Chapter 3
Archetypical Chemical Exposure Problems

Human exposure to chemicals may occur via different human contact sites and target organs (such as discussed in Chap. 2), and also under a variety of exposure scenarios; broadly speaking, an exposure scenario is a description of the activity that brings a human receptor into contact with a chemical material, product, or medium. Chemical exposure investigations (typically consisting of the planned and managed sequence of activities carried out to determine the nature and distribution of hazards associated with potential chemical exposure problems) can be properly designed to help define realistic exposure scenarios—and then subsequently used to address human exposure and likely response to chemical toxicants.

Indeed, it has become apparent that human exposures to chemicals found in human environments and/or in various consumer products may occur via multiple routes, as well as from multiple sources. Accordingly, it is important in a comprehensive assessment of potential human exposure problems or situations, to carefully evaluate all possible combinations of pathways and sources—and then to further aggregate these exposures over time (and perhaps spatially as well, to the extent considered appropriate for a given receptor). Ultimately, the development of a spatiotemporal, multi-source, multi-chemical, and multi-route framework that holistically addresses a potential receptor's vulnerability seems imperative, if a reliable risk determination outcome is to be achieved. This chapter apprises the typically significant exposure scenarios that can be expected to become key players in the assessment of human exposure to, and response from, chemical hazards; it goes on to provide a general framework that may be used to guide the formulation of realistic exposure scenarios, as necessary to generate credible risk assessments.

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3.1 Formulation of Archetypical Chemical Exposure Problems

Human populations may become exposed to a variety of chemicals via several different exposure routes—represented primarily by the inhalation, ingestion/oral, and dermal exposure routes (Fig. 3.1). Congruently, human chemical uptake occurs mainly through the skin (from dermal contacts), via the inhalation passage (from vapors/gases and particulate matter), and/or by ingestion (through oral consumptions). Under such circumstances, a wide variety of *potential* exposure patterns can be anticipated from any form of human exposures to chemicals. As an illustrative example, a select list of typical or commonly encountered exposure scenarios in relation to environmental contamination problems might include the following (Asante-Duah 1998; HRI 1995):

- Inhalation Exposures
  - Indoor air—resulting from potential receptor exposure to contaminants (including both volatile constituents and fugitive dust) found in indoor ambient air.
  - Indoor air—resulting from potential receptor exposure to volatile chemicals in domestic water that may volatilize inside a house (e.g., during hot water showering), and then contaminate indoor air.
  - Outdoor air—resulting from potential receptor exposure to contaminants (including both volatile constituents and fugitive dust) found in outdoor ambient air.

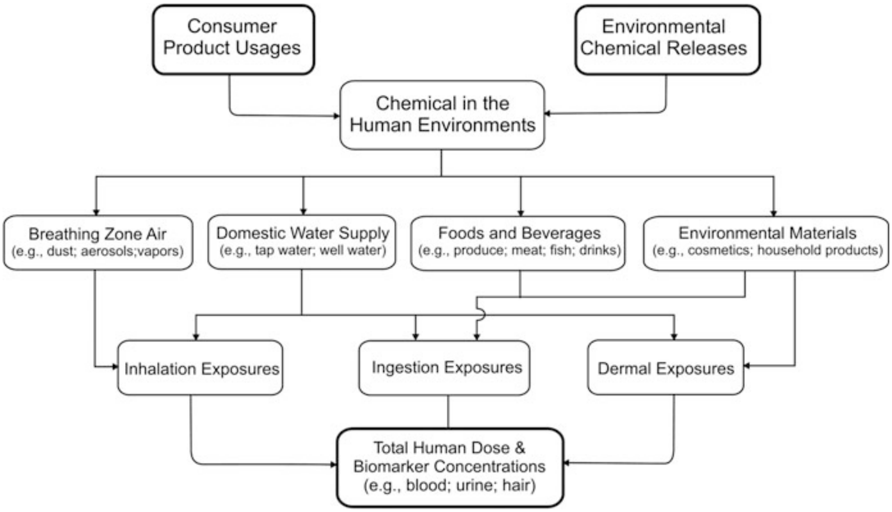

Fig. 3.1 Major types of human exposures to chemicals: a simplified 'total' human exposure conceptual model

  - Outdoor air—resulting from potential receptor exposure to volatile chemicals in irrigation water, or other surface water bodies, that may volatilize and contaminate outdoor air.

