Introduction

This section summarizes how mass flux (J) and mass discharge (M_d) estimates can be applied at sites to address characterization, remediation, and receptor mitigation objectives. Uses of mass flux and mass discharge are grouped in the following categories (see Figure 1-1):

- site characterization and CSM development
- potential impacts and exposure evaluation
- remedy selection and design
- performance monitoring, evaluation, and optimization
- compliance monitoring
- site prioritization

Sections 3.1–3.6 and Table 3-1 describe each use and present case study examples. Additional case example information, including references and web links, is provided in Appendices A and B. Section 3.7 uses a conceptual example to illustrate how mass flux and mass discharge information can be applied. Section 3.8 discusses important regulatory considerations associated with the application of mass flux or mass discharge measurements.

3.1 Site Characterization and Conceptual Site Model

Mass flux and mass discharge estimates have several applications relating to site characterization. In most cases mass flux/discharge estimates can also be used to evaluate potential impacts to receptors and to assess performance of a future remedy. Following is a list of site characterization uses for mass flux and mass discharge estimates. Additional detail about these and other applications is provided in Table 3-1.

Australia Site Basu et al. (2009) used a flux-based site management approach at a DNAPL-impacted site in Australia to develop an improved CSM and to provide information for more effective and efficient site management. The approach incorporated historical site data with flux measurements to provide insight into the distribution of contaminant mass within the source zone and between the source and plume. Using this approach, they concluded that (a) residual trichloroethene (TCE) in the source zone was small and primarily in low- permeability zones, (b) the plume was disconnecting from the source, (c) biodegradation in the plume was minimal, and (d) residual TCE in the vadose zone was a source of TCE mass moving into the plume during infiltration events. These observations provide the basis for making decisions regarding remedial selection and design.

- Establish baseline mass discharge from a source zone to a plume (i.e., source strength) at a given point in time.
- Identify source zone hot spots and evaluate mass flux distribution of contaminant mass (i.e., those locations where the source is contributing the highest mass discharge to the plume). See example in box at right.
- Determine mass attenuation rates between transects along a common flow path.
- Evaluate whether contaminant mass is primarily contained within high- or low-conductivity (transmissive) zones (high or low *K*).
- Compare the mass discharge distribution of electron donors and acceptors across a transect to the contaminant mass discharge distribution to determine whether specific locations need enhancement as part of the remedy.
- Compare source zone mass discharge (i.e., source strength) to the estimated plume attenuation rate to determine whether multiple sources may be contributing to a plume.

Table 3-1. Summary of mass flux and mass discharge applications

Use/application	Purpose	How applied Mass flux (grams per m^2 per year)	How applied Mass discharge (grams per year)	Case study example

1. Site characterization and conceptual site model	(a) Establish baseline source strength	Measure mass discharge across a transect at downgradient edge of the source zone; use to prioritize site based on source strength; use to select and design remedy; compare baseline with post-remedy mass discharge measurements to assess performance (Soga, Page, and Illangasekare 2004).		Fort Lewis Military Reservation, Wash.: Used a 10-well transect with passive flux meters and a variation of the integral pumping test to establish baseline source zone flux distribution and mass discharge for comparison to post-remediation measurements to assess remediation performance and effectiveness (Brooks et al. 2008).
	(b) Identify source zone hot spots and mass flux distribution	Measure baseline mass flux distribution across transect at downgradient edge of source zone; use to select and target remedy based on where the highest mass flux occurs; compare to post-remedy mass flux distribution to assess performance (Soga, Page, and Illangasekare 2004).		DNAPL-impacted site in Australia incorporated historical site data with flux measurements to better assess the distribution of contaminant mass in the source zone and between the source and plume (Basu et al. 2009).
	(c) Evaluate mass attenuation rates within specific areas of the plume	Measure mass discharge across two or more transects along a common flow path; the difference between mass discharge measurements is the attenuation rate over the portion of the plume between transects (assuming system equilibrium); use changes in localized attenuation rates to assess remedy performance and effectiveness.		Kao and Wang (2001) and Landmeyer et al. (2001) used transects of multilevel monitoring wells to calculate mass discharge and attenuation rates between transects.

Table 3-1 (continued)

Use/application	**Purpose**	**How applied Mass flux (grams per m^2 per year)**	**How applied Mass discharge (grams per year)**	**Case study example**

1. Site characterization and conceptual site model (continued)	(d) Determine whether contaminant mass is mainly within high- or low-transmissive zones	Measure mass flux distribution along transect near the source zone and compare with the groundwater flux distribution and lithology.		Basu et al. (2006) conducted depth-discrete flux monitoring indicating that the zone of higher permeability and lower concentrations needs to be considered as a target zone for remediation because it represents a relatively large portion of the source strength, which shows that focusing remediation only in the zone of high concentrations may be "suboptimal." Basu et al. (2009) used mass flux and specific discharge measurements to demonstrate that residual DNAPL mass was present in low-permeability zones and that source treatment was unwarranted.
	(e) Evaluate aqueous electron donor/ acceptor supply and localized availability	Measure the mass flux distribution of electron acceptors and donors across one or more transects and compare to the contaminant mass flux distribution to target enhancements if needed. Use information to refine characterization of biodegradation reactions (i.e., terminal electron-accepting processes) responsible for contaminant attenuation.		Former manufacturing plant, Stuttgart, Germany—Evaluated natural attenuation between two transects downgradient of the source zone. Mass discharge at each transect used to estimate first-order biodegradation rates. Changes in mass discharge of electron acceptors and metabolic by-products between transects was also evaluated to provide additional lines of evidence for biodegradation (Bockelmann, Ptak, and Teutsch 2001).
	(f) Determine whether multiple sources may be contributing to a plume		If plume attenuation rate exceeds the mass discharge from a known source zone, then there are additional source(s).	Methyl tertiary-butyl ether (MtBE) site, Calistoga, Calif.—Mass discharge estimates suggest that a release from one site is probably responsible for supply well impacts (Einarson et al. 2005).

