Cooperative Research Centre for **Contamination Assessment and Remediation of the Environment**

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A safer, cleaner environmental future

TECHNICAL REPORT NO.31

Flux-based criteria for management of groundwater

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CRC for Contamination Assessment and Remediation of the Environment

Technical Report no. 31

Flux-based criteria for management of groundwater

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Executive summary

This report reviews guidance, documents, tools and industry practice relating to the application of mass flux-based criteria for the management of groundwater contamination. It aims to determine where further work should be carried out to realise the advantages of mass flux-based assessment of groundwater contamination, and to identify the most reliable and promising methods for further research and application.

This report has a focus on Australian regulations and practice; however, similar approaches to the assessment and management of contaminated groundwater are applied internationally and the findings and recommendations of this report can be expected to have general applicability.

The key findings of the study are:

- There is widespread interest internationally in the application of the concepts of mass flux and mass discharge of contaminants, and these concepts are being applied in some countries. At a recent international conference1 on remediation of soil and groundwater, of a total of 870 papers, 33 papers referred to the concept of mass flux, and 35 papers referred to mass discharge.
- The concepts are recognised in Australian regulations and practice as being useful in understanding the significance of soil and groundwater contamination and in determining the requirements for clean up and management. Examples of how flux is used in Australia include:
  - Contributing to the conceptual site model and understanding risk
  - Better understanding how concentrations of contaminants may vary in the future
  - Assisting in determining whether remediation is required, or management can be accepted
  - Assisting in selecting remediation methods
  - Assisting in the design of a remedial method
  - Assisting in assessing the performance of remediation methods, and
  - Providing a compliance measure and a measure for closure.
- Methods for estimating mass flux and mass discharge for dissolved phase contaminants include:
  - Transect methods
  - Well capture/pump test methods
  - Passive flux meters
  - Transects based on isocontours, and
  - Solute transport models.

[1] Battelle Eighth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California, May 21–24, 2012.

It was found that mass flux and mass discharge concepts can be of greatest benefit in:

- Determining when remediation is required
- Assisting in assessing the performance of remediation methods
- Providing a compliance measure, and
- Providing a measure for closure.

Suggestions are provided for metrics relating to determining when remediation is required, when closure has been achieved, and in assessing the performance of remedial measures.

Because the application of mass flux and mass discharge concepts has the potential to offer significant benefits and much is already known internationally about their application, it is important to encourage the application of these concepts in Australia.

It is recommended that:

- Guidance and training programs be developed to explain and apply the concepts in developing conceptual site models, understanding the time variation of contaminant plumes, establishing an appropriate remedial response, designing remedial methods, assessing the significance and risk of contaminant plumes, assessing the performance of remediation methods, and in showing that CUTEP has been achieved
- Guidance and training programs be developed on the application of various methods for measuring mass flux and mass discharge, including transect methods, passive flux meters, integral pumping tests, modified integral pumping tests, the isocontour analytical method, and solute transport models
- Specific metrics be developed and demonstrated through demonstration projects, particularly pertaining to decision making and achieving regulatory compliance on matters such as the selection of remedial response, the performance of remedial methods, CUTEP, closure, and sustainability, and to encourage inclusion of these concepts and metrics in the National Remediation Framework
- Consideration be given to the development of a tool (software) to simplify the application of these methods, and
- Consideration be given to the potential to develop low cost passive flux meters.

Abbreviations

ANZECC	Australian and New Zealand Environment Conservation Council
CRC CARE	Cooperative Research Centre Contamination Assessment and Remediation of the Environment
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CUTEP	Clean up to the extent practicable
DEC	Department of Environment and Conservation
DNAPL	Dense non-aqueous phase liquid
GIL	Groundwater investigation level
IPT	Integral pump test
ITRC	Interstate Technology and Regulatory Council
LNAPL	Light non-aqueous phase liquid
MIPT	Modified integral pump test
NAPL	Non-aqueous phase liquid
NEPM	*National Environment Protection (Assessment of Site Contamination) Measure*
NSW	New South Wales
PFM	Passive flux meter
TCE	Trichloroethylene
TCW	Tandem circulating well
TM	Transect method
UK	United Kingdom
USA	United States of America

Glossary

Auditor	A person who is appointed or accredited under environmental legislation to act on behalf of an environmental agency in certifying that land is suitable for its proposed use
CUTEP	Clean up to the extent practicable as described in EPA Victoria Publication 840: If it is impracticable to clean up groundwater to the level needed to restore beneficial uses, EPA Victoria may accept that clean up to the extent practicable has occurred and that, subject to appropriate ongoing management, further clean up is not required (EPAV, 2002)
Environmental agency	A government organisation that has responsibility for implementing legislation and regulations. In this report the term government agency is used interchangeably with government authority
Mass discharge	The total mass of a contaminant passing through a defined plane (mass/time), and usually refers to the total mass of a contaminant associated with a plume conveyed through a plane
Mass flux	The mass of a contaminant passing through a defined area (mass/time/area), which is usually a subset of a plume cross section
Non-aqueous phase liquid (NAPL)	A liquid that is present in soil or groundwater as a separate phase and is potentially mobile. An example is petroleum fuel that might float on the groundwater. Where the NAPL has a density less than water it is referred to as a Light non-aqueous phase liquid (LNAPL) and where the density is greater than water it is referred to as a dense non-aqueous phase liquid (DNAPL). Where NAPL has become distributed and adsorbed on soil particles and is no longer mobile but still forms a source of dissolved phase contamination, it is referred to as adsorbed phase
Remediation	The actions to assess or break a source-pathway-receptor linkage and thereby manage risks associated with the presence of contaminants in the environment

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1. Introduction

1.1 Background

Decision making in Australia and internationally to regulate the management of contaminated groundwater environments, including the setting of remediation goals, is generally based on criteria that are defined in terms of contaminant concentrations. For example, in Australia the *National Environment Protection (Assessment of Site Contamination) Measure* (the NEPM) sets criteria for contaminants in groundwater as groundwater investigation levels (GILs). These concentration-based criteria can be used to identify situations where a potentially unacceptable risk to a beneficial use may exist, and they are often used in regulatory decision making for the management of groundwater contamination in the absence of other relevant guidance.

While the concentration of a contaminant is a key indicator of the potential for impact of a contaminant on the health of persons and biota, in many circumstances contaminant mass flux (the mass flowrate of a contaminant across a boundary) and mass discharge can also be important considerations and will be referred to when making decisions relating to remediation progress and acceptance of groundwater contamination. In some situations significant decreases in mass flux and discharge occur even though a concentration compliance criterion or a clean-up target has not been met, and thus measurement of mass flux or mass discharge may provide an alternative means of demonstrating the effectiveness of remediation.

The concepts of mass flux and mass discharge have gained considerable recognition internationally; at a recent international conference[2] on remediation of soil and groundwater, of a total of 870 papers, 33 papers referred to the concept of mass flux, and 35 papers referred to mass discharge.

Despite general recognition of the usefulness of mass flux concepts and their widespread use, there is not a consensus or guidance on how mass flux or mass discharge measures may be used or the endpoints that should apply. Hadley and Newell (2012), for example, note the difficulty that is being experienced in gaining formal acceptance of mass flux and mass discharge concepts by the regulatory agencies.

There is a need to:

- Establish how to apply groundwater mass flux and mass discharge information in the assessment and remediation of groundwater contamination in Australia
- Determine how to better measure contaminant mass flux in groundwater, and
- Define how mass flux and mass discharge can be useful and beneficial as a regulatory tool, and gain regulatory acceptance of the concepts.

The Cooperative Research Centre Contamination Assessment and Remediation of the Environment (CRC CARE) is commencing the development of a program of work related to mass flux-based assessment of groundwater contamination.

[2] *Battelle Eighth International Conference on Remediation of Chlorinated and Recalcitrant Compounds*, Monterey, California, May 21–24, 2012.

It is envisaged that there will be three stages of research and policy development:

- An initial review
- Field testing and evaluation of selected technologies related to relevant applications, and
- Development of policy and guidance.

This project is focussed on the first stage of this work, and includes:

- A review of national and international policy, regulation and practice regarding the use of mass flux and mass discharge in the assessment of groundwater contamination in Australia and overseas
  - the situations where the application of these measures can be of benefit
  - how this complies with current Australian regulatory policies and guidance, and
  - whether current policies and guidance can form an impediment to the application of mass flux and mass discharge concepts in assessment and remediation
- A review of the technical options and techniques for measurement of groundwater mass flux and mass discharge, including a summary of the advantages and disadvantages of each technique and the situations where its application can be of value
- The identification and recommendation of a limited number of technology options that could be evaluated in field situations and that have the potential for further adoption in Australia, and
- Conceptualisation of how a mass flux or mass discharge approach might be applied and adopted in Australia, and how application might vary and be preferable depending on groundwater environments, flow conditions and/or other factors, and how current policies and guidance could usefully be varied to encourage the use of the approach.