- Ingestion Exposures
  - Drinking water—resulting from potential receptor oral exposure to contaminants found in domestic water used for drinking or cooking purposes.
  - Swimming—resulting from potential receptor exposure (via incidental ingestion) to contaminants in surface water bodies.
  - Incidental soil ingestion—resulting from potential receptor exposure to contaminants found in dust and soils.
  - Crop consumption—resulting from potential receptor exposures to contaminated foods (such as vegetables and fruits produced in household gardens that utilized contaminated soils, groundwater, or irrigation water during the cultivation process).
  - Dairy and meat consumption—resulting from potential receptor exposure to contaminated foods (such as locally grown livestock that may have become contaminated through the use of contaminated domestic water supplies, or from feeding on contaminated crops, and/or from contaminated air and soils).
  - Seafood consumption—resulting from potential receptor exposure to contaminated foods (such as fish and shellfish harvested from contaminated waters or that have been exposed to contaminated sediments, and that consequently have bioaccumulated toxic levels of chemicals in their edible portions).

- Dermal Exposures
  - Showering—resulting from potential receptor exposure (via skin absorption) to contaminants in domestic water supply.
  - Swimming—resulting from potential receptor exposure (via skin absorption) to contaminants in surface water bodies.
  - Direct soils contact—resulting from potential receptor exposure to contaminants present in outdoor soils.

These types of exposure scenarios will typically be evaluated as part of an exposure assessment component of a public health risk management program. It should be emphasized, however, that this listing is by no means complete, since new exposure scenarios are always possible for case-specific situations; still, this demonstrates the multiplicity and inter-connectivity nature of the numerous pathways via which populations may become exposed to chemical constituents. Indeed, whereas the above-listed exposure scenarios may not all be relevant for every chemical exposure problem encountered in practice, a number of other exposure scenarios not listed or even alluded to here may have to be evaluated for the particular local conditions of interest—all the while recognizing that comprehensive human exposure assessments must include both direct and indirect exposure from ingredients found in various environmental compartments (such as in ambient air, water, soil, the food-chain, consumer products, etc.). In any event, once the complete set of potential exposure scenarios has been fully determined for a given situation, the range of critical exposure pathways can then be identified to support subsequent evaluations.

In the end, careful consideration of the types and extent of potential human exposures, combined with hazard assessment and exposure-response information, is necessary to enable the completion of a credible human health risk assessment. For instance, the hazard assessment for a consumer product or component thereof relates to the potential human health effects, and the exposure-response assessments involve an examination of the relationship between the degree of exposure to a product or component and the magnitude of any specific adverse effect(s). Additionally, the exposure assessment (which is very critical to determining potential risks) requires realistic data to determine the extent of possible skin, inhalation, and ingestion exposures to products and components (Corn 1993). Subsequent efforts are then directed at reaching the mandated goal of a given case-specific risk determination—recognizing that the goal of a human health risk assessment under any given set of circumstances would typically be to describe, with as little uncertainty as possible, the anticipated/projected risk (or indeed an otherwise lack of risk) to the populations potentially at risk (e.g., a given consumer or population group); this is done in relation to their exposure to potentially hazardous/toxic chemicals that may be contained in a variety of consumer/household products and/or found within their inhabited/occupied environments. Ultimately, the resulting information generated can then be used to support the design of cost-effective public health risk management programs.