Table 3-1 (continued)

Use/ application	Purpose	How Applied Mass flux (grams per m^2 per year)	How Applied Mass discharge (grams per year)	Case study example

2. Potential impact and exposure assessment	Estimate the actual and allowable mass discharge to potential receptors		Measure the mass discharge contributing to downgradient receptor exposure; compare to allowable mass discharge based on acceptable exposure point concentration and mixing zone assumptions (see Section 3.2).	Service station, Tahoe City, Calif.—Used mass discharge estimate from a transect of wells to estimate the maximum concentration to an adjacent river (Buscheck, Nijhawan, and O'Reilly 2003). Fuel release site, Morro Bay, Calif.— Used mass discharge framework to evaluate potential threat of MtBE plume to nearby water supply wells (Beckett, Stanley, and Walsh 2005). Industrial site, Conn.—Evaluated decreasing mass discharge across three transects situated between the DNAPL source zone and a river. Used to characterize natural attenuation processes for TCE and by-products along groundwater flow path and support mass balance assessment (Chapman et al. 2007).
3. Remediation selection and design	(a) Establish/ develop appropriate remedial action objectives (RAOs)	Use baseline mass flux estimates to establish appropriate reduction targets as potential RAOs. Use mass flux/mass discharge reductions to evaluate RAOs and revise if necessary.	Use baseline mass discharge estimates to establish appropriate reduction targets as potential RAOs. Use mass flux/mass discharge reductions to evaluate RAOs and revise if necessary.	
	(b) Select and design remediation systems	Determine the permeability of mass flux hot spots and geologic units to assist with technology selection (e.g., some technologies do not effectively treat mass in low-permeability units); use knowledge of contaminant mass flux relative to lithology to design well placement, injection parameters, etc. (e.g., targeted remediation of hot-spot areas, permeable reactive barrier design based on maximum mass flux zones).	Use the target reduction in mass discharge (e.g., 90%, 99%, 99.9%, etc.) to screen for applicable technologies.	Fuel terminal, San Jose, Calif.—Conducted a demonstration project using mass flux measurements from a transect of oxygen delivery wells and transects of upgradient and downgradient monitoring wells to compare dissolved oxygen delivery and demand. Results used to evaluate the scale and location of a treatment system (Buscheck, Nijhawan, and O'Reilly 2003).

Table 3-1 (continued)

Use/application	Purpose	How applied Mass flux (grams per m^2 per year)	How applied Mass discharge (grams per year)	Case study example
4. Remediation performance monitoring and optimization	(a) Assess remediation performance	Measure changes in source zone mass flux to determine whether treatment system is performing as planned.	Measure changes in source zone mass discharge to determine whether treatment system is performing as planned.	DNAPL sources, Hill Air Force Base, Utah and Fort Lewis Military Reservation, Wash.—Used a 10-well transect at each site, with passive flux meters and a variation of the IPT, to establish baseline source zone flux distribution and mass discharge. Used changes in source zone mass flux and discharge to assess remediation performance (Brooks et al. 2008Brooks, M. C., A. L. Wood, M. D. Annable, K. Hatfield, J. Cho, C. Holbert, P. S. C. Rao, C. G. Enfield, K. Lynch, and R. E. Smith. 2008. “Changes in Contaminant Mass Discharge from DNAPL Source Mass Depletion: Evaluation at Two Field Sites,” Journal of Contaminant Hydrology 102: 140–53.). Well 12A Superfund site, Tacoma, Wash.—Mass discharge was used to assess source zone remediation performance and establish compliance targets. The goal was to reduce source zone mass discharge by 90% as both the source and plume were treated (USEPA 2009).
	(b) Evaluate remediation efficiency	Compare baseline to current mass flux distribution to evaluate whether targeted hot-spot areas are being addressed, the rate of mass flux decline (if sufficient data available), the benefit of additional remediation, and the distribution of injected reagent.	Compare baseline to current mass discharge to evaluate the effectiveness of treatment to date and the rate of decline in mass discharge; use to extrapolate remediation time frame if sufficient data available (need longer-term performance data to reduce uncertainty).	Former gas station site, Ontario—Used three transects to evaluate benzene, toluene, ethylbenzene, and xylenes (BTEX) mass flux reduction downgradient of oxygen-releasing compound treatment zone. Mass discharge used to evaluate degree to which natural attenuation was occurring (Chapman et al. 1997).
	(c) Optimize remediation system operations and monitoring	If performance monitoring indicates that remedy is not practicable, can use current mass flux distribution to evaluate alternative technologies or remedial configurations. Use mass flux distribution across transect to identify data gaps in monitoring network.	If performance monitoring indicates that remedy is not effective, use current mass discharge to evaluate alternative technologies.	Well 12A Superfund site, Tacoma, Wash.—Mass discharge was used to assess source zone remediation performance and establish compliance targets. Set 90% mass discharge reduction goal as trigger for transition to alternative remedy (MNA) (USEPA 2009). Service station, Strathroy, Ontario—Mass flux and discharge data used to optimize delivery of dissolved oxygen to permeable reactive barrier (Chapman et al. 1997).