The intent is that this review consider and not duplicate work already carried out in Australia, including field-scale efforts through CRC CARE, CSIRO, and others to better quantify mass flux and evaluate the usefulness of groundwater mass flux techniques and measures in evaluating risk and assessing the success of remediation.

The application of mass flux-based methods does not currently have formal regulatory acceptance in Australia as a compliance measure; however, the methods are often applied in the assessment of groundwater contamination and in its remediation, and it is the intention of this report to encourage broader discussion that will lead to agreement on the use of mass flux and mass discharge methods in Australia.

Note that the project focuses on mass flux and mass discharge associated with groundwater contamination, particularly in the form of dissolved phase. Some consideration is given to the use of mass flux relating to free phase transport; however this is a relatively small part of this report.

The concept of mass flux and mass discharge is used in many other fields; however, these other areas are not considered in this report. These areas include: migration of vapours volatilising from soil and groundwater contamination, wastewater (particularly loads of contaminants entering receiving waters), landfills (flux through a liner system that gives rise to groundwater contamination, and landfill gas), and sediments (particularly contaminant fluxes arising from sediments into the water column).

2. Comparison of mass flux-based assessment

This section has the objective of defining the various situations in which mass flux-based assessment can offer advantages over a conventional concentration-based assessment, the nature of the measurements that can be helpful in decision making as to whether a remediation or management response is required, and the extent to which conventional approaches deal with the issues and their adequacy.

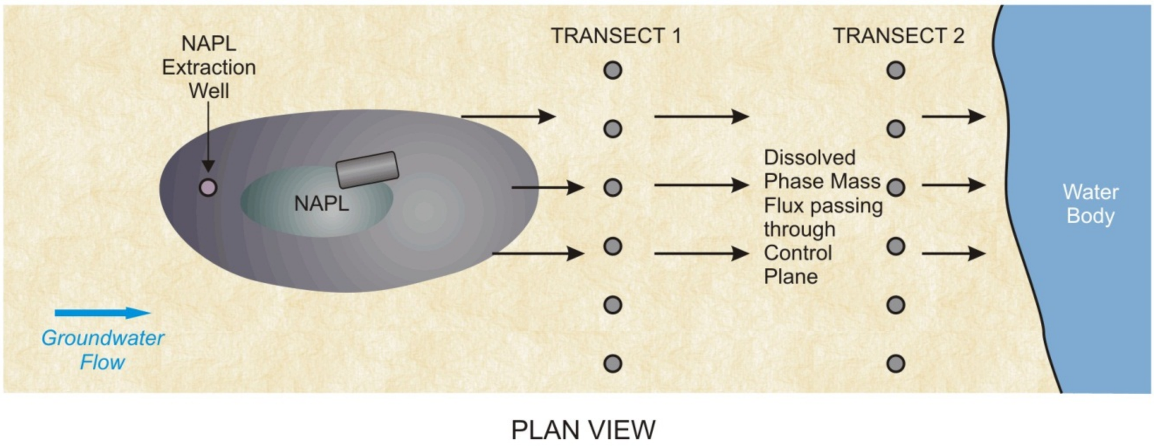
The purpose of carrying out this initial analysis was to determine how to structure the review, and if there were particular situations on which this report should focus, or whether the review should be cast widely. For example, it is known that mass flux concepts are valuable for certain situations, such as:

- Providing a useful measure of the contaminant concentration in a surface water which would result from discharge of contaminant(s) and whether the discharge will adversely affect the aquatic ecosystems of the surface water, and
- Assisting in understanding the relative contribution and longevity of source zones to a contamination plume, and where treatment should be directed.

Because there are many possible applications and interlinking factors, a matrix approach has been adopted in order to simplify the initial conceptualisation of the issues. Figure 1 illustrates the concepts relating to mass flux in diagrammatic form.

In particular, consideration has been given to:

- The nature and form of the contaminant source, e.g. whether the source is a free phase (e.g. dense non-aqueous phase liquid (DNAPL) or light non-aqueous phase liquid (LNAPL)) or adsorbed phase, and the chemical composition (e.g. organic, inorganic, soluble or insoluble)
- The nature and form of the contaminant flux that flows from the source material and the pathway, e.g. whether it is migrating as a free phase, dissolved phase or vapour phase, migrating via groundwater or the unsaturated zone
- The beneficial uses to be protected, such as for soil: human health, aesthetic enjoyment, ecological systems, and for groundwater: human health, primary contact recreation, maintenance of ecosystems, stock water, irrigation, and other uses
- The location and setting where the impact on beneficial uses may occur, e.g. whether these occur close to or distant from the source, the spatial extent of impact (e.g. length of shoreline affected and extent of dilution in the receiving water; or the area and extent of a groundwater plume and its relationship to potential use of the groundwater); and the area and extent of vapour impact (e.g. on land subject to development), and
- The importance of the mass flux measurement to the decision that is being made, e.g. assessing or quantifying factors such as risk (potential extent, severity), rate of mass loss and longevity of effect (e.g. through natural attenuation or treatment), the potential for application of particular clean-up methods, or evaluation of the efficacy of a particular clean up method that is being applied.



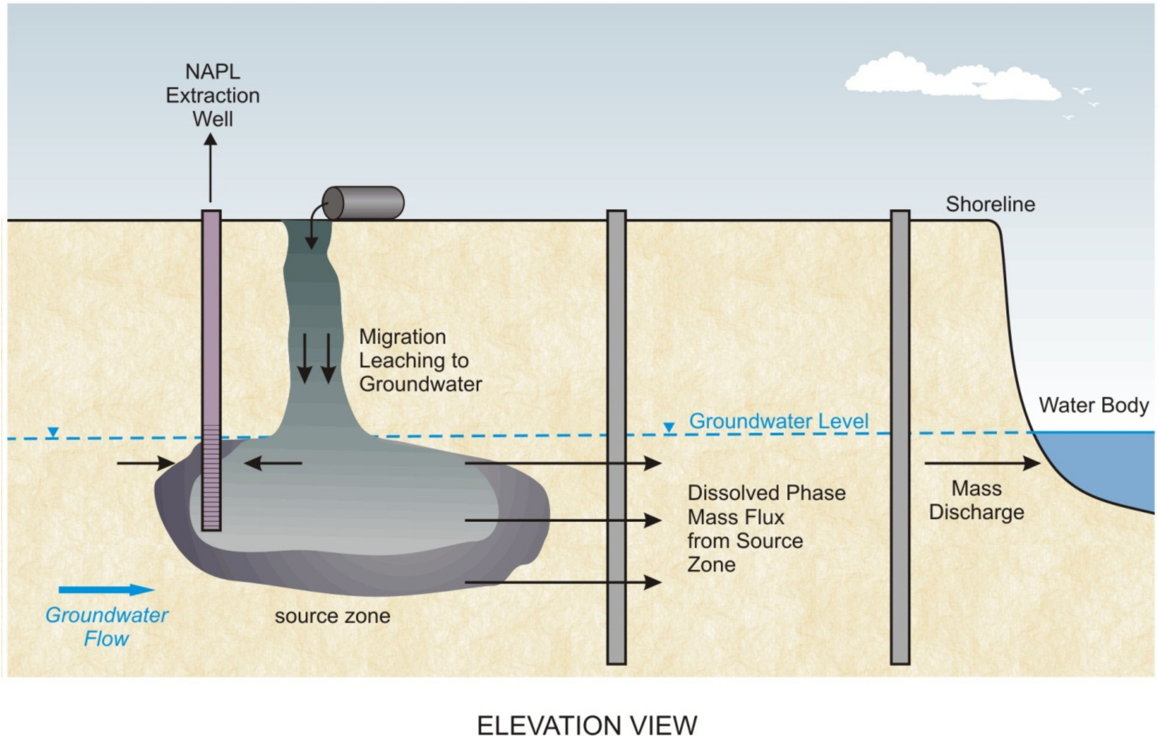


Figure 1. Mass flux of groundwater contamination potentially affecting a groundwater user or water body.

The potential for application of mass flux in the various situations listed above is shown in table 1. In preparing this table, it was found that there was potential for application of the mass flux concepts to all of the issues listed.