3.1.1 The Case for Human Exposures to Airborne Chemical Toxicants

Airborne pollutants can generally be transported over long distances—and this could result in the deposition of pollutants very far removed from the primary source of origination (i.e., far away from where they were first produced or used). For example, high levels of pesticides (such as DDT, chlordane, and toxaphene) have been found to be present in beluga whales from the Arctic—i.e., in locations where such chemicals were not known to have been used (see, *e.g.*, Barrie et al. 1992; Dewailly et al. 1993; Lockhart et al. 1992; Muir et al. 1992; Thomas et al. 1992). In fact, airborne chemical toxicants can very well impact population groups that are geographically widely dispersed. Of particular interest are air emissions from chemical release sources (such as industrial facilities) that often represent a major source of human exposure to toxic or hazardous substances; indeed, the emissions of critical concern often relate to volatile organic chemicals (VOCs), semi-volatile organic chemicals (SVOCs), particulate matter, and other chemicals associated with wind-borne particulates such as metals, PCBs, dioxins, etc. As a consequence, air pollution presents one of the greatest risk challenges to human health globally—especially recognizing the characteristically long list of health problems potentially caused or aggravated by air pollution, including various forms of respiratory ailments, cancers, and eye conditions/irritations (Holmes et al. 1993).

Airborne chemical toxicants can indeed impact human population via numerous trajectories. For instance, among several other possibilities and issues, volatile chemicals may be released into the gaseous phase from such sources as landfills, surface impoundments, contaminated surface waters, open/ruptured chemical tanks or containers, etc. Also, there is the potential for subsurface gas movements into underground structures such as pipes and basements, and eventually into indoor air. Additionally, toxic chemicals adsorbed to soils may be transported to the ambient air as particulate matter or fugitive dust. Moreover, several consumer products and materials in the human living and work environments will tend to release potentially hazardous chemicals into the human breathing zone/space.

Overall, chemical release sources can pose significant risks to public health as a result of possible airborne release of particulate matter laden with toxic chemicals, and/or volatile emissions. In fact, even very low-level air emissions could pose significant threats to exposed individuals, especially if toxic or carcinogenic contaminants are involved. Consequently, there is increased concern and attention to the proper assessment of public health risks associated with chemical releases into air. Of particular concern, it has become recognized that certain air pollutants have a direct effect on the ability of the human body to transport oxygen (Berlow et al. 1982). For example, lead poisoning interferes with the body's ability to manufacture hemoglobin (which carries oxygen in the red blood cells)—and this can produce severe chronic anemia; carbon monoxide replaces oxygen on hemoglobin molecules—and thus reduces the efficiency with which the blood transfers oxygen to the cells. Also, some toxic gases (such as the oxides of sulfur and nitrogen, and also ozone) that are often found in the smog of cities as a result of industrial pollution can present major health hazards; for example, nitrogen and sulfur oxides typically will form very strong acids when they dissolve in the water present in membrane linings—and these gases can cause damage to the bronchial tubes and alveoli.

Finally, it is noteworthy that, to enable credible risk estimation in relation to human exposure to airborne chemical toxicants, there usually should be a reliable appraisal of the airborne concentrations of the target chemicals. The chemical concentration in air—oftentimes represented by the 'ground-level concentration' (GLC)—is a function of the source emission rate and the dilution factor at the points of interest (usually the potential receptor location and/or 'breathing zone').

3.1.1.1 Indoor Air Quality Problems: General Sources of Indoor Volatile [Organic] Chemicals

There are a number of different kinds of indoor environments—with the most prominent consisting of offices or commercial buildings, homes, and schools—

each with unique characteristics and associated problems. Generally speaking, indoor exposure sources may exist due to indoor activities (such as via showering activities, or the use of certain consumer products) and/or as a result of particular building characteristics (including those that culminate in releases from building structural components). Indoor exposures also can occur when substances are transported from outdoor sources into a building [as for example, when contaminated soil is tracked into buildings, or gases volatilize from underlying contaminated soil or groundwater—usually referred to as 'vapor intrusion' (discussed further below)].

Regardless of the sources, indoor air contaminants can impose significant risks onto occupants of the invaded structure. For instance, among other potential indoor air quality issues, certain volatile organic compounds (VOCs), such as formaldehyde and toluene, can have concentrations tens of times higher indoors than they are outdoors due to off-gassing from synthetic building materials, furnishing, etc. Additional significant contributors to such indoor emissions may include chemically-formulated personal care products, insecticides, household cleaners, etc. Ultimately, poor indoor air quality can elicit a variety of health symptoms ranging from respiratory ailments such as asthmatic wheezing and chronic lung disease to non-specific symptoms such as headache, fatigue, and general discomfort. In reality, individual sensitivities can vary considerably, and multiple pollutants and/or building factors may additionally contribute to protracted and 'erratic' symptoms—potentially making it difficult for investigators to pinpoint specific causative agents.