Table 3-1 (continued)

Use/application	Purpose	How applied Mass flux (grams per m^2 per yer)	How applied Mass discharge (grams per year)	Case study example
5. Compliance monitoring	Monitor compliance with regulatory objectives	Measure mass flux at appropriate locations and compare to acceptable compliance targets for mass flux reduction.	Measure mass discharge at appropriate locations and compare to acceptable compliance targets for mass discharge reduction.	Well 12A Superfund site, Tacoma, Wash.—Mass discharge was used to assess source zone remediation performance and establish compliance targets. The goal was to reduce source zone mass discharge by 90% while both the source and plume were being treated (USEPA 2009).
6. Site prioritization	Prioritize sites based on mass discharge from the source (i.e., source strength) or to a potential receptor			Multiple California sites—Compared mass flux and/or discharge estimates to maximum concentrations from monitoring wells. Showed that sites with the highest concentrations are not necessarily the sites with the highest mass discharge (Buscheck, Nijhawan, and O'Reilly 2003). Chlorinated solvent site, Austria—Used IPT method to evaluate mass discharge at three transects to quantify relative strengths of different source zones contributing to a plume, to determine which source zones to target for further characterization and remediation (Bauer et al. 2004). Additional examples of mass discharge/mass flux applications include Verreydt et al., 2013; Brusseau et al., 2013; and Johnston et al., 2014.

3.1.1 Mass Balance Assessments Using Mass Discharge

ITRC's *Enhanced Attenuation: Chlorinated Organics* (ITRC 2008a) defines a mass balance assessment as including a quantitative estimation of the source strength (i.e., source zone mass discharge) into a dissolved phase plume, which is then compared to the plume attenuation rate. If the mass discharge from the source is greater than the plume attenuation rate, then the dissolved plume will expand in length. If the mass discharge and plume attenuation rates are similar in magnitude, then the plume will be stable. And if the mass discharge is less than the plume attenuation rate, then the mass delivered by the plume will decrease.

In general, the plume attenuation rate can be evaluated using models and/or historical concentration data and standard lines of evidence, such as contaminant concentration vs. time and/or distance plots along the plume centerline, molar fraction plots, and the distribution of geochemical indicator parameters (e.g., electron acceptors and donors, dissolved oxygen, nitrate, Fe(II), sulfate, methane, redox potential, pH, etc.). There are several excellent references on this topic including Chapelle et al. (2003) and Wiedemeier et al. (1998, 1999, 2004). However, as shown previously in Figure 2-7, the plume attenuation rate can be misinterpreted if "losses" due to sorption or diffusion into low-permeability zones (i.e., changes in mass storage) and dispersion are not considered in the case of expanding or shrinking plumes.

Figure 3-1 lists the components of a mass balance assessment. Benefits of performing a mass balance assessment can include the following:

- refining the CSM with respect to the quantitative significance of processes affecting source strength and plume attenuation
- identifying data gaps that require further characterization
- providing an additional line of evidence that validates a plume stability evaluation
- facilitating the prediction of changes to plume extent caused by the reduction in mass discharge during source zone treatment

Mass discharge estimates at a site can be used to support a mass balance assessment in the following manner:

- For stable plumes, mass discharge can be used to facilitate the estimation or validation of the plume attenuation rate.
- For expanding plumes, the mass discharge from the source zone can be used to predict the future stable extent of the plume.
- Measuring the reduction in mass discharge during or after source zone treatment can be used to predict the corresponding change in aqueous plume extent downgradient of the source zone.

Components of a mass balance assessment are described by Borden et al. (1997), Chapelle et al. (2003, 2004), Imbrigiotta et al. (1997), Looney et al. (2006), and Wiedemeier et al. (1998, 1999, 2004).

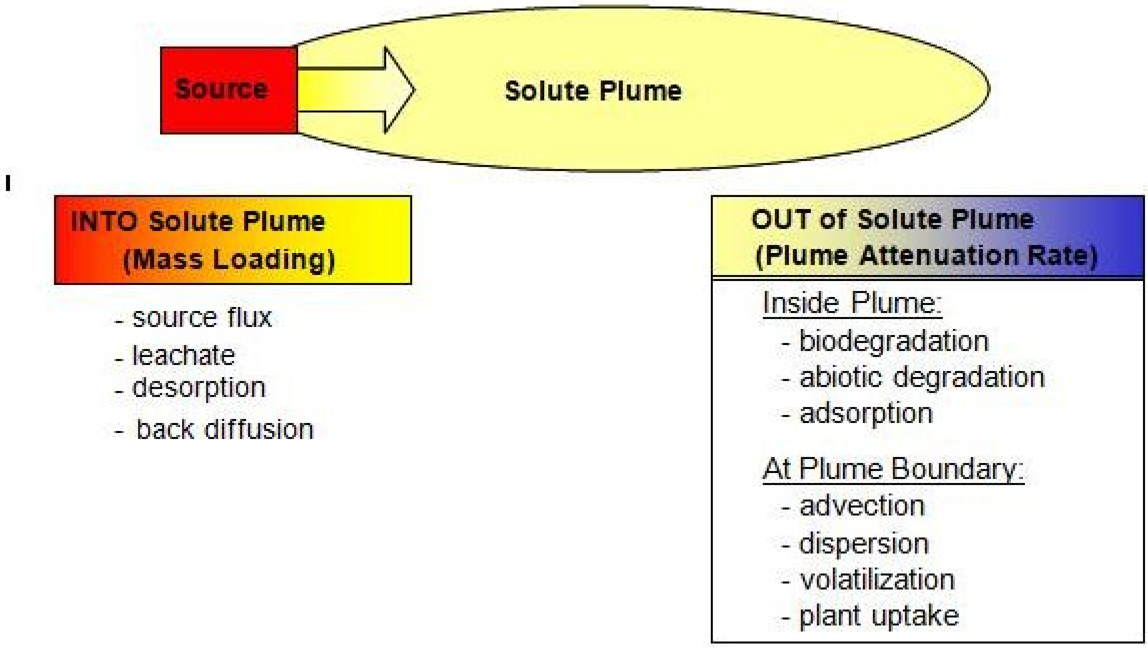

Figure 3-1. Example of mass balance for a dissolved plume. (Modified from ITRC 2008a.)

