, observe trends in dietary preferences indicated by those data. There is no requirement that a receptor consume every food item in the list; however, the diet is constrained by two rules: (1) any food item with a non-zero minimum preference value must be part of the diet,[3] and (2) the summation of dietary preferences must equal 100 percent of the entire diet.

[3] In general, the three or four dietary items with the highest maximum values have non-zero minimum values. As a result, the sampling routine usually completes 100 percent of the diet quickly.

Table 15-4 provides an example of the construction of a dietary matrix for a raccoon assigned to a stream margin habitat. The raccoon's dietary composition is constructed based on the prey preference data on various plants, prey, and media shown, and includes both terrestrial and aquatic food items. Based on the preference data, the Ecological Exposure Module might construct the dietary matrix shown in the Example Dietary Matrix column of Table 15-4.

Table 15-4. Example of Dietary Preferences for Raccoon

Food Item	Minimum Preference Value (% of diet)	Maximum Preference Value (% of diet)	Example Dietary Matrix (% of diet)	Cumulative Diet (% of diet)
Soil invertebrates	0	90	45	45
Fruits	25	86	26	71
Forbs	10	66	12	83
Small mammals	0	35	5	88
Benthic organisms	0	25	7	95
TL3 fish	0	23	5	100
TL4 fish	0	23	0	
Small birds	0	19	0	
Earthworms	0	10	0	
Grain	0	10	0	
Roots	0	10	0	
Silage	0	10	0	

Information on receptor species' dietary composition comes from a wide range of data sources and is of two general types. Some data consist of reported quantities of certain items eaten by particular individuals in a localized or site-specific study. These data consist of measured stomach contents, nest or burrow contents, or counts of items observed to be eaten during a particular time span. The principal sources for these data are the *Exposure Factors Handbook* (U.S. EPA, 1993) and Sample et al. (1997). The second type of information consists of qualitative reports of items documented to be eaten. These reports reflect a compilation of observations and measurements for the species in general, and are reported as descriptions of the species' potential diet. The principal sources of this type of data are the Army Corps of Engineers' *Species Profile Series*, the American Society of Mammalogists' *Mammalian Species Series*, and various field guides and handbooks (e.g., Willner et al., 1980).

When only qualitative data were available, the assignment of estimated dietary fractions was based primarily on a set of decision rules implemented by a senior ecologist to maintain consistency in interpreting qualitative descriptions. References to a diet item that implied a single most significant component, such as "primary food source," "bulk of the diet," or "consumes mostly," were assigned a minimum of 50 percent dietary composition. Items that are of secondary importance but that would always make up at least some portion of the diet were assigned a minimum of 10 percent. Descriptions implying occasional sources of food were given a minimum of zero and a maximum of 10 percent. A few species have relatively limited diets and eat only one dietary item. For example, the cerulean warbler eats insects almost exclusively. In these cases, the exclusive diet item (insects) was assigned a minimum of 95 percent and a maximum of 100 percent. The quantified dietary profiles were entered into the exposure factor database as maximum and minimum preference values for each prey category.

15.2.3 Calculate Applied Dose for Receptors in Terrestrial Habitats

The applied dose for mammals and birds assigned to terrestrial habitats is calculated as a function of the contaminant concentrations in soil, drinking water (e.g., streams or surface impoundments), and contaminated plants and prey. The calculation is a summation of time-dependent exposures to contaminated media, plants, and prey. The following example presents the methods and equations for estimating the applied dose to the short-tailed weasel in a forest habitat. The discussion is organized around five elements required to support the exposure calculation:

1. Spatial boundaries that define exposure;
2. Development of the dietary matrix;
3. Contribution to exposure from drinking water;
4. Contribution to exposure from soil, plants, and terrestrial prey; and
5. Calculation of total applied dose.