Because mass flux concepts can be applied to a wide range of contaminant situations, a further analysis has been carried out to explore how the mass flux concept can be relevant to the various situations that apply in assessment and remediation of soil and groundwater contamination. This is summarised in table 2. It can be seen from this analysis:

- In terms of regulatory importance, to date mass flux has generally been used as a tool to assist in quantifying and understanding aspects important in the assessment of risk, completeness of clean up, and time to complete clean up.

Mass flux has not yet been commonly used as a measure that has been explicitly defined as a criterion that, if complied with, provides an endpoint in itself

- In terms of requirements for measurement, the mass flux may need to be able to be related to changes in the residual mass, composition and risk posed by the contamination, and
- In terms of requirements for other accompanying information, this can include, for example, measuring the total mass and different forms of contamination present, and the risk posed by the residual contamination.

It can be seen from this analysis that it is important to be able to relate the mass flux information to tangible outcomes.

Table 1. Potential for application of mass flux and/or mass discharge.

Source	Migrating as		Potential application of mass flux and/or mass discharge			
		Site characterisation	Assessing risk (potential extent/ severity, longevity of impact and typical beneficial use affected)	Determining the rate of mass loss	Assessing the potential for application of clean-up methods	Assessing the performance of an existing clean up method
NAPL	LNAPL/ DNAPL	✓	✓ (e.g. human health)	✓	✓	✓
	Dissolved	✓	✓ (e.g. human health, ecological)	✓	✓	✓
	Vapour	✓	✓ (e.g. human health)	✓	✓	✓
Adsorbed	Dissolved	✓	✓ (e.g. human health, ecological)	✓	✓	✓
	Vapour	✓	✓ (e.g. human health)	✓	✓	✓

Table 2. Considerations relating to the application of mass flux and mass discharge to assessment and remediation.

	Objective	Relevance of mass flux/mass discharge	Requirements for measurement	Other information that may be required
Site characterisation	Understand the contamination and develop a Conceptual Site Model.	In understanding contamination at the site, how it might affect receptors on site and off site, and how it might be addressed.	Measurements to characterise geology, hydrogeology, source, pathways, flow rate, concentration, and impacts on receptors.	Whether mass loss is occurring.
Assessing the potential for application of a clean up method	Establish if a particular clean up method will achieve a material benefit in terms of reducing risk, or reducing time that a source will remain.	In determining whether a particular clean up method will provide a material benefit in terms of reducing risk or reducing the time over which risk will require management.	Measurement of the rate of mass reduction by a particular clean up method, and whether this will be material in reducing the time and risk, or increasing the completeness of clean up.	Measurement of the total mass that is present, against which reduction can be measured. The form of the contaminant, as clean-up methods can be specific to a particular form. Measurement of the effect of the clean up method and mass reduction on other contamination characteristics and risk (e.g. mass reduction may result in little reduction in risk; or alternatively may have a great reduction in risk (if the mass reduction selectively reduces the fraction of volatile toxic components)).
Mass loss	Establish if the rate of mass loss is such that it is important in determining the time that the source will remain.	In determining whether the time that the source will remain is acceptable with respect to the risk that it presents and the requirement for ongoing management. Whether the rate of mass loss is important in determining the time that a source will remain, or whether alternative methods need to be implemented to increase the rate of mass loss.	Measurement of the mass flux leaving a source area, in terms of the rate of migration of NAPL, dissolved phase, or vapour phase. Measurements need to be able to be used to determine total mass flux.	Delineation of source and existing mass. Measurement of rate of mass loss through other means that do not involve migration (e.g. biodegradation).
Assessing risk	Establish whether the rate of migration of a contaminant gives rise to an unacceptable risk.	In determining whether the presence or concentration of a contaminant at a receptor location of interest gives rise to an unacceptable risk.	Measurement of the mass flux at locations where it can be related to the presence or concentration of the contaminant at the receptor location of interest.	Measurement of the concentration at the receptor location of interest. The area of interest to the receptor. Whether mass flux is related to risk (e.g. measuring the composition of the contamination, or the presence or concentration at the receptor location of interest).

3. Regulatory considerations

3.1 International regulatory practice

In order to add to our understanding of how mass flux and mass discharge might be included in regulations relating to the assessment and remediation of contaminated land and groundwater, a review was carried out to determine whether mass flux has been incorporated into regulations relating to contaminated land and groundwater either nationally or internationally.

Colleagues in the USA, Canada, Germany, Austria, Belgium, France, Italy, Holland and the UK were contacted. In addition, information in the CRC CARE Contaminated Sites Law and Policy Directory was reviewed, and the experience and opinions of Australian site auditors was sought.

It was found that:

- Generally, regulatory requirements relating to the remediation of soil and groundwater are specified in terms of concentration rather than mass flux or mass discharge. This occurs because of adverse effects to human health and ecological receptors is usually directly dependent on concentration or has been determined toxicologically by concentration exposures, and hence the absence of adverse effects (and an acceptable situation) relies on the concentration of contaminants being below a level at which there is no adverse effect.
- Despite the central focus on concentration, the use of mass flux and mass discharge is being widely applied in the soil and groundwater remediation industry as an aid to understanding contamination problems, and is a matter of considerable interest to many regulatory agencies, particularly in the USA, Canada, Austria, France, Germany, Poland, Italy, the Czech Republic and Holland. There is a general sense that the application of the concepts of mass flux and mass discharge has the potential to offer improved understanding and more balanced outcome in soil and groundwater assessment and remediation; however, very few jurisdictions have formally recognised the concepts in formulating regulations.

3.2 International guidance on the use of flux

3.2.1 General

Despite the primary focus on concentration, the use of mass flux is recognised as being an important consideration by regulatory agencies, particularly in situations where clean up is proposed or implemented, and as there is a growing awareness of the practical difficulty and unsustainability of achieving full compliance with concentration criteria. As noted above, there have been a number of papers and documents prepared showing how mass flux and mass discharge can be helpful when remediating sites. For example, Basu et al. (2006) report a growing consensus among technical groups and regulatory agencies that contaminant flux and contaminant mass discharge should be used as alternate performance metrics for site assessment and remediation design at contaminated sites. Hadley and Newell (2012) similarly note the benefits and need for regulatory agencies to include the concepts in framing their guidance, but express concern about how long it is taking for this to occur.

3.2.2 USA

The document prepared by Interstate Technology and Regulatory Council (ITRC) – *Use and Measurement of Mass Flux and Mass Discharge* (ITRC 2010) provides an excellent and balanced discussion of the use of mass flux and mass discharge in contaminated site decision making in the USA. This document has been particularly referred to and drawn from in the preparation of this report, and readers are encouraged to refer to it.

The ITRC (2010) document considers and distinguishes both mass flux and mass discharge, and provides information relating to:

- The concept and theory of mass flux and mass discharge
- Applications for mass flux and mass discharge, and
- Measuring mass flux and mass discharge.

There are many case examples now reported in the literature where mass flux and mass discharge concepts are being applied, although formal regulatory acceptance is still evolving. One of the key drivers is to obtain a balanced view of what is practicable in terms of remediation and risk reduction, with the concepts of mass flux and mass discharge being seen to offer advantages in providing this balanced view. For example, this is an underlying premise of a recent paper by Hadley and Newell (2012), and is included in other papers, such as that by Engblom, Kirkman and Falta (2012), that discusses the application of mass flux concepts in evaluating the performance of plume capture and reduction in risk, and how the information can be used to set reasonable expectations for remedial performance.

Much of the activity in the USA centres on measuring and improving the performance of remediation, for example Clayton and Krembs (2012) used mass flux concepts to optimise the design and performance of biobarriers for the treatment of perchlorate, trichloroethylene (TCE), chromium and high explosives; Mowder et al. (2012) applied mass flux concepts in the detailed characterisation of a perchlorate plume to achieve better characterisation of source areas and hence improve remedial design and performance; and Su et al. (2012) applied mass flux concepts in evaluating the capture zone for perchlorate remediation systems.

There is an evolution occurring, with systems becoming quite advanced in terms of computation and measurement. An interesting example of this for the case of in situ bioremediation is the deployment of automated mass flux based remediation performance monitoring platforms to encourage rapid metrics-based remedy evaluation and stakeholder consensus (Kram et al. 2012). This work has involved integration of environmental sensors, telemetry, geographical information systems and geostatistical algorithms for automatically generating two and three-dimensional contour images and time stamped renderings and playback loops of sensor attributes, and multivariate analyses through a cloud-based project management platform (Kram et al. 2012).