Mass discharge estimates between two transects across a plume along a common flow path can estimate the mass attenuation rate in the portion of the plume between the transects, which can then be used with similar plume segment rates to assess the plume attenuation rate. Estimating attenuation rates between transects must consider the contaminant travel time between the transects. For example, if mass discharge is changing at the upgradient transect in response to source zone treatment, then the attenuation rate calculation must account for the time it takes for that effect to reach the downgradient transect. Otherwise, the mass attenuation rate will be too low or, conceivably, negative.

An emerging “mass balance” use for mass discharge estimates is to determine whether multiple sources may be contributing to a single plume or comingled plumes. Because mass discharge is a good indicator of source strength, it may help determine whether a given source has the ability to generate/sustain a given plume or whether another source must be present. Comparing the mass discharge from a known source to the estimated plume attenuation rate can indicate whether an additional source is present, particularly if the plume attenuation rate is comparable to the known source mass discharge and the plume is still increasing. Using mass discharge estimates in this way can also lead to improved allocation of remedial resources and of responsibilities and liability among multiple responsible parties.

3.2 Potential Impact and Exposure Evaluation

There is a growing recognition that mass flux data can supplement concentration data to provide a more complete measure of the potential impact to a receptor posed by a contaminant plume. Point concentrations alone do not provide sufficient information to calculate downgradient impacts. For example, two plumes with the same contaminant concentrations may affect receptors differently because one plume may be moving faster and therefore discharging greater contaminant mass over time. Additionally, one plume may attenuate rapidly, while another is sustained for many years, yielding dramatically different potential exposure time frames.

Mass discharge can be particularly important if the contaminant discharge from the plume mixes with clean water at or before an exposure point such as a supply well or surface water body. In such cases, mass discharge to the mixing zone is more important to estimate accurately than the point concentration. However, site characterizations generally focus more on concentration data than on the hydraulic conductivity and/or groundwater fluxes, so risk assessments often have to rely on uncertain groundwater flow estimates and cannot account for spatial differences in flow rates.

Einarson and Mackay (2001) proposed a framework for using mass discharge to prioritize site cleanups by considering the interaction of a contaminant plume with a downgradient water supply well. The framework uses mass discharge to estimate the resulting exposure concentration in water produced from the well. To make this calculation, the following equation was presented:

$$C_{sw} = M_d \div Q_{sw} \qquad (3\text{–}1)$$

where

C_{sw} = contaminant concentration in water extracted from the supply well, M/L^3 (e.g., mg/L)

M_d = mass discharge of plume located near edge of water supply well capture zone, *M/t* (e.g., g/d)

Q_{sw} = pumping rate of supply well, L^3/t (e.g., L/d)

Consider the following example. A plume with a mass discharge of 1,000 mg/d TCE (as measured across a transect at the junction of the edges of the plume and the well capture zone) is captured by a domestic well with a pumping rate of 1,000 L/d. The resulting concentration in the domestic water supply would be 1.0 mg/L (1,000 mg/d ÷ 1,000 L/d). However, if the same plume were captured by a large public water supply well pumping 1,000,000 L/d (about 200 gallons per minute [gpm]), then the resulting concentration in water extracted by the water supply well would only be 0.001 mg/L, which is below the maximum contaminant level (MCL) for TCE. While cleanup goals should not rely on blending in a supply well, this example reflects the importance of mass discharge in assessing potential impacts to a receptor, remedial strategies, and prioritizing site cleanups.

This same approach can be applied to groundwater plumes that discharge or threaten to discharge to a surface water body. For example, Burton et al. (2002) discuss an approach at a Maryland site where managers calculated the contaminant mass discharge to a river using point concentrations and groundwater discharge estimates and then proposed the use of a mixing zone to estimate potential exceedances of surface water quality criteria. The Mass Flux Toolkit (Farhat, Newell, and Nickols 2006) has calculation modules for both water supply well and surface water discharge scenarios.

3.3 Remedy Selection and Design

Mass flux and mass discharge data can be particularly valuable during the remediation planning process, including the development of remedial action objectives (RAOs), technology selection, and remedial design. Specific applications of mass flux or mass discharge data for each of these stages of remediation planning are described in more detail below. Additional applications involving mass flux or discharge for performance monitoring and optimization are discussed in Section 3.4.

3.3.1 Remedial Action Objectives

Complete source remediation within a reasonable time frame can be a difficult goal to accomplish due to technical and economical limitations. Regardless, it may be desirable to establish interim goals or RAOs based on partial source remediation and mass discharge reduction. An example of this application might be to reduce source zone mass discharge to a level that can accommodate implementation of a long-term MNA remedy for the dissolved-phase plume or to facilitate a risk-based RAO. In such cases, the mass flux or mass discharge targets can be used as RAOs, in addition to or in place of concentration-based RAOs, to provide a more meaningful trigger for transitioning to the MNA or risk-based remedy.

3.3.2 Remedy Selection

Remedial technologies vary in their ability to treat contaminants within low-permeability zones. For example, remedies that rely on groundwater capture or emplacement of chemical/biological agents typically address contaminants mainly in the transmissive zones, while remedies such as excavation, in situ mixing, physical containment, and in situ heating can reasonably address both the low-permeability and transmissive zones. Therefore, understanding the contaminant mass distribution, whether contaminant mass is predominantly in low-permeability or transmissive zones, will lead to better remedy selection and design. Measuring mass flux can provide this information.

Similarly, measuring mass flux across transects within the plume can improve estimates of plume attenuation rates and mass loss over time. Understanding the distribution as well as the seasonal and long-term stability of attenuation rates within the plume can lead to better remedy selection and remedy targeting in areas that need additional treatment and enhanced attenuation. At some point, it may be useful to reevaluate technology selection and pursue an alternate remedy. Sequenced technologies may even be part of the formal remedial strategy. Mass flux can be the metric triggering reevaluation.

3.3.3 Remedial Design

Prior ITRC documents (ITRC 2004, 2008a) have concluded that mass flux estimates can improve remediation decisions historically based on only concentration estimates because mass flux estimates can help locate areas contributing the most and the least contaminant mass to a plume.