Spatial Boundaries for Exposure. All of the contaminant concentrations to which a receptor is exposed are spatially consistent; that is, each receptor may only be exposed to contaminant concentrations that overlap with its home range. However, it is not assumed that 100 percent of the diet originates from the home range; the Ecological Exposure Module prorates exposure based on the ratio between the area of the home range and the total habitat area. For example, if the home range for the weasel (~135,000 m^2) is 20 percent larger than the forest habitat, the calculated exposure is prorated by a factor of 0.8 that effectively reduces the applied dose to 80 percent of the dose that would have occurred had the weasel taken all of its food from within the AOI.

Development of Dietary Matrix. The Ecological Exposure Module uses the dietary preference database to construct the short-tailed weasel's diet for each iteration. The database includes all the relevant prey categories and the range of reported dietary preferences. As suggested in Table 15-5, the dietary matrix can vary considerably from iteration to iteration. The values shown in the last column comprise 100 percent of the weasel's diet for one iteration. Note that the data set follows the two constraints for the prey preference random sampling algorithm: (1) the diet includes all items with non-zero minimum preference values, and (2) the dietary preferences sum to 100 percent.

Table 15-5. Example Dietary Preferences for Short-Tailed Weasel

Food Item	Minimum Preference Value (%)	Maximum Preference Value (%)	Value for Realization (%)
Small mammals	50	80	63
Small herpetofauna	0	45	0
Soil invertebrates	0	25	13
Small birds	0	25	24
Total diet			100

Exposure Contribution from Ingestion of Surface Water. The Ecological Exposure Module estimates exposure due to surface water ingestion by calculating the total average concentration (dissolved plus particle-bound) for all surface waters found within the home range. This average includes any reach and/or surface impoundment that intersects the home range. Thus, it is implicitly assumed that the receptor does not prefer one waterbody over another. For example, if the weasel's home range overlaps two stream reaches with calculated surface water concentrations of 2.2E-06 mg/L and 9.3E-07 mg/L, respectively, the average drinking water concentration for contaminant *y* is 1.6E-06 mg/L.

Exposure Contribution from Ingestion of Soil, Plants, and Prey. The Ecological Exposure Module reads concentrations in plants, prey, and soil from the Terrestrial Food Web Module. For prey, these concentrations are spatially averaged for the prey's home range. For soil and soil invertebrate concentrations, the spatial averaging is defined by the home range of the short-tailed weasel. That is, the weasel is assumed to consume soil and soil invertebrates from within its home range, and the concentrations of these food items are assumed to be homogenous within the weasel's home range. For concentrations in small vertebrates, the weasel may take any prey that overlap its home range. Consequently, any small mammalian, avian, or herpetofaunal species that are assigned to the habitat are potential prey for the short-tailed weasel. This may include species within the weasel's home range, as well as species that simply overlap the weasel home range; thus, there is exposure variability associated with the prey selection (i.e., the home range of the prey species) due to potential differences in tissue concentrations in small vertebrates that may be eaten. To address this variability, the Ecological Exposure Module reads the minimum and maximum concentrations in mobile prey categories, such as small mammals, and randomly selects a value from that range. Thus, the exposure concentrations reflect the full range of prey combinations that could be eaten by the short-tailed weasel. Table 15-6 provides an example exposure profile for contaminant *y* for the weasel (calculated by the Terrestrial Food Web Module and passed to the Ecological Exposure Module). The diet includes incidental ingestion of soil, as well as the ingestion of contaminated soil invertebrates, small mammals, birds, and herpetofauna. A single concentration for soil, plants, and "local" food items, such as earthworms, is passed to the Ecological Exposure Module; however, for terrestrial prey categories that are relatively mobile, the Ecological Exposure Module receives a range of minimum and maximum prey concentrations and chooses one from within that range. A uniform distribution for prey concentrations is assumed to represent free access by predators to any prey that have access to its home range.