In terms of regulatory acceptance, the application of mass flux and mass discharge concepts is still evolving in the USA. Regulatory compliance is usually defined in terms of whether the concentration of contaminants has been reduced to below certain target levels. This can be expected, as contaminant concentration is usually the key measure of suitability for use of groundwater and surface water. Nevertheless, it is recognised in the USA that measures of mass flux and mass discharge can be relevant to assessing the significance and risk associated with contamination, and in the effectiveness of remediation. As such, mass flux or mass discharge can sometimes form a compliance measure in the USA (ITRC 2010).

The Australian regulatory system has similar objectives to the USA regulatory system, and Australia can draw from the USA experience and guidance.

3.2.3 European countries

Various European countries are collaborating on projects that include mass flux in assessing and remediating groundwater contamination, and the situation is similar to that described above in the USA.

With respect to the formal inclusion of mass flux concepts in legislation and regulations, this review only identified Austria and Germany as being advanced in this.

Austria

The following information on the Austrian system has been obtained from a colleague in the Environment Agency Austria (Muller 2012a).

In assessing groundwater contamination, mass flux is being written into legislation in Austria. These are currently in draft and it is expected that these will be formally adopted in the near future. The use of mass flux in Austria is referred to in the following context:

- The generic assessment of groundwater contamination refers to trigger values and intervention values
- Groundwater contamination (plumes) are delineated in comparison to background values and trigger values, which are usually defined by 60% of the intervention value on a precautionary basis
- Intervention values are generally equal to drinking water values (ecotoxicological criteria have not been established)
- Concentrations higher than the intervention value are not generally acceptable, but may be deemed to be tolerable on a site-specific basis
- Contaminant mass fluxes are used to identify serious groundwater contamination
- A groundwater flow of greater than 500 m^3/d is deemed to be significant, given the hydrological and hydrogeological settings that are commonly encountered in Austria, and
- Groundwater contamination is serious (generally intolerable), if the contaminant mass flux of a plume exceeds the product of the intervention value x significant groundwater flow.

In the remediation of groundwater in Austria, mass flux can be used:

- As a complementary site-specific remediation target value
- As a criterion to control efficacy and efficiency of remediation measures, and
- To terminate inefficient remediation measures, when remediation targets (target values) are unlikely to be achieved within a specific period (site-specifically defined, mid- to long-term, which means 5–20 years).

An example of this approach is the work carried out in Europe by Austria and Germany (the INCORE project), and more recently by a group of organisations from Poland, Italy and the Czech Republic (the FOKS project) (Muller 2012b). In this work, the integral pumping test method was used to quantify mass fluxes across control planes, and to allow for some backtracking towards source zones.

Note that the concept of mass flux is commonly applied in other areas of Austrian environmental regulation, such as discharges of treated wastewater, and most of the activity-specific wastewater treatment ordinances provide a complementary system of limit values for concentrations and for mass fluxes (Muller 2012b).

Germany

The following information on the German system has been obtained from a colleague in the German Federal Environment Agency (Frauenstein, J 2012, pers. comm., 2 November).

Germany has a federal structure similar to Australia. Groundwater is widely used for drinking purposes, and the legal system seeks to avoid any adverse effect on groundwater quality. However, in practice this has been found to not be possible, as there has been a serious legacy of groundwater contamination. In establishing regulations for soil and groundwater contamination, it was found that the trigger values prescribed by the groundwater and soil regulations were not consistent. The groundwater regulations allowed only a very minor difference between what was determined to be an insignificant change in groundwater quality, and a harmful level of contamination, and required that this change would be measured at the point between unsaturated and saturated zone where the contamination from the unsaturated zone leaches into the groundwater. Satisfying the groundwater concentration trigger levels was found to be difficult and required remediation measures that were disproportionate to the level of effect in many situations. Because of these difficulties, Germany is working to harmonize the groundwater and soil regulations, and is proposing to allow a mixing zone for leaching of 1m in the saturated zone to bridge the disparity.

With respect to the use of flux concepts, the origin of the Austrian approach is the Baden-Württemberg Land (provincial capital: Stuttgart) in southern Germany (Muller 2012a). Baden-Württemberg incorporated this concept in legislation pertaining to groundwater in 1998 (*Sozialministeriums und des Umweltministeriums Baden-Württemberg 1998*). It is understood that Baden-Württemberg applies this only to regulating inputs to groundwater (leaching from the unsaturated zone (or by release in the saturated zone) as described above), and has set a different benchmark to Austria regarding significant flow which is tolerable at the concentrations of their trigger-values. For the purposes of this report a copy of the 1998 legislation was obtained and translated; this indicated that the source flow from contaminated soil is taken into account, maximum fluxes to groundwater are specified, and various groundwater depths are considered (*Sozialministeriums und des Umweltministeriums Baden-Württemberg 1998*). However, the regulations are complex and it was not possible to determine the detail of how the regulations apply in practice.

Other European countries

As noted above, this review only identified Austria and Germany as being advanced in the formal inclusion of mass flux concepts in legislation and regulations, although other countries have interest in the idea. By way of example, in developing the soil policy for The Netherlands, discussions took place on the application of mass flux-based assessment standards. It was determined that there were advantages and disadvantages, but mass flux concepts have not yet been introduced to regulate soil and groundwater contamination (Swartjes 2012). It was seen that the mass flux approach offers advantages in including two relevant criteria: availability and time, but has a significant disadvantage in that mass fluxes are more difficult to assess in practice and there is not a universal approach that can be applied (Swartjes 2012).

3.3 Australian regulatory practice

3.3.1 Introduction

The *National Environment Protection (Assessment of Site Contamination) Measure 1999* (Cwlth) (the NEPM) is an important national guidance document; it is under review, and a revised draft was issued in 2010. A search of the NEPM documents indicates that flux is not referred to in the text in either of the 1999 or 2010 sets of documents. With respect to the assessment of groundwater contamination, Schedule B6 of the NEPM is a *Guideline on risk based assessment on groundwater contamination*; however, this guideline is general in nature and recommends that where changes in groundwater quality are observed, state guidance should be referred to.

State guidance relating to the assessment of soil and groundwater contamination generally does not provide detailed guidance, and in most cases the terms mass flux and mass discharge are not explicitly referred to in regulatory guidance. New South Wales provides more detailed guidance than other states on groundwater contamination assessment and management, and the *Guidelines for the Assessment and Management of Groundwater Contamination (2007)* (DEC 2007) published by New South Wales Department of Environment and Conservation (NSW DEC) (now EPA) refers to considering mass flux in the context of carrying out groundwater contaminant fate and transport modelling, and also in evaluating natural attenuation[3].

It can be concluded that, in Australia, assessment of the impact of contamination focuses on contaminant concentration rather than mass flux or mass discharge, as concentration is the key factor in establishing whether contamination will pose a risk to human health and other biological species. As such, guidance focuses on ensuring that the concentrations of contaminants do not exceed levels that would give rise to adverse effects.

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[3] Reference is made in the guidelines to UK Environment Agency 2000, *Guidance on the assessment and monitoring of natural attenuation of contaminants in groundwater*, Environment Agency, Bristol, http://publications.environmentagency.gov.uk/pdf/SR-DPUB95-e-e.pdf

While mass flux is generally not referred to explicitly, the concept of mass flux and mass discharge of contaminants is nevertheless recognised by the regulatory agencies and consultants as being useful in understanding the significance of contamination and in determining the requirements for clean-up and management. Examples of this are discussed in the following sections.

3.3.2 Contributing to the site conceptual model and understanding risk

Developing a sound conceptual model of site contamination is an essential aspect of contamination assessment in Australia, and is specifically referred to in some Australian guidance (e.g. DEC 2006). While regulatory guidance does not explicitly refer to mass flux and mass discharge in the development of a site conceptual model, it is recognised that mass flux and mass discharge can provide a more complete measure of the potential impact to a receptor posed by a contaminant plume. For example, mass flux can provide a measure of the rate of movement and attenuation of a plume of contamination and the future variations in concentration. These are important matters for determining the length of the plume, the potential for exposure, and the length of time exposure will occur; all key factors in determining the risk that the contamination poses. Point concentration data alone does not provide this information.

As an example of this, if a mass flux analysis shows that the rate of natural mass loss over an area is greater than the mass flux into the area, then it may follow that the plume is naturally reducing and the risks to receptors will reduce over time. Conversely, if the rate of loss is much less than the mass flux, then it might be that the plume is increasing and the risk will increase over time.

3.3.3 Better understanding of resulting concentrations of contaminants

Understanding the risk that plumes of contamination pose, whether they are migrating off site, whether they are increasing or decreasing in extent, and the concentrations of contamination that result are important aspects of Australian regulatory decision making. While contaminant concentrations are the primary measure of adverse effect and acceptability, the time that will be taken to restore beneficial uses is referred to in regulatory decision making, and can be an important measure of the acceptability of a remedial method (DEC 2006; EPAV 2002).