Remediation technologies vary in their ability to treat mass in high- and low-*K* zones (Sale et al. 2008). Understanding the distribution of mass flux across transects and how it relates to the lithology and/or the distribution of groundwater flux across the transects can provide valuable information for placement of pumping wells, injection points, and monitoring wells.

An example of how mass flux can influence remedial design is the use of a permeable reactive barrier, such as a zero-valent iron wall or biobarrier. Such barriers must be designed to provide sufficient reactive capacity and retention time to treat the incoming contaminant mass. Thus, both groundwater velocity and contaminant mass are important design parameters. Mass flux estimates provide the necessary data inputs and indicate contaminant distribution across the treatment plane. In conjunction with other data, mass flux can indicate where the barrier thickness or reactive capacity needs to be increased to adequately treat the incoming contaminant mass. Designing the barrier based on average groundwater velocity alone could underestimate the treatment capacity and/or retention time needed and predispose the permeable reactive barrier to premature exhaustion and failure.

3.4 Performance Monitoring and Optimization

Mass flux/discharge estimates can be used to evaluate changes within the source zone or plume, remedy performance, and system optimization. For example, if a cleanup is not reaching milestones when anticipated, mass flux/discharge can be used to more precisely quantify the changes that are occurring and to identify physical and operational problems.

The combination of mass flux/discharge estimates and point concentration estimates facilitates the determination of contamination trends and analysis of remedial system operations better than either alone. Mass flux/discharge estimates can provide valuable information to determine whether or how soon remedial goals will be met, to decide when and where to transition between technologies, and to optimize remediation technology performance (USEPA 2003). Following are some ways that mass flux/discharge information can benefit remediation performance monitoring and optimization:

- Mass flux and mass discharge measurements can better assess the effects of source zone treatment, particularly if remediation is likely to disproportionally affect higher- and lower-*K* zones because the mass flux distribution identifies source zone hot spots where the greatest mass is being discharged, which allows for better treatment targeting. Mass flux reductions in the targeted hot-spot zones better demonstrate the effects of treatment than point concentration data alone in systems where flows change due to natural or artificial conditions because concentration and flow are integrated into a single metric.

- Post-remediation mass flux mapping can be used to evaluate remediation effectiveness and estimate the potential benefits of additional remediation efforts and/or the efficacy of MNA. For example, in cases where concentrations are depleted in high-*K* zones but not in low-*K* zones, a change in remediation approach may be required if mass reductions in low-*K* zones are needed to achieve site closure. Alternatively, mass flux data from more transmissive zones may reveal that treatment of these areas alone may achieve the desired effects and goals as quickly as treatment of the entire area.

Hill Air Force Base, Utah The effectiveness of a surfactant flood to treat a DNAPL source at the Hill Air Force Base Operable Unit 2 was evaluated by monitoring changes in contaminant mass discharge downgradient of the source. While a substantial (>90%) reduction in TCE mass discharge was noted, dichloroethene (DCE) mass discharge increased as a result of source treatment. These results suggest the surfactant used for in situ flushing enhanced reductive dechlorination of TCE. Even with this increase, the total molar discharge of TCE and DCE declined almost 90% as a result of partial DNAPL mass removal from the source zone (Brooks et al. 2008).

- Contaminant mass discharge estimates quantify the benefits of concentration reductions, whether through engineered remediation systems or MNA. For example, calculation of mass flux in each well along a transect, and for the well group as a whole, is the first step in treatment impact analysis (see boxes at right and on next page). However, additional data management will increase understanding further. Qualifying well data that show little or no contaminant flux reduction (for example, due to poor reagent distribution or other operational problems resulting in ineffective treatment) will provide a clearer picture of past treatment impact and show the potential value of specific efforts to improve treatment in those areas.

- Mass flux analyses can reveal treatment impacts on subsurface hydrodynamics. For example, portions of the subsurface may become clogged due to precipitation of inorganic by-products or biomass growth. Mass flux estimates over time can indicate how the mass flux distribution has changed in response to such impacts.

Figure 2-7 illustrates an important point to consider when using mass flux estimates in assessing remediation performance and changes over time. The mass flux at any location along a plume represents the combined effects of contaminant transport, destructive attenuation (if any), and storage processes (sorption and diffusion into low-*K* zones). Losses of contaminant mass to storage create a mass flux deficit relative to the flux that is later observed at plume maturity. It is therefore important to recognize that, in a transient plume, storage losses can be inadvertently interpreted as degradation.

3.5 Compliance Monitoring

The change in mass flux or mass discharge at the source zone quantifies source remediation performance, while in the dissolved-phase plume it documents the response of the plume to source or plume remediation. The key metric in evaluating remediation performance is the change in mass flux or mass discharge from baseline estimates.

Similarly, mass flux and mass discharge can be used for regulatory compliance monitoring to augment concentration-based data. For example, concentration data may indicate an exceedence of the regulatory standard at the compliance point. However, mass flux data may indicate there is little flow or discharge occurring. Conversely, where concentration data are low, mass flux data could indicate much higher than expected mass discharge is occurring due to higher groundwater flow despite the lower contaminant concentration. In both cases, compliance metrics could be based on the maintenance of or reduction to a low or zero mass flux to prevent impacts to downgradient receptors.

Using Mass Flux for Compliance Monitoring Upon detecting volatile organic compounds (VOCs), mainly TCE, in Well 12A in 1981, USEPA conducted an investigation, and the Time Oil building was identified as the primary source area. The Time Oil building is located approximately 2000 feet northeast of well 12A and has a long history of paint and lacquer manufacturing and waste-oil recycling that dates back to approximately 1923. As USEPA became involved with the site, several remedial actions were implemented, including a groundwater extraction system which continues to operate but is ineffective in reducing contaminant mass or maintaining hydraulic control of dissolved- phase groundwater contamination. As remediation efforts continued, USEPA and the Washington State Department of Ecology have developed a proposed plan combining thermal remediation with the existing groundwater extraction system to reduce source zone contamination. An RAO listed in the proposed plan requires the reduction of mass flux by 90% at the source zone flux plane, identified as the 300 ppb TCE isopleth, and meeting the 5 ppb TCE MCL criteria in fringe- area compliance wells. Passive treatment is expected to occur in the zone between the 300 and 5 ppb TCE isopleths (USEPA 2001b).