Table 15-6. Example Exposure Concentrations to Contaminant *y* for Short-Tailed Weasel

Food Item	Minimum Concentration (mg/kg)	Maximum Concentration (mg/kg)	Value for Iteration (mg/kg)
Soil (incidental)	3.8E-06	3.8E-06	3.8E-06
Small mammals	1.3E-06	6.7E-05	1.3E-05
Small herpetofauna	5.4E-07	5.4E-07	5.4E-07
Soil invertebrates	8.4E-06	8.4E-06	8.4E-06
Small birds	2.3E-08	7.8E-07	7.7E-07

Calculation of Total Applied Dose. After the Ecological Exposure Module constructs the dietary matrix and selects (from the outputs of other modules) exposure concentrations for relevant media, plants, and prey items to which the receptor has access (i.e., that overlap with the receptor's home range), the appropriate ecological exposure factors are used to calculate the total applied dose for each year in the simulation as shown in Equation 15-1 (all concentrations are converted to a wet weight basis).

$$Dose^{i}_{rec} = \frac{\sum \left(IR^{i}_{food} C^{j}_{food} FracPrey^{i\ \ j}_{food} \right) + \left(IR^{i}_{food} C_{soil} FracSoil^{i} \right) + \left(IR^{i}_{water} C_{water} \right)}{BodyWt^{1}} Frac^{i}_{HomeRange} \quad (15\text{-}1)$$

where

$Dose^{i}_{rec}$	=	total applied dose for receptor *i* (mg/kg-day)
IR^{i}_{food}	=	total ingestion rate of food for receptor *i* (kg/day)
C_{food}^{j}	=	concentration food item *j* to which receptor *i* may be exposed (mg/kg tissue)
$FracPrey^{i}{}_{food}^{j}$	=	dietary fraction of food item *j* for receptor *i* (unitless)
C^{i}_{soil}	=	average concentration in surficial soil in home range for receptor *i* (mg/kg)
$FracSoil^{i}$	=	dietary fraction of soil ingested by receptor *i* (unitless)
IR^{i}_{water}	=	ingestion rate of drinking water for receptor *i* (L/day)
C_{water}	=	average concentration in surface water within home range for receptor *i* (mg/L)
$BodyWt^{i}$	=	body weight of receptor *i* (kg)
$Frac^{i}_{HomeRange}$	=	fraction of home range for receptor *i* within habitat (unitless).

The applied dose reflects media and food concentrations for a single year in the simulation. For each realization (i.e., each time the Ecological Exposure Module runs), the module will read new data on media, prey, and food concentrations and construct a new dietary matrix from the dietary preference database. Although the exposure factors (e.g., body weight, food ingestion rate) and physical description (e.g., fraction of home range in the habitat) will remain constant throughout the simulation, the exposure profile will change over time as a function of changing media and food concentrations, as well as the random selection of dietary items.

15.2.4 Calculate Applied Dose for Receptors in Margin Habitats

The applied dose to mammals and birds assigned to margin habitats is calculated using essentially the same methodology described for terrestrial habitats. Equation 15-1 is modified to add the incidental ingestion of sediment, as appropriate, to the exposure pathways that contribute to the total applied dose. The list of dietary preferences for margin receptors is typically longer than that for terrestrial receptors because many species of mammals and birds that live margin habitats consume both aquatic biota and terrestrial biota. However, there are two subtle differences worth noting with respect to the exposure calculations for mammals and birds that are exposed to contaminated media and aquatic biota from waterbodies in margin habitats.

1. **Exposure to Aquatic Biota within a Margin Habitat.** As described in Sections 8 and 12, contaminant concentrations in sediment, surface water, and aquatic biota are calculated for each stream reach and surface waterbody within the AOI. The Surface Water Module reports these contaminant concentrations on a reach-specific and waterbody-specific basis. That is, even though stream reaches may be connected, the Surface Water Module may predict different contaminant concentrations. As a result, the exposure concentrations in sediment, surface water, and aquatic biota must be averaged prior to being used as inputs to Equation 15-1. The calculated concentrations in media and food are averaged for those reaches and waterbodies that overlap the home range for any mammalian or avian receptor assigned to a margin habitat. For example, the home range for an osprey assigned to a stream habitat might include three fishable stream reaches. The concentration in TL4 fish eaten by the osprey would be the average TL4 fish concentration across all three reaches. The underlying assumption is that a receptor may take food from any fishable reaches or waterbodies within its home range; therefore, the exposure concentration is an effective average for the receptor's home range.