Mass flux information can be and is used in some cases to assist in understanding whether plumes are increasing, stable or are decreasing in extent and, as noted above, is specifically referred to in New South Wales guidance (DEC 2006). For example, mass flux across transects at different locations along a plume can indicate whether the rate of mass loss is such that the mass flux is decreasing along the length of a plume, and hence that the plume extent will decrease rather than increase. Conversely, mass flux measurements may show that the plume has not reached equilibrium and is increasing in extent. These types of analyses could provide an additional line of evidence to support application of monitored natural attenuation strategies as noted in *CRC CARE Technical Report 15* (Beck & Mann 2010).

Mass discharge can provide a measure of the mass of contaminant that will be entering a receiving water body or a pumping well, and hence the concentration that will result, and this is used for some sites in Australia to assess risk to beneficial uses. Consideration of the mass discharge rate might show that, based on the surface water flow or pumping rate, the resulting contaminant concentration will be so diluted that acceptable water quality criteria will not be exceeded. If this is the case and it is accepted for management purposes, then monitoring could have the objective of confirming that the mass discharge remains at an acceptable level. Conversely, if the rate of discharge is large or increasing, then the resulting concentrations may exceed acceptable water quality criteria indicating that clean up is required.

Australian case example: an industrial precinct had been filled with mining residues that were giving rise to very high concentrations of groundwater contamination by metals such as arsenic and copper, and the groundwater was discharging into a large tidally flushed river. Estimates and measurements showed that, although the concentrations of contaminants in the groundwater exceeded the river water quality criteria by orders of magnitude, the mass discharge of contaminants would not be distinguishable from the background levels of contaminants with the river flows being much greater (> 100 000 times) than the groundwater flows, and it was clear that the receiving water criteria would not be exceeded. It was concluded that the discharge would not affect the beneficial uses of the river (such as maintenance of ecosystems, and fishing) and, from this perspective, posed a low risk and was not determining the requirements and priority for remediation. In this situation, periodic monitoring of on-shore wells and river water provides confirmation that the contaminant mass discharge is not unexpectedly increasing, and the risk remains low.

However, it was a consideration as to whether the groundwater discharge through the shoreline posed an unacceptable risk to the shoreline ecosystems, as the criteria for protection were greatly exceeded at the point where the groundwater discharged. In this case, the shoreline comprised a permeable engineered rock wall, and represented a highly modified environment. The regulatory agency considered its policy in this matter, and concluded that the shoreline ecosystem did require consideration and protection, although it was recognised that the risk and level of urgency for works was low.

3.3.4 Assisting in determining whether remediation is required

It is a critical area for all practising in the field of site assessment and remediation as to whether remediation is required, or not. Application of strict concentration-based criteria is a stringent requirement, as often the distribution of contamination will be variable and non-uniform, with small pockets of higher concentration quite often being the norm.

In Australia the environmental regulatory agencies generally do not accept that any contamination that exceeds the concentration criteria and adversely affects beneficial uses (e.g. of the groundwater or land) can be allowed to remain, and it is usually mandated that clean up be carried out. After clean up has been attempted and if the risk is not unacceptable and it becomes clear that further clean up is not practicable, then the regulatory agency may agree that further clean up is not required, and the residual contamination is managed.

Experience and research shows that concentration criteria can rarely be achieved everywhere at a site or in a groundwater plume within an acceptable timeframe and / or expenditure of resources. It has been argued that it should not be necessary to embark on clean up in situations where it is clear at the outset that clean up is not practicable; however, this has generally not been accepted by regulatory agencies other than in a few cases. It has also been suggested that Australia should introduce a target (desirable standard) and an intervention level, which would only mandate clean up if a serious level of contamination is present (rather than a minor localised exceedance). To date, this has not been accepted by the regulatory agencies.

It is possible that the application of mass flux and mass discharge considerations, similar to that in Germany, could be helpful in such situations. Mass flux and mass discharge can assist in understanding risk and the implications for long term stewardship of sites, and therefore whether remediation is required.

Whether a plume is contained to a site can be an important matter in determining the requirement for remediation, as it can be possible to manage contamination that is on site, whereas it is difficult to manage contamination that is off site. There is also a general as of right use to groundwater, and this makes it important that contamination that has migrated off site be cleaned up to the extent practicable. In this context, mass flux and mass discharge concepts may be useful; for example, if it can be shown that the rate of mass loss (e.g. through natural attenuation) is such that contamination will reduce and will be contained within the site.

3.3.5 Assisting in selecting remediation methods

Predicting the effectiveness of a remedial method in reducing the concentrations of contaminants to acceptable levels and the time that will be taken to restore the beneficial uses of groundwater are key matters in selecting one remediation method over another, and are a key aspect of Australian regulatory decision making as to whether to endorse a proposed clean up approach or not.

Some remediation methods such as in situ chemical oxidation, in situ chemical reduction extraction methods (e.g. multi-phase vacuum extraction) rely on contamination or reagents being able to migrate rapidly through an aquifer with high mass flux, and may be relatively ineffective where the contamination is stored in low permeability zones with low mobility and low mass flux. Such methods can result in much of the contamination remaining unrecovered or untreated – a critical factor in reaching a decision as to whether the method should be applied or not. In the case of NAPL, transmissivity can be a useful measure of the ability of NAPL to be recovered, and has potential to be used as a primary measure of where a method might be applied or not. Conversely, some remediation methods (such as excavation, containment and high energy in situ methods) do not rely on mass flux and can be relatively effective in removing contamination and restoring beneficial uses even where contamination is stored in relatively low permeability zones. However, while potentially applicable to source areas, it may not be practicable to extend such methods to the treatment of dissolved phase contamination surrounding the source area, and there may be an ongoing residual impact on beneficial uses.

While the latter considerations are important in Australian regulatory decision making, generally they are not explicitly explained or measured in terms of mass flux, although transmissivity has recently been referred to as a measure of NAPL recovery.

Combining measurements of groundwater flow, permeability and mass flux with measurements of contaminant concentrations can provide a better understanding of where contaminants are stored; for example, whether in a low permeability matrix with low flux (which presents a challenge to low energy in situ treatment methods), or whether contaminants are migrating through high permeability zones where reagents can be directed making in-situ methods potentially applicable. These considerations are currently applied in Australia for the assessment of contamination, although generally the discussion will not explicitly refer to mass flux.

Mass flux measurements across transects or through particular transmissive zones can be helpful in understanding the distribution of contaminants and the effectiveness of treatment methods, and these concepts are currently applied. Direct measurement of the mass of contaminant in the various geological units can also be important; it is possible that contaminants will be effectively restricted to low permeability units through physical restriction on flow, or may be restricted by adsorption (such as through cation exchange). Sampling and analysis of the various units may be a method of providing more direct measures of where contamination is stored, and the role of mass flux in treatment effectiveness.

3.3.6 Assisting in the design of a remedial method

Estimates of mass flux can assist in locating areas contributing the most and the least contaminant mass to a plume, and hence can provide valuable information for placement of pumping wells, injection points, and monitoring wells (ITRC 2004, 2008 & 2010).

For certain remedial methods that rely on the provision of sufficient treatment capacity and retention time to treat the incoming contaminant, such as a permeable reactive barrier, both groundwater velocity and mass flux are important design parameters. Mass flux estimates can provide information on the contaminant distribution across the treatment plane, and assist in determining the barrier thickness and reactive capacity. Relying on groundwater velocity and contaminant concentration may not identify zones where the mas flux is relatively high and additional capacity is required. These considerations are currently applied in Australia, although the application of permeable reactive barriers is infrequent.

Similarly, mass flux measurements can identify where the greatest mass is being discharged, and where treatment should be targeted. For example, if it is found that mass flux is large in some localised zones, then treatment of these zones may be able to achieve an overall reduction in concentration down gradient that avoids the need to treat all areas of the source zone. The large variations in flux that can commonly occur are illustrated in figure 2. This thinking is an important underlying factor in the current support for high resolution characterisation of source areas that is seen in the USA (for example, a panel session was devoted to this at the 2012 Battelle Conference[4]). This is particularly important for chlorinated solvent (DNAPL) sites, where it can be difficult to locate and delineate the source area. An example of this for a site with a TCE plume is the use of passive flux meters to identify zones with significantly different mass transit,

[4] Stream A Panel Session: “Site Characterisation: Determining the Right Amount for Decision Making”, Battelle Eighth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California, May 21–24.

and to use this in the selection of an appropriate remediation technology (Basu et al. 2006).