An example of the proposed use of mass flux and mass discharge as compliance monitoring parameters is contained in the preferred remedy in the proposed plan for the Well 12A Superfund site located in Tacoma, Washington (USAPA 2009, see box at right). Mass flux data for the site would be used for two purposes:

- Mass flux data obtained at monitoring wells closer to the active groundwater treatment areas may be used to optimize the treatment system and to focus treatment in areas that are exhibiting higher mass flux.
- The mass discharge across a plane of transect monitoring wells would be monitored over time. This plane of measurement wells will be situated along the downgradient boundary of the active treatment zone. Mass discharge estimates across this plane of monitoring wells will determine when the remedial goal of 90% reduction has been achieved. Once this goal has been achieved, and concentrations of contaminants of concern (COCs) are below applicable MCLs at compliance monitoring wells, the groundwater extraction and treatment system will be shut down.

3.6 Site Prioritization

Because mass discharge provides a quantitative estimate of source strength and an estimate of the potential impacts to downgradient receptors, it can help regulators and responsible parties prioritize among different sites. For example, two sites that have relatively similar concentrations could have significantly different potentials for affecting resources or impacting receptors. But this distinction may not be evident based on concentration data alone. By improving assessment of source strength, plume attenuation rate, and potential impacts to a receptor, mass discharge at the source zone or within the plume can be used as an additional tool to help regulatory agencies or responsible parties prioritize cleanup resources and time frames within a site or among multiple sites In this way, mass discharge information provides additional context for evaluating point concentration data and the potential threat to receptors and beneficial uses at the site.

Using mass discharge to prioritize site cleanup and manage environmental liabilities is increasingly being performed by industry—sometimes outside the regulatory framework. Examples of where mass discharge estimates have been used by Chevron to prioritize site cleanups are described by Buscheck, Nijhawan, and O’Reilly (2003). Also, there are large industrial companies that are voluntarily measuring mass discharge downgradient from their contaminated properties to better define their environmental liabilities (M. D. Einarson, personal communication, 2009). Newell et al. (2011) developed a Plume Magnitude Classification system, where mass discharge is used to classify the strengths of groundwater plumes from very small “Mag 1 plumes” (mass discharge < 0.001 grams per day) to very strong “Mag 10 plumes” (mass discharge > 100,000 grams per day). Finally, at sites where mass discharge analyses show potentially significant risks to downgradient receptors, remediation can be performed to mitigate the risk of future impacts to those receptors.

3.7 Conceptual Examples for Using Mass Flux and Mass Discharge

This section presents a conceptual site example of how mass flux/discharge estimates discussed in the previous sections can be applied. The example is based on a hypothetical site with simplified geologic conditions.

3.7.1 Site Setting

In this example, a DNAPL source zone is situated at the site, and there is one COC that exceeds cleanup criteria in groundwater. The source area is underlain by three hydrostratigraphic units, which have been impacted by DNAPL migration below the release area (see Figure 3-2):

- Unit 1: fine-grained, silty sand with low permeability
- Unit 2: coarse-grained sand with high permeability
- Unit 3: fine-grained, silty sand with low permeability

A water supply well is situated downgradient of the source zone and is screened through all three hydrostratigraphic units. The majority of water pumped by the supply well is transmitted through Unit 2 because this unit is highly transmissive relative to Units 1 and 3. Figure 3-3 illustrates the cross section (transect A-A’) of the capture zone for the supply well, which extends beyond the boundary of the source zone.

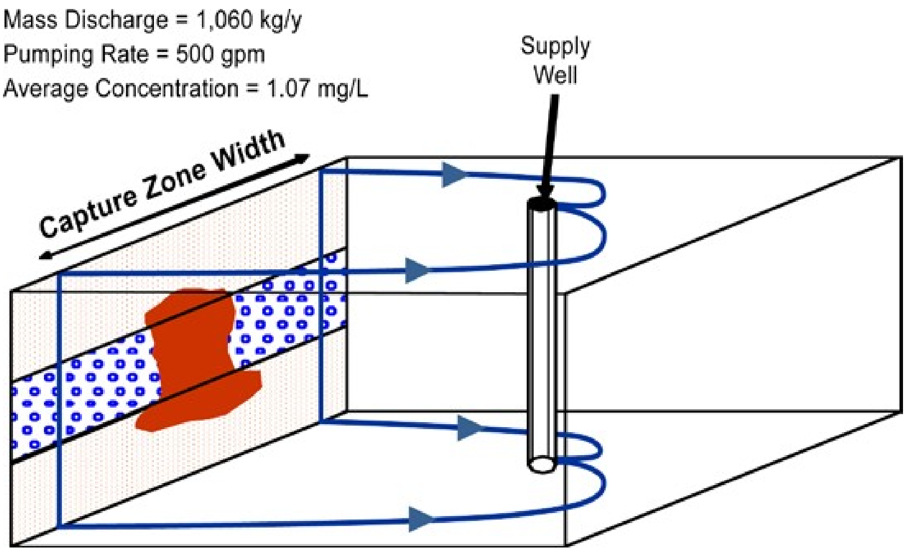

Figure 3-3. Source zone along transect A-A'. (Graphic courtesy Porewater Solutions, Inc.)