It is notable that indoor sources of VOCs have indeed become ubiquitous—resulting in detectable levels of contaminants in indoor air at numerous locations, often at concentrations above 'regulatory levels' of concern. Thus, being able to distinguish between vapor intrusion and other indoor sources of VOCs is quite important in any likely risk management and abatement efforts designed to protect potential receptors from possible exposures to such contamination. At any rate, it is also noteworthy here that various other mechanisms can actually add and/or exacerbate indoor air quality problems as a whole; thus, it is imperative to consistently make the best effort to understand all potential sources, and to ultimately carry out reasonably holistic evaluations—i.e., one that, among other things, judiciously/effectually utilize proper sampling equipment and analytical protocols for such problem situations.

3.1.1.2 Chemical Vapor Intrusion into Buildings

Vapor intrusion (VI) of chemicals generally refers to the migration of volatile chemicals from the subsurface into an overlying building; more specifically, it is defined as the vapor-phase migration of (usually toxic) VOCs from a subsurface environment (e.g., contaminated soil and/or groundwater) into overlying or nearby structures/buildings (e.g., through floor slabs and foundation joints or cracks, gaps around utility lines, etc.), subsequently accumulating (to potentially 'unacceptable' or ‘unsafe’ levels) and potentially persisting in the indoor air—ultimately with consequential impacts on the indoor air quality, and thus potentially posing risks to building occupants. Generally speaking, VOCs are characterized by relatively high vapor pressures that permit these compounds to vaporize and enter the atmosphere under normal conditions; because of these characteristics, the VI phenomenon is particularly unique or prevalent to this class of organic chemicals. Still, it is also notable that although VOCs typically present the most common concerns in regards to vapor intrusion issues, there are a number of other contaminant families that may similarly engender vapor intrusion problems—including other ‘vapor-forming’ chemicals such as some SVOCs, elemental mercury, and radionuclides.

By and large, volatile chemicals in buried wastes or other subterranean contaminated soils/groundwater can emit vapors that may in turn migrate through subsurface soils (and/or via sub-slabs, crawlspaces, etc.) into the indoor air spaces of overlying buildings. When this happens, the chemical concentrations in the released soil gas typically would decrease (or attenuate) as the vapors migrate through materials from the contamination sources into the overlying structures. This attenuation is usually the result of processes that control vapor transport in the soil materials (e.g., diffusion, advection, sorption, and potentially biotransformation), as well as processes that control the transport and dilution of vapors as they enter the building and mix with indoor air (e.g., pressure differential and building ventilation rates). Indeed, several other physicochemical and ambient environmental factors may generally affect the ultimate fate and behaviors of the chemicals of interest in any given VI problem situations.

As an archetypical illustrative example of a VI problem scenario, consider a situation whereby chlorinated solvents or petroleum products are accidentally released at an industrial or commercial facility—which then migrates downward and reaches groundwater where it can slowly dissolve and form contaminant plumes. Subsequently, the volatile compounds can volatilize and travel upwards as soil vapors to reach the ground surface; in situations where buildings or other occupied structures sit atop such ground surface, contaminant vapors can seep through foundation cracks/joints and contaminate indoor air—presenting potentially serious public health concerns. Indeed, in view of the fact that many of the typical volatile compounds [such as benzene, tetrachloroethylene/perchloroethylene (PCE) , and trichloroethylene (TCE)], are considered carcinogenic, there is always the concern that even relatively low levels of such chemicals inhaled by building occupants can pose unacceptable long-term health risks. On the other hand, evaluation of the VI pathway tends to be complicated by ‘background’ volatile compound contributions (e.g., due to potential confounding effects of household VOC sources from consumer products, etc.), as well as considerable spatial and temporal variability in soil vapor and indoor air concentrations. Undeniably, vapor migration from subsurface environments into indoor air is often affected by many variables—not the least of which include building characteristics, anthropogenic conditions, and meteorological influences or seasonal changes; subsequent attenuation due to diffusion, advection, sorption, and potential degradation processes may also occur during movements from the contaminant source into the receptor exposure zones. Consequently, it makes more sense to employ 'multiple lines of evidence' to support and adequately/holistically evaluate the vapor intrusion pathway and associated potential risks to public health.