2. **Exposure to Aquatic Biota in Adjacent Margin Habitat.** Margin receptors are presumed to rely on those fishable reaches that occur within their home range as the source of both aquatic food items and drinking water. However, a receptor's access to fishable reaches is not strictly constrained within its own habitat. In many instances, stream corridors are located adjacent to wetlands and, because receptors are likely to use reaches in each of these habitats as a source of food, adjacent margin habitats are delineated so that "reach crossover" can occur freely (i.e., habitats and home ranges overlap reaches in each habitat). For example, a stream margin located adjacent to a permanently flooded forest wetland would likely be delineated such that the habitat includes a part of both waterbodies. Consequently, the home range of a kingfisher assigned to the stream margin could

overlap both the stream and wetland, allowing this receptor to eat fish from either waterbody. The fish concentration to which the kingfisher is exposed would be the average tissue concentration, by trophic level, across the wetland and stream reaches that intersect its home range. The 3MRA modeling system models wetlands as distinct reaches, and, in this example, a forested wetland and a stream corridor would each be delineated and modeled separately by the system. The ecological connection that allows the kingfisher to take fish from both the stream and wetland is not reflected in the modeling simulation performed by the Surface Water Module.

The Ecological Exposure Module performs the averaging functions described above based on the data describing the habitats and home ranges for margin receptors and uses those average concentrations as inputs in Equation 15-1.

15.3 Module Discussion

15.3.1 Strengths and Advantages

The Ecological Exposure Module was developed to predict spatially explicit exposures to chemical contaminants for mammalian and avian receptors. Designed to address long-term, low-level exposures to chemical contaminants, the module offers several advantages for national-scale applications, and is flexible enough to perform site-specific analyses. The major strengths of the module include the following:

- **Exposure profiles calculated as total applied dose.** The vast majority of ecotoxicological data relevant to long-term exposures are reported as applied doses. Therefore, the Ecological Exposure Module was developed to report a time series of annual average applied doses so that the module would be broadly applicable to a large number of chemical contaminants. Although other metrics for exposure were considered (e.g., dietary concentrations, body burden), the module was designed to calculate applied dose so that EPA could take full advantage of a substantial body of data on reproductive and developmental effects associated with chronic exposures. This approach is consistent with EPA guidelines and the practice of ecological exposure assessment in numerous peer-reviewed ecological risk assessments conducted by EPA.

- **Maintains predator-prey relationships for soil, plant, and prey concentrations in space and time.** A major strength of the Ecological Exposure Module is its ability to calculate the total applied dose for each receptor assigned to each habitat within the AOI. For receptors in margin habitats, this is particularly important because the diet may include food items from both the terrestrial and aquatic food webs, as well as incidental ingestion of contaminated sediment and surface water. The module maintains the spatial relationship for all contaminated media and food items so that the aggregate exposure is calculated consistently for each year of the simulation. In addition to these advantages, the module avoids unnecessary conservatism by prorating exposure based on size of the receptor's home range, explicitly recognizing that feeding is not constrained by the habitat boundaries.

- **Dietary variability is addressed in the selection of food items.** The Ecological Exposure Module addresses this important source of variability by (1) sampling from the minimum and maximum concentrations predicted by the Terrestrial Food Web Module for appropriate food categories, and (2) using a random sampling algorithm to select dietary preference fractions for each food category. The former method explicitly recognizes that the food categories (e.g., small mammals) are intentionally general and that the specific prey items may vary substantially depending on feeding opportunities. The latter method, which is similar to the sampling algorithms used in the Aquatic Food Web Module, recognizes that the dietary proportions will be highly variable with season and other environmental conditions. Representing this variability (rather than assigning fixed, point estimates for diet) represents a significant improvement to the state-of-the-science for national-scale analyses.