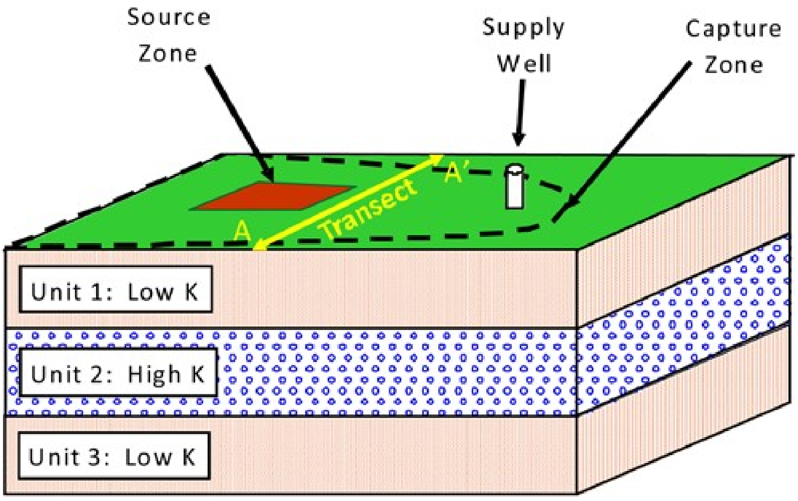

Figure 3-2. Site setting. (Graphic courtesy Porewater Solutions, Inc.)

3.7.2 Use of Mass Flux for Site Characterization and CSM Development

As part of the remedial investigation (RI) for the site, the mass flux and mass discharge were estimated along the transect A-A' corresponding to the cross-section location shown in Figure 3-2 downgradient of the DNAPL source zone. Figure 3-3 presents a transect through the three hydrostratigraphic units, including the extent of the source zone in each of the three units. The mass discharge from the source zone in Units 1, 2, and 3 was estimated to be 10, 1000, and 50 kg/year, respectively, for a total mass discharge of 1060 kg/year. This estimate of mass discharge represents a baseline measurement prior to remedial activities at the site. For the conceptual model, the mass discharge data provide an important characterization of the source architecture relative to sediment geology. In this case, the greatest mass discharge occurs in the most transmissive unit, which is an important consideration for remedial planning as discussed below. The aquifer attenuation capacity was calculated to be approximately 500 kg/year in the dissolved-phase plume downgradient of the source zone. Because the mass discharge from the source zone is larger than the aquifer attenuation capacity, the dissolved-phase plume will expand over time. Additional monitoring should be conducted to confirm this analysis. Optional modeling can be conducted using the source strength (i.e., mass discharge from the source) as an input, as well as user-defined attenuation properties, to evaluate the future steady-state length of the plume.

3.7.3 Potential Impact and Exposure Evaluation

With the supply well pumping 500 gpm, the supply well capture zone was determined to extend beyond the DNAPL source zone (Figure 3-4) so that the supply well captures the full source zone mass discharge in addition to clean water beyond it. The average COC concentration in water extracted from the supply well is determined using the eq. 3-1 presented in Section 3.2. Based on the pumping rate and total mass discharge over all three hydrostratigraphic units, the average concentration at the supply well was estimated to be approximately 1 mg/L. Assuming that the regulatory concentration limit for the COC at the supply well is 0.2 mg/L, the mass discharge from the source zone must be reduced by at least 860 kg/year to ensure that the groundwater concentration is below the 0.2 mg/L regulatory limit. For this example, the effects of aquifer attenuation are ignored. If considered, they would justify a higher mass discharge target from the source zone. This example demonstrates the benefit of relying on mass discharge data, which more closely correlate to the remedial objectives for protection of a supply well or surface water body, rather than relying on one or a series of point-specific concentration estimates.

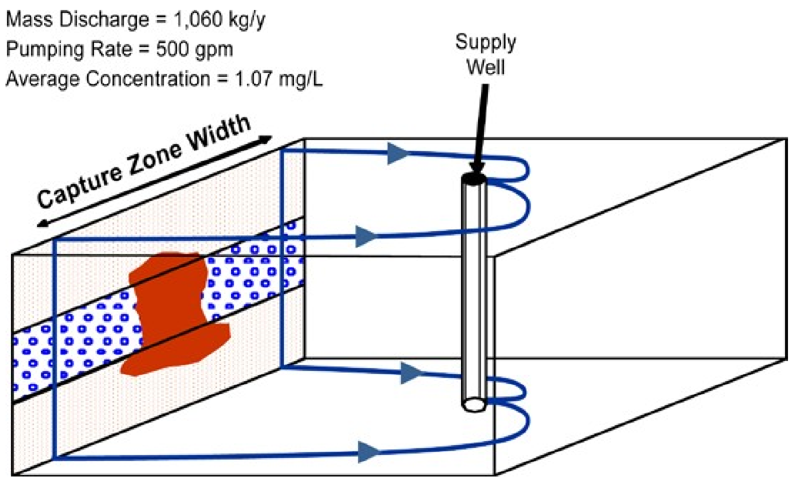

Figure 3-4. Mass discharge to a supply well. (Graphic courtesy Porewater Solutions, Inc.)

The potential impacts of a plume of groundwater contamination on usage of groundwater or on receiving water bodies are proportional to the strength of the mass discharge of the plume. Clearly a large mass discharge would present more of a potential problem to large-scale consumption of water than a small mass discharge, and the same would be true of receiving water bodies, as illustrated by Leu and Hadley (1987). This current ITRC document has focused on approaches and techniques for measuring mass discharge. With more quantitative correlations between mass discharge and actual water usage and base flow or assimilative capacity of surface waters, perhaps a more useful and quantitative classification could be developed to be able to categorize plumes by mass discharge. This type of plume magnitude classification system would provide a way of matching remediation and management strategies for plumes in proportion to their potential impacts. This idea is identified as a research need in Section 6.