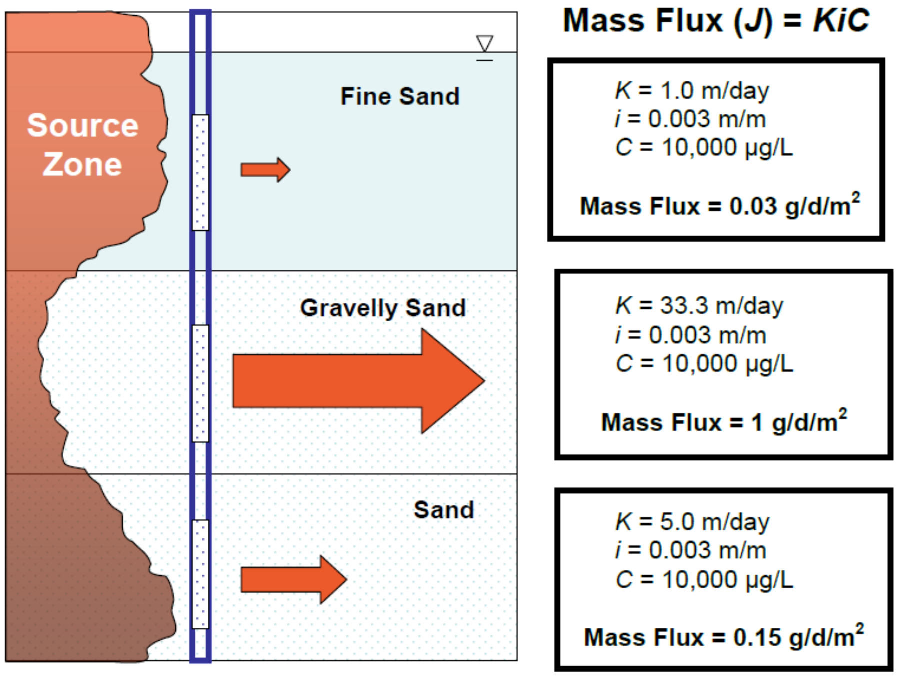

Figure 2. Identifying high mass flux zones to prioritise treatment locations (reproduced from ITRC, 2010 p. iv).

3.3.7 Assisting in assessing the performance of remediation methods

Mass flux and mass discharge methods together with concentration data can be used to assess the performance of a remediation method when in operation, and to confirm that it is performing as designed. This is now very commonly adopted in the USA, with many papers at a recent conference on Remediation of Chlorinated and Recalcitrant Compounds[5], for example, referring to mass flux as a performance measure. If the performance is not as expected, then mass flux measurements can assist in understanding where contaminant reduction is less than expected, and where improvement can be directed.

Mass flux measurements can also assist in quantifying natural attenuation rates; this is of particular value where the remediation strategy involves natural attenuation. An example of this was reported by Bockelmann, Ptak and Teutsch (2001), where the use of pumping wells located along control planes perpendicular to the groundwater flow were used to estimate mass loss in a heterogeneous aquifer in Germany, overcoming difficulties of quantifying mass loss through conventional point concentration measurements. This is illustrated in figure 3. Note that in applying this approach, field measurement and preparing estimates of fluxes would need to be repeated some time apart to confirm that the differences in flux result from attenuation, and not movement of the contaminant plume.

[5] Battelle Eighth International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey California, May 21–24, 2012.

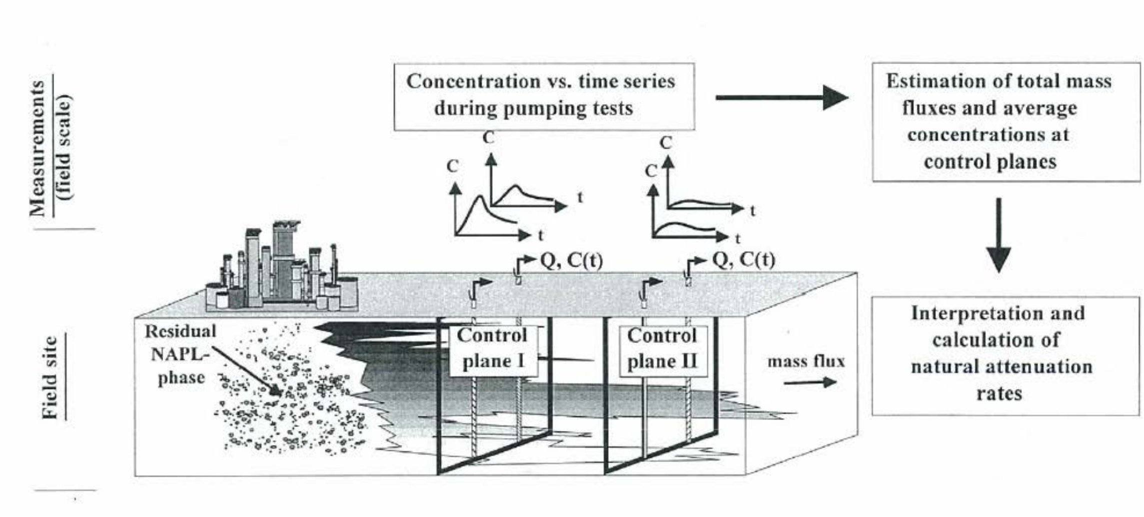

Figure 3. Using a two-plane flux approach to quantify natural attenuation (reproduced from Bockelmann, Ptak & Teutsch, 2001 p. 437).

Circumstances where mass flux or mass discharge concepts can be, and in some cases are, used in Australia include:

- Measurements of mass flux across transects to provide a measure of the extent to which contaminant mass is being removed from the system, something that is difficult to determine from concentration data alone. This information can assist in determining if treatment has been well targeted, or can be redirected to hot spots to achieve greater effectiveness.
- Measurements of mass flux across transects to distinguish whether the mass reduction is occurring through treatment, or through natural attenuation, and therefore provide information relevant to determining whether active treatment can cease and ongoing contaminant mass reduction can occur through natural means.
- Measurements of mass flux to determine the extent to which contaminant concentration is achieved through treatment, and the efficiency of usage of treatment reagents or application of a treatment method. Thus, this information may identify that treatment at certain locations is not contributing to the overall treatment effort, allowing treatment to be discontinued at those locations and directed to other locations where it will be more effective.
- Measurements of mass flux to identify where treatment has affected the hydrodynamics of the hydrogeological system. For example, if treatment causes clogging of the aquifer and less effective performance, then this might be able to be identified and quantified through mass flux measurements.
- Measurements of mass flux to distinguish whether changes in contaminant concentration arise from treatment, natural degradation, or storage within the aquifer (perhaps through diffusion or adsorption), or a release of contaminant from storage (perhaps through diffusion or desorption). This can lead to a better understanding of contaminant rebound and the time over which treatment will be required to achieve certain residual contaminant concentrations.

3.3.8 Providing a compliance measure

In Australia, contaminant concentration is usually adopted as a compliance measure, as concentration provides a direct measure of whether groundwater is fit for use. However, if concentration can be related to mass flux, then in principle mass flux or mass discharge could be adopted as an alternative compliance measure, although the author is not aware of situations where this has been explicitly adopted. This has particular relevance in the situation where the contaminant is discharging into a flowing body of water (such as a river), or affects a well where groundwater is being pumped out for use, and where the resulting concentration in the water body or pumped groundwater is dependent on the mass flux or mass discharge of the contaminant.

In Australia the concept of clean up to the extent practicable (CUTEP) is widely considered when deciding whether clean up has progressed to an acceptable endpoint (e.g. publication 840 (EPAV 2002), New South Wales groundwater guidance (DEC 2007)). While reaching decisions on this involves considering a range of factors, the mass of contaminant entering wells or reducing through treatment compared with the mass of contaminant remaining in the source zone and aquifer is a key factor in regulatory decision making. Because of this, mass flux or mass discharge measurements have potential to form a key regulatory measure, although this has not been the case to date. In the case of NAPL recovery, transmissivity provides a measure of localised contaminant mass flux into recovery wells, and has potential to provide a measure that can be used to show that CUTEP has been reached.

In Australia, environmental legislation recognises the concept of ecologically sustainable development, and there is a growing recognition that a simple strict application of concentration as a regulatory end point may not provide the most sustainable outcome, and measures such as mass flux and mass discharge that provide information on extent, significance and longevity of effect are useful concepts that need to be considered.