Finally, it is worth mentioning that VI is considered an 'emerging' and growing public health problem/concern that requires deliberate planning efforts—and even more importantly, careful assessment and management strategies to avert potential 'hidden' but serious public health hazard situations. This might mean implementing aggressive VI pathway assessment at potentially contaminated sites or impacted structures—and then ensuring the implementation of appropriate vapor mitigation measures, as necessary.

3.1.2 Water Pollution Problems and Human Exposures to Chemicals in Water as an Example

Historically, surface waters were among the first environmental media to receive widespread attention with regards to environmental/chemical pollution problems. This attention was due in part to the high visibility and extensive public usage of surface waters, as well as for their historical use as 'waste receptors' (Hemond and Fechner 1994). Anyhow, surface water contamination may also result from contaminated runoff and overland flow of chemicals (from leaks, spills, etc.), as well as from chemicals adsorbed onto mobile sediments. In addition, it has to be recognized that groundwater resources are just about as vulnerable to environmental/chemical contamination; typically, groundwater contamination may result from the leaching of toxic chemicals from contaminated soils, or the downward migration of chemicals from lagoons and ponds, etc. Further yet are the likely complexities associated with possible groundwater–surface water interactions—since this would usually affect the mixing and transfer of contaminants from one source to the other in a rather complex manner. Ultimately, there is a crucial water quality problem that engenders important exposure scenarios worth devoting significant resources to help resolve.

Next, another major but often seemingly 'hidden' concern with regards to water quality management programs that should not be overlooked relates to the issue of eutrophication—i.e., the nutrient enrichment of the water and the bottom of surface water bodies. Indeed, human-made eutrophication has been considered one of the most serious global water quality problems for surface water bodies during the past few decades. Meanwhile, it is worth mentioning here that increasing discharges of domestic and industrial wastewater, the intensive use of crop fertilizers, the rise in airborne pollution, and the natural mineralization of streamflows can be seen as some of the primary causes of this undesirable phenomenon. Typical symptoms of eutrophication include, among other things, sudden algal blooms, water coloration, floating water-plants and debris, excretion of toxic substances that causes taste and odor problems in drinking water production/supply systems, and sometimes fish kills. These symptoms can result in limitations of water use for domestic, agricultural, industrial, or recreational purposes. In addition, the nitrates coming from fertilizer applications tend to eventually become drinking water hazards, especially because the nitrate ion (NO_3^-) is reduced to the nitrite ion (NO_2^-) in the human body following the consumption of the nitrate-containing water—and the nitrite destroys the ability of hemoglobin to transport oxygen to the cells; in fact, high nitrate concentrations in drinking water are particularly dangerous to small infants.

In the end, the appraisal of human exposure to chemicals in contaminated water problems should address all intake sources—including that resulting from water ingestion, as well as from dermal contacting and inhalation of the volatile constituents in water. Finally, it is also worth mentioning the fact that groundwater is extensively used by public water supply systems in several places around the world; thus, it is always important to give very close attention to groundwater pollution problems in chemical exposure evaluation programs.

3.1.3 Contaminated Soil Problems and Human Exposures to Chemicals on Land

Contaminated soils may arise in a number of ways—many of which are the result of manufacturing and other industrial activities or operations. In fact, much of the soil contamination problems encountered in a number of places globally are the result of waste generation associated with various forms of industrial activities. In particular, the chemicals and allied products manufacturers are generally seen as the major sources of industrial hazardous waste generation that culminates in contaminated soil problems. These industries generate several waste types, such as organic waste sludge and still bottoms (containing chlorinated solvents, metals, oils, etc.); oil and grease (contaminated with polychlorinated biphenyls [PCBs], polyaromatic hydrocarbons [PAHs], metals, etc.); heavy metal solutions (of arsenic, cadmium, chromium, lead, mercury, etc.); pesticide and herbicide wastes; anion complexes (containing cadmium, copper, nickel, zinc, etc.); paint and organic residuals; and several other chemicals and byproducts that have the potential to contaminate lands. Ultimately, such industrial and related activities lead to the births of contaminated lands that are generally seen as complex problems with worldwide implications.