- **Designed to evolve with changing assessment goals, new science, and improved data.** Given the state-of-the-science on predicting ecological exposure concentrations, one of the primary design goals for the Ecological Exposure Module was flexibility. The module currently predicts contaminant concentrations for 17 food categories; however, the module could be easily modified to include additional categories or to collapse existing categories into fewer categories to further reduce run time or to better reflect the data for a particular chemical constituent. Similarly, the module currently handles each receptor home range as a unique spatial element, even though the system aggregates these home ranges into four bin sizes. The Ecological Exposure Module can handle either level of resolution based on how the site layout file is constructed. Lastly, the module was designed with future modifications in mind that address the evolving science and data for ecological risk assessment (e.g., calculating receptor-specific lifetime average doses rather than annual average doses).

15.3.2 Uncertainty and Limitations

The methodology developed to characterize potential ecological exposures, as implemented by the Ecological Exposure Module, carries certain assumptions and limitations, and acknowledges several important sources of uncertainty.

- **The physical description of the spatial dimensions of ecological exposure are fixed for each site.** The Ecological Exposure Module calculates the applied doses to receptors for a single random placement of four home range sizes within habitats delineated at each site. Although the representative habitats were delineated using available GIS coverages to represent potential habitats at a given site, the habitats that may actually be present at any site may be very different from those delineated in the site layout. Despite the fact that the home ranges were chosen at random and retain predator-prey interactions, these are fixed in the site layout file.

- **The 3MRA system is designed to model a single chemical stressor released within the AOI for each simulation.** Given the design goals for the 3MRA modeling system (e.g., to support national-level assessment strategies of WMUs, waste streams, and contaminants), exposure to multiple contaminants or contaminant releases outside of the AOI are not considered. In addition, background concentrations of contaminants are not considered in developing exposure estimates, nor are other potential nonchemical stressors, such as habitat fragmentation. This introduces an unquantifiable uncertainty in the prediction of total exposure and risk.

- **The exposure calculations are highly dependent on reliable estimates of plant and prey concentrations, as well as random selection of plant/prey dietary preferences represented in the dietary matrix.** Ultimately, the veracity of the exposure estimates is a function of the data used in predicting tissue concentrations in dietary plants and prey. As discussed in Section 11 on the Terrestrial Food Web Module, there is significant uncertainty associated with the use of empirical data and default factors used to predict the uptake and accumulation of contaminants from media into biota.

- **The exposure profiles generated by the Ecological Exposure Module are based on the annual average concentrations in food items and media.** Consequently, concentration spikes due to episodic events (e.g., rain storms) or elevated WMU source releases following waste additions are not evaluated. In addition, the annual average approach does not capture elevated exposures during critical life stages. More specifically, the module predicts exposures only for adult animals; intrayear contaminant exposures to juveniles, often with very different dietary preferences, are not predicted.

- **Exposure doses are adjusted to account for the proportion of a species' required home range provided at a site.** However, no adjustment is made to account for differences in species diversity in small versus large habitat patches or in disturbed versus undisturbed areas. The 3MRA modeling system assumes that receptor species occur in their assigned representative habitats regardless of a site's position in the landscape. In fact, it is probably unlikely that all of the receptor species, particularly those less adapted to human impacts and development, would be present. Moreover, when the habitat patches at a site are small, it is questionable whether the entire receptor group would use the habitat.

- **The dietary preferences for each receptor remain constant throughout each year in the simulation.** The Ecological Exposure Module constructs the dietary preferences for each receptor based on dietary data covering one or more seasons. Some of the seasonal variability in the diet is captured indirectly by the hierarchical algorithm used to determine the dietary preferences. However, the algorithm is implemented on data across multiple seasons and, therefore, does not necessarily reflect seasonal differences. Similarly, the estimation of ingestion rates was based on average, gender-neutral body weights and does not account for differences in size, season, habitat, or activity level. However, prey preferences are represented by distributions that are intended to reflect some of the natural variation in wildlife feeding behaviors.

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