3.7.4 Remediation Selection and Design

In this example, based on the target reduction from 1060 to 200 kg/year for mass discharge and assuming that mass removal from the low-permeability units (1 and 3) will be negligible, a reduction in mass discharge of at least 81% from Unit 2 is required (Figure 3-3). This level of mass discharge reduction may be difficult to achieve, and thus it may be necessary to implement a long-term plume management strategy to ensure additional attenuation of the plume is achieved downgradient of the source zone or that the plume is hydraulically contained until the mass discharge reduction is achieved.

A technology that includes the injection of soluble substrates (e.g., enhanced bioremediation or in situ chemical oxidation) into Unit 2 was considered for this example site. Although such a technology may not achieve efficient distribution of the soluble substrate into the less-permeable Units 1 and 3, these units have such a small component of mass discharge relative to Unit 2 that remediation may still be effective. Therefore, while desorption from Units 1 and 3 will increase in response to concentration gradient increases caused by remediation of Unit 2, the release of contaminants adsorbed to the soil may not be rapid or large enough to require remediation of the low-*K* zones.

3.7.5 Performance Monitoring

In this example, prior to full-scale implementation, a pilot test was conducted to evaluate the feasibility of treatment using a soluble substrate injection technology. The pilot test was conducted over a relatively long period of time, and the mass discharge was estimated across the transect shown in Figure 3-3 at several time intervals during and at the end of the pilot test. Comparison of the pilot test data to the baseline mass discharge estimate supports estimation of the time required to achieve the RAOs provided that the pilot test duration was sufficiently long for its maximum impact to be observed.

The mass flux distribution was also evaluated at the end of the pilot test and compared to the baseline mass flux distribution. This comparison provided a comprehensive assessment of the portion of the source zone that was most effectively remediated and the portion where remediation was limited during the pilot test. These data were used to confirm that a specific remedial technology was or was not feasible and, if necessary, to adjust the remedial design prior to full-scale implementation to improve the remedial efficiency and impact.

After six months of operating the full-scale system, a similar mass flux distribution assessment provided valuable information on the longer-term performance of the remedy. This assessment was used to confirm the remediation time frame estimate and to adjust the remedial implementation.

3.8 Regulatory Considerations

3.8.1 Remedies That Temporarily Increase Mass Flux

As noted earlier, some remedies, such as source zone bioremediation, may increase mass flux across the DNAPL/groundwater interface (ITRC 2008b). Thus, bioremediation of DNAPL source zones may cause a temporary increase in mass flux away from the source area that could, in turn, cause a temporary expansion of the plume, particularly with respect to contaminant breakdown products (notably vinyl chloride when TCE is present). Recent research has suggested that this temporary increase in breakdown product distribution could be beneficial as the volume of the plume increases, which increases the rate of biodegradation of the breakdown products (ITRC 2008b). While these are desirable attributes and practices for bioremediation, they contradict conventional thinking and regulatory agency preferences for approaches that limit contaminant spreading. Understanding and effectively monitoring the effects of enhanced dissolution or degradation remedies will enable project managers to determine whether the system is working as planned and to be confident that the effects of treatment can be controlled with the proper engineering.

3.8.2 Mass Flux to Complement/Support Concentration-Based Decision Making

Regulations and regulatory policies typically focus on groundwater concentrations in the decision-making process without consideration of mass flux. This focus is understandable since risk assessments generally use exposure point concentrations as input to assess the risk to a given receptor. However, as discussed in Section 3.2, mass flux/discharge information provides an additional line of evidence to assess potential impacts to receptors. Thus, a more practical procedure is to use mass flux/discharge information in conjunction with point concentration data. For example, although concentration data may exceed risk-based standards for a nearby receptor, there may be little flow or contaminant movement, except within small zones. Mass flux/ discharge measurements can be used to refine the risk assessment by determining the total contaminant mass likely to reach the receptor. If measurements indicate minimal mass flux or mass discharge, the potential risk may be acceptable. Using mass flux data with point concentration data from wells allows an more informed decision based on a more complete picture of contaminant magnitude, distribution, mobility, and, ultimately, actual threat to receptors.

Mass flux can also be helpful in establishing remediation performance requirements. For example, complete source removal may not be feasible within a reasonable time frame at all DNAPL source zones, so it may be useful to establish interim RAOs for DNAPL source zones that recognize the limitations to complete source removal (Sale et al. 2008). In such cases, it can be helpful to establish interim remedial goals and performance metrics based on partial source treatment demonstrated by reductions of mass flux and mass discharge from the source area. For example, source goals could include mass flux/discharge reductions to achieve plume stability and protect downgradient receptors or to reduce the mass flux/discharge to the point that the remaining concentration and risks can be controlled more cost-effectively by some other active treatment technology. Goals based on both contaminant concentration and mass flux/discharge information ideally are more achievable and feasible.

3.8.3 Summary

The review of case studies showed that containment mass flux/discharge estimates have been useful for several site management objectives and that evaluating mass flux/discharge can improve CSMs and lead to more efficient remediation. Specific findings from the case study review include the following:

- **Mass information has improved decision making.** For example, it has been used as an interim remediation goal and trigger for transition between technologies.
- **Mass information has reduced remediation costs.** For example, mass flux estimates have been used to identify high-priority target treatment layers in stratified aquifers, leading to more cost-effective cleanup.
- **Mass information has been used to prioritize sites.** For example, responsible parties have used mass

discharge estimates to identify sites that must be remediated first and to schedule remediation in regional flow systems with multiple sources.

- **Mass information has been used to predict and evaluate remediation performance.** Mass discharge, high-resolution mapping, and available analytical tools have provided the basis to estimate natural attenuation rates, plume responses to source treatment, and remediation time frames.
- **Transect data have proven to be particularly valuable.** Well transects have provided more credible estimates of natural attenuation rates than the more typical practice of relying on a line of wells along a flow path because transect data are less susceptible to temporal and spatial variations in flow direction and strength.

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