In addition to the above situations involving direct releases at a given locale, several different physical and chemical processes can also affect contaminant migration from contaminated soils; thus, contaminated soils can potentially impact several other environmental matrices. For instance, atmospheric contamination may result from emissions of contaminated fugitive dusts and volatilization of chemicals present in soils; surface water contamination may result from contaminated runoff and overland flow of chemicals (from leaks, spills, etc.), and chemicals adsorbed to mobile sediments; groundwater contamination may result from the leaching of toxic chemicals from contaminated soils, or the downward migration of chemicals from lagoons and ponds; etc. Consequently, human exposures to chemicals at contaminated lands may occur in a variety/multiplicity of ways—including via the following more common example pathways:

- Direct inhalation of airborne vapors, and also respirable particulates.
- Deposition of airborne contaminants onto soils, leading to human exposure via dermal absorption or ingestion.
- Ingestion of food products that have been contaminated as a result of deposition onto crops or pasture lands, and subsequent introduction into the human food chain.
- Ingestion of contaminated dairy and meat products from animals consuming contaminated crops or waters.
- Deposition of airborne contaminants onto waterways, uptake through aquatic organisms, and eventual human consumption of impacted aquatic foods.
- Leaching and runoff of soil contamination into water resources, and consequential human exposures to contaminated waters in a water supply system.

Contaminated lands, therefore, will usually represent a potentially long-term source for human exposure to a variety of chemical toxicants; thus, risk to public health arising especially from soils at contaminated lands is a matter of grave concern.

3.1.4 Human Exposures to Chemicals in Foods and Household/Consumer Products

Food products represent a major source of human exposure to chemicals, even if in incrementally minute amounts. For example, a number of investigations have shown that much of the seafood originating from most locations globally contains detectable levels of environmental pollutants (such as Pb, Cr, PCBs, dioxins and pesticides). Also, chemicals such as tartrazine, a previously revered food preservative that was widely used in some countries, has now been determined to cause allergies in significant numbers of human populations; consequently, there is a clear move away from the use of such chemicals—as, for example, is demonstrated by the fact that 'chips' and indeed many other food items sold in South Africa had at some point in time proudly displayed on the packaging that the products are 'tartrazine-free', etc. (Personal Communication with Dr. Kwabena Duah). At any rate, because of the potential human exposure to the variety of toxic/hazardous chemicals, it is very important to understand the potential human health risks associated with these exposures and the likely public health implications of such chemicals being present in the food sources or other consumer products.

In general, human dietary exposure to chemicals in food (and indeed similar consumable or even household products) depends both on [food] consumption patterns and the residue levels of a particular chemical on/in the food or consumer product—generally expressed by the following conceptual relationship (Driver et al. 1996; Kolluru et al. 1996):

$$\text{Dietary Exposure} = f(\text{Consumption}, \text{Chemical concentration}) \tag{3.1}$$

Typically, as an example, multiplying the average consumption of a particular food product by the average chemical concentration on/in that food provides the average ingestion rate of that chemical from the food product. In reality, however, estimation of dietary exposure to chemicals—such as pesticides or food additives—becomes a more complex endeavor, especially because of the following likely factors (Driver et al. 1996; Kolluru et al. 1996):

- Occurrence of a particular chemical in more than one food item.
- Variation in chemical concentrations in food products and other consumer items.
- Person-to-person variations in the consumption of various food products.
- Variation in dietary profiles across age, gender, ethnic groups, and geographic regions.
- Fraction of consumable food product actually containing the chemical of concern (e.g., treated with a given pesticide).
- Possible reductions or changes in chemical concentrations or composition due to transformation during transport, storage, and food preparation.