Where complete source removal is not feasible, goals and performance metrics based on achieving certain mass flux or mass discharge levels for the source area could be formulated, perhaps on the basis of achieving levels that correspond to plume stability or protect down gradient receptors, and perhaps on the basis that long term restoration of beneficial uses will be obtained through natural attenuation. While this is possible in principle, the author is aware of only one situation (example 1 below) where mass flux or mass discharge has been explicitly adopted as a specific compliance measure.

Two Australian case examples are useful in illustrating how mass flux and mass discharge concepts are being considered:

Example 1: Mass flux concepts are being applied in the assessment and remediation of a brominated VOC groundwater plume (comprising tetrabromoethane (TBA) and its breakdown products) in Perth, Western Australia (Argyle Diamonds 2012, Johnston et al. 2010a, 2012 and 2013). The plume extended under light industrial premises and threatened to adversely affect a river some 350 m down gradient. Pump and treat was adopted as the primary remedial strategy, and an initial estimate of dissolved mass flux of 104 g/day coming from the DNAPL source zone was made using passive flux meters, and further down gradient the flux was estimated to be 20–25 g/day, measured using an integral pump test. The reduction in mass flux along the plume occurred through natural attenuation. After a few years of pumping the mass flux from the source zone has decreased significantly (more rapidly than expected) and in 2011 the mass flux had reduced (from 104 g/day) to 40 g/day, a significant reduction.

Mass flux has been incorporated in the site management plan as a metric of remediation performance. This metric has particular value in that that flux measured close to the source zone is a leading indicator of groundwater concentrations leaving the site, and operation of the down gradient plume capture wells are determined by groundwater quality targets established for down gradient properties, the measured flux leaving the source area, and the known rates of attenuation between the source and the down gradient properties. The application of these concepts is new in Australia, and the project has recently gained an environmental award[6] in recognition of the advances being made.

Example 2: The discharge of contaminants from groundwater, surface water and air deposition to Cockburn Sound (the Sound) in Western Australia has been of concern for many years. The discharge of nutrients to the Sound is a particular issue, and work is underway to determine the contribution from the various transport routes (groundwater, surface water, air) (Cockburn Sound Management Council 2006). The mass discharge occurring via groundwater submarine discharge has potential to be significant. Loveless and Oldham (2009) note that groundwater discharge nutrient load has been traditionally estimated from nutrient concentrations in upland monitoring wells; however, despite monitoring over a ten year period showing a 70% reduction in the total anthropogenic nitrogen load into the Sound, chlorophyll-a levels in the waters of the Sound had only slightly improved (Smith et al. 2003), raising concerns regarding the accuracy of the monitoring well estimates.

In order to improve the groundwater mass flux estimate of nutrients, Loveless and Oldham (2009) undertook monitoring of groundwater wells in a 53 m transect in early summer, late summer and mid-winter. The well transect was located parallel to groundwater flow and perpendicular to the shore line. Losses in nitrogen and increases in phosphorous were observed along the discharge pathway, beyond those from mixing with coastal water, and were attributed to chemically and biologically mediated reactions.

Suggestions regarding specific metrics that can be applied in various situations are provided in section 5.2.

3.3.9 Conclusions regarding current Australian regulatory practice

It can be seen from the preceding discussion that mass flux and mass discharge measurements can be important in current Australian regulatory decision making, and are sometimes applied. In most cases, however, while the concepts are useful and often underlie regulatory decision making, it is unusual for decision making to be based on an explicitly defined mass flux or mass discharge measure, an exception being in the case of example 1 from section 3.3.8. A brief summary of the situation, drawing from the preceding sections of this report, is provided in table 3.

While mass flux and mass discharge measures are usually not explicitly referred to, there is considerable potential benefit to consider these measures and concepts in a

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[6] Certificate of Merit, Golden Gecko Awards, http://www.dmp.wa.gov.au/goldengecko/index.html

more structured way in Australian regulatory decision making and guidance. This is discussed in the next section.

Table 3. Current role of mass flux and mass discharge in regulatory decision making in Australia, and opportunities.

Aspect	**Current Role of mass flux and mass discharge in regulatory decision making**
Site conceptual model	Mass flux and mass discharge concepts are sometimes applied to assist in understanding contamination, its movement and potential for impact. Generally mass flux and mass discharge are not primary measures.
Variation of plumes with time	Mass flux is sometimes used to assist in understanding the variation in extent of plumes, whether they are increasing or decreasing in extent, and whether plumes will migrate off site. Generally mass flux and mass discharge are not primary measures.
Requirement for remediation or management	Mass flux is sometimes used to assist in decision making as to whether remediation or management is required.
Selecting remediation methods	Mass flux concepts are considered when assessing the effectiveness of particular remedial methods in removing source material and restoring beneficial uses. Generally mass flux will be only one of a number of measures that are used to decide whether a remedial method should be selected.
Assisting in the design of a remedial method	Mass flux measurements are considered in the design of remedial methods.
Assisting in assessing the performance of remediation methods	Mass flux and mass discharge measures are sometimes considered when assessing the performance of remediation methods, although usually not as an explicit measure.
Providing a compliance measure	Mass flux and mass discharge can be important measures in deciding whether compliance with regulatory requirements has been achieved, although current practice usually will not refer to these measures explicitly. An example of this is in deciding whether CUTEP has been achieved. In the case of NAPL recovery, measures related to mass flux such as transmissivity are being proposed as a primary measure of compliance, but have not yet been applied. In some situations mass flux or mass discharge can be linked to restoration of beneficial uses (i.e. achieving certain contaminant concentrations) and could be used as a primary measure of compliance; however this does not appear to have been applied to date.

3.4 Summary of how mass flux information can be used

The previous sections outline various ways in which mass flux concepts may be usefully applied to contamination problems. The key findings are:

- There is a growing recognition of the benefit of application of mass flux and mass discharge concepts in the assessment and remediation of contaminated sites.
- Generally mass flux and mass discharge concepts will be used in conjunction with other measures (such as concentration) that form the basis for regulatory decision making, to provide more understanding and to assist in decision making. There is

a growing recognition that a simple strict application of concentration as a regulatory end point may not provide the most sustainable outcome, and measures such as mass flux and mass discharge that provide information on extent, significance and longevity of effect are useful concepts that need to be considered.

- Measuring the vertical and horizontal variations in mass flux from complex source areas (particularly through a high-resolution characterisation process) can assist in targeting clean up to high flux source areas, can significantly improve the effectiveness of remediation, and reduce the volume of source zone to be treated and the overall cost and time for remediation.
- Measuring mass flux can be important in determining the applicability of particular clean up technologies and in predicting their performance. Measurements of mass flux could be used as an interim remediation goal and trigger for transition between technologies.
- Mass information can be used to prioritise sites for clean up.
- Measuring the variations in mass flux across transects at various locations along a plume can assist in understanding whether a plume is stable, growing or reducing in extent, the risk posed by the plume, and the longevity of effect. In this respect, a mass flux endpoint could be established as a criterion for regulatory decision making for a particular site.
- Measuring mass flux across transects at various locations along a plume can assist in understanding the significance of mass loss and attenuation, whether through treatment or natural processes, and the duration over which these processes will need to take place to reduce the concentrations of contaminants to acceptable levels. In this respect, a mass flux endpoint could be established as a criterion for regulatory decision making for a particular site.
- Measuring mass discharge can assist in understanding the effect of a plume on the contaminant concentrations that will occur in a receiving water body, or in groundwater extracted from a pumping well. In this respect, a mass flux endpoint could be established as a criterion for regulatory decision making for a particular site.

3.5 The drivers for applying mass flux and mass discharge concepts

It can be seen from the preceding section that there are strong drivers for applying mass flux and mass discharge concepts in the assessment, remediation and management of contaminated sites in Australia. In particular, these drivers include:

- Improved understanding of the requirements for remediation and management
- Introducing and encouraging a greater focus on the load and extent of contamination in Australian regulatory decision making, particularly on whether remediation is required, whether remediation that has been undertaken is sufficient, and assisting in achieving closure on contaminated sites, and

- Considerable savings in cost and resources, by providing a measure that can more simply confirm that remediation is or is not practicable, or has reached a practicable endpoint.

Discussion on what is needed to apply the concepts of mass flux and mass discharge to Australian contaminated sites is included section 5 of this report.

4. Measuring mass flux and mass discharge

4.1 Introduction

When considering measurement and interpretation measurement of mass flux, an understanding of the elements that affect the mass flux is required. Where the contaminant is present as dissolved phase in the groundwater, contaminant mass flux through a plane is a function of the concentration of the contaminant and the flux of groundwater through the plane. Contaminant mass flux will also be controlled by the rate at which mass from the source zone transfers to the dissolved phase in groundwater, and the existence of processes that give rise to mass loss. Mass flux variability is dependent on these factors and consideration needs to be given to understanding their importance and what measurements need to be taken to characterise the mass flux and mass discharge.