In the end, the inherent variability and uncertainty in food consumption and chemical concentration data tend to produce a high degree of variability in the concomitant dietary exposure and risk for a given chemical. For instance, the dietary habits of a home gardener may result in an increase or decrease in exposure—possibly attributable to their unique consumption rates, as well as the contaminated fractions involved.

In general, individual consumers may indeed ingest significantly different quantities of produce and, depending on their fruit/vegetable preferences, may also be using more of specific crops that are efficient accumulators of contaminants/chemicals (or otherwise). Consequently, both food consumption and chemical concentrations data are best represented or characterized by dynamic distributions that reflect a wide range of values, rather than by a single value. Under such circumstances, the distribution of dietary exposures and risks may be determined by using both the distribution of food consumption levels and the distribution of chemical concentrations in food (see, e.g., Brown et al. 1988; Driver et al. 1996; National Research Council [NRC] 1993a, b, c; Rodricks and Taylor 1983; USEPA 1986a, b, c, d, e, f).

3.2 Quantification Process for the General Types of Human Exposures to Chemical Toxicants

The likely types and significant categories of human exposures to a variety of chemical materials that could affect public health risk management decisions are generally very much dependent on the specific routes of receptor exposures; the fundamental quantification elements that may be utilized for the key distinctive routes of general interest are annotated below (Al-Saleh and Coate 1995; Corn 1993; OECD 1993).

- *Skin Exposures*. The major types of dermal exposures that could affect public health risk management decisions consist of dermal contacts with chemicals present in consumer products or in the environment, and also dermal absorption from contaminated waters. Dermal exposures that results from the normal usage of consumer products may be expressed by the following form of generic relationship:

$$\text{Dermal Exposure} = \frac{\{[\text{CONC}] \times [\text{PERM}] \times [\text{AREA}] \times [\text{EXPOSE}]\}}{[\text{BW}]} \tag{3.2}$$

  where: CONC is the concentration of material (in the medium of concern); PERM is the skin permeability constant; AREA is the area of exposed skin (in contact with the medium); EXPOSE is the exposure duration (i.e., duration of contact); BW is the average body weight.

  In general, fat-soluble chemical substances, and to some extent, the water-soluble chemicals can be absorbed through even intact skins—also recognizing that, by and large, skin characteristics such as sores and abrasions may facilitate or enhance skin/dermal uptakes. Environmental factors such as temperature and humidity may also influence skin absorption of various chemicals. Furthermore, the physical state (i.e., solid *vs*. liquid *vs*. gas), acidity (i.e., pH), as well as the concentration of the active ingredient of the contacted substance will generally affect the skin absorption rates/amounts.

- *Oral Exposures*. Ingestion takes place when chemical-containing food materials, medicines, etc. are consumed via the mouth or swallowed. The major types of chemical ingestion exposures that could affect public health risk management decisions consist of the oral intake of contaminated materials (e.g., soils intake by children exercising pica behavior), food products (e.g., plant products, fish, animal products, and mother's milk), and waters. Ingestion exposures that results from the normal usage of consumer products may be expressed by the following form of generic relationship:

$$\text{Oral Exposure} = \frac{\{[\text{CONC}] \times [\text{CONSUME}] \times [\text{ABSORB}] \times [\text{EXPOSE}]\}}{[\text{BW}]} \tag{3.3}$$

where: CONC is the concentration of material (i.e., the concentration of the contaminant in the material ingested—e.g., soil, water, or food products such as crops, and dairy/beef); CONSUME is the consumption amount/rate of material; ABSORB is the per cent (%) absorption (i.e., the gastrointestinal absorption of the chemical in solid or fluid matrix); EXPOSE is the exposure duration; BW is the average body weight.

The total dose received by the potential receptors from chemical ingestions will, in general, be dependent on the absorption of the chemical across the gastro-intestinal (GI) lining. The scientific literature provides some estimates of such absorption factors for various chemical substances. For chemicals without published absorption values and for which absorption factors are not implicitly accounted for in toxicological parameters, absorption may conservatively be assumed to be 100%.

- *Inhalation Exposures to Volatiles*. Exposures to volatile chemical materials that results from the normal usage of consumer products may be expressed by the following form of generic relationship:

$$\text{Inhalation Exposure to Volatiles} = \frac{\{[\text{VAPOR}] \times [\text{INHALE}] \times [\text{RETAIN}] \times [\text{EXPOSE}]\}}{[\text{BW}]} \tag{3.4}$$

where: VAPOR is the vapor phase concentration of material (i.e., the concentration of chemical in the inhaled air); INHALE is the inhalation rate (of the exposed individual); RETAIN is the lung retention rate (i.e., the amount retained in the lungs); EXPOSE is the exposure duration (i.e., the length of exposure of the exposed individual); BW is the average body weight (of the exposed individual).

It is noteworthy that, as an example, showering—which represents one of the most common and universal human activities—generally encompasses a system that promotes release of VOCs from water (due to high turbulence, high surface area, and small droplets of water involved). In fact, some studies have shown that risks from inhalation while showering can be comparable to—if not greater than—risks from drinking contaminated water (Jo et al. 1990a, b; Kuo et al. 1998; McKone 1987; Richardson et al. 2002; Wilkes et al. 1996). Thus, this exposure scenario represents a particularly important one to evaluate in a public health risk assessment, as appropriate. In this case, the concentration of any contaminants in the shower air is assumed to be in equilibrium with the concentration in the water. In another example that takes into consideration the fact that the degree of dilution in the indoor air of a building is generally far less than situations outdoors, contaminant vapors entering/infiltrating into a building structure may represent a significantly higher risk to occupants of such buildings. In fact, the migration of subsurface contaminant vapors into buildings can become a very important source of human exposure via the inhalation route. As appropriate, therefore, a determination of the relative significance of vapor transport and inhalation as a critical exposure scenario should be given serious consideration during the processes involved in the characterization of chemical exposure problems, and in establishing environmental quality criteria and/or public health goals. Risk assessment methods can generally be used to make these types of determination—i.e., as to whether or not vapor transport and inhalation represent a significant exposure scenario worth focusing on in a given study. For example, a risk characterization scenario involving exposure of populations to vapor emissions from cracked concrete foundations/floors can be determined on such basis, in order for responsible risk management and/or mitigative measures to be adopted.

- *Inhalation Exposures to Particulate Matter.* Exposures to inhalable chemical particulates that results from the normal usage of consumer products may be expressed by the following form of generic relationship:

$$\text{Inhalation Exposure to Particulates} = \frac{\{[\text{PARTICLE}] \times [\text{RESPIRABLE}] \times [\text{INHALE}] \times [\text{ABSORB}] \times [\text{EXPOSE}]\}}{[\text{BW}]} \tag{3.5}$$

where: PARTICLE is the total aerosol or particulate concentration of material; RESPIRABLE is the % of respirable material; INHALE is the inhalation rate; ABSORB is the % absorbed; EXPOSE is the exposure duration; BW is the average body weight. It is noteworthy that, in general, only particulate matter of size $\leq 10\ \mu\text{m}$ (referred to as PM-10 or PM10) can usually be transported through the upper respiratory system into the lungs.

In addition to the above major exposure situations, it must be acknowledged that accidental exposures may also occur via the same routes (i.e., from dermal contact, oral ingestion, and/or inhalation). Furthermore, chemical vapors or aerosols may be absorbed through the lungs.

Indeed, the analysis of potential human receptor exposures to chemicals found in our everyday lives and in the human living and work environments often involves several complex issues. In all cases, however, the exposures are generally evaluated via the calculation of the average daily dose (ADD) and/or the lifetime average daily dose (LADD). Typically, the carcinogenic effects (and sometimes the chronic non-carcinogenic effects) associated with a chemical exposure problem involve estimating the LADD; for non-carcinogenic effects, the ADD is commonly used. The ADD differs from the LADD, in that the former is not averaged over a lifetime; rather, it is the average of the daily dose pertaining to the actual number of days of exposure. Additionally, the maximum daily dose (MDD) will typically be used in estimating acute or subchronic exposures. Details of the requisite algorithms for estimating potential human exposures and intakes under variant scenarios are elaborated in Chap. 9.