The ITRC (2010) guidelines on mass flux and mass discharge methods lists five basic methods for estimating mass flux and mass discharge for dissolved phase contaminants:

- Transect methods – using individual monitoring points to integrate concentration and flow data
- Well capture/pump test methods – extracting groundwater and measure the flow and mass discharge from the wells
- Passive flux meters – estimate mass flux directly in wells
- Transects based on isocontours, and
- Solute transport models.

Each of the methods is described and compared with the other methods in the following sections.

While most of this review focuses on dissolved phase contaminants, the measurement of mass flux and mass discharge for free phase contaminants (NAPL) is included in one of the later sections.

4.2 Transect methods

The transect method involves estimating the mass flux from the concentrations of contaminants measured in a series of wells along a transect across the plume (perpendicular to the flow direction), and the groundwater velocity (the Darcy velocity) or flux through the area represented by each well.

Mass flux = concentration x water flux

An illustration of how multiple well transects can be used to measure mass flux and mass discharge is shown in figure 4.

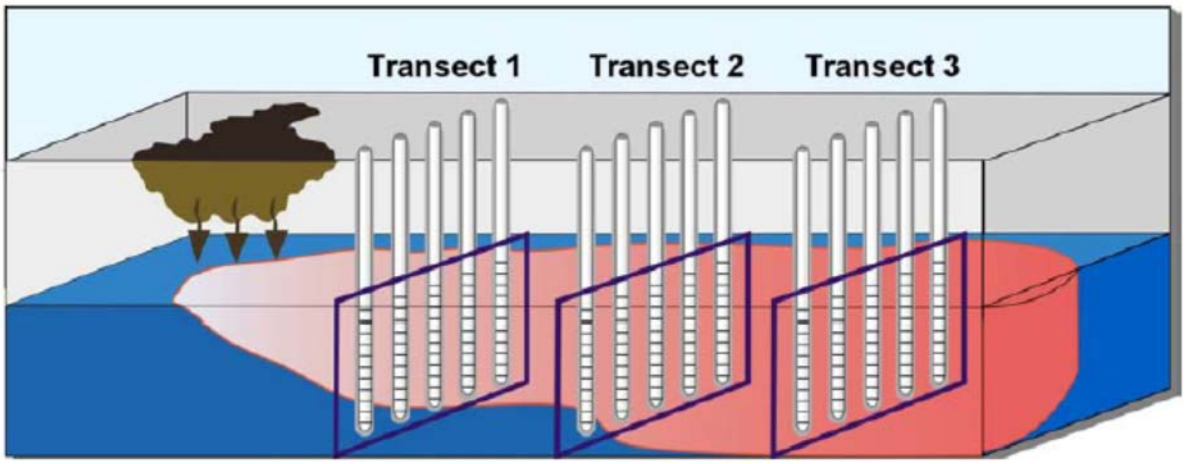


Figure 4. Use of multiple well transects to measure mass discharge and mass flux (reproduced from ITRC 2010, p. vi).

With this method:

- The plane across the plume is divided into a series of sub areas (horizontally and vertically)
- Concentrations are interpolated from well measurements
- Groundwater velocity (q) is estimated from hydraulic gradient (i) and hydraulic conductivity (K) (q = K*i) measurements; there are tools that provide high-resolution hydraulic head and soil type data, such as a high resolution piezocone (ITRC 2010)
- The concentration measurements and flow estimates need to be at sufficiently close vertical and horizontal spacings to characterise the vertical and horizontal variations that exist in the aquifer. Estimates of the concentration and velocity at each point will need to be made either based on direct measurement and simple interpolation, or more advanced methods such as kriging, nearest neighbour, Thiessen polygons, or specialised software
- Usually the groundwater flow is horizontal, but if there is a significant vertical component then this should be included in the estimates
- The measurements should preferably extend over the full width and depth of the plume
- Mass discharge is the sum of the mass contributions from each sub area
- Estimating the mass discharge at transects at different locations away from the source zone can provide estimates of the increases in mass discharge that are occurring as the plume moves forward, or the reductions in mass discharge that are occurring through mass loss mechanisms.

Key points regarding the transect method are:

- Measurements must be spaced sufficiently closely to provide a detailed characterisation of the variations in concentration and flow rate that exist in the aquifer. Often there will be considerable variation, and this will necessitate a large number of closely spaced monitoring points both vertically and horizontally (high resolution characterisation), with accuracy in general improving with the number of monitoring points. This can be a major limitation and restriction on developing a detailed characterisation of mass flux.

- Single level concentration measurements using wells screened across the full depth of the plume (or to an aquitard) and pumped to provide a flow-weighted average concentration for the location can be (and are widely) used to provide mass discharge estimates. While these will not provide a detailed vertical characterisation and are likely to be approximate and uncertain, they nevertheless may provide useful estimates. There are differing views on the appropriateness of this approach and whether detailed characterisation is necessary to validate the estimates that single level sampling provides.
- There are various methods of estimating uncertainty; these include Monte Carlo methods and geostatistical methods (ITRC 2010). Uncertainty can arise from uncertainty in the actual concentration, hydraulic conductivity and hydraulic gradient; uncertainty in interpolation, and uncertainty that localised areas with high mass flux may not be included.
- Mass flux can be calculated for any dissolved constituent that is migrating with the groundwater flow.

An example of the application of the transect method is the investigation of a dissolved phase hydrocarbon groundwater plume flowing towards the Canning River in Perth, Western Australia (Westbrook et al. 2005). Transects of multiport wells were located along the riverbank and into the river, providing information on the vertical and longitudinal extents of the hydrocarbon plume (Westbrook et al. 2005).

4.3 Groundwater well test methods

There are various methods of estimating mass discharge based on pumping from groundwater wells. These include the well capture method, the integral pump test method, and the tandem circulating wells method.

These methods involve pumping from a well to collect information that is representative of the groundwater in a particular location, and relating this to groundwater flow to provide a measure of the mass discharge.

4.3.1 Well capture method

The well capture method involves using an extraction well to fully capture a contaminant plume, and estimating the mass discharge by measuring the concentration and flow rate of the well.

Mass discharge = (concentration from the extraction well) x (flow rate of the extraction well)

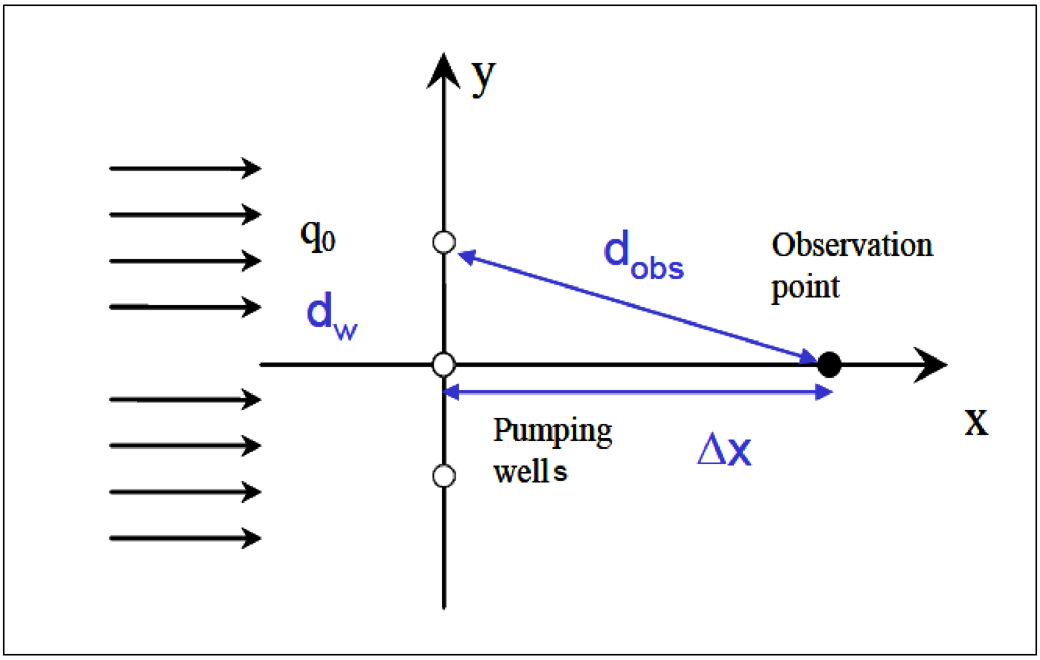
Key points regarding the method are:

- A single value estimate of mass discharge is provided; information about the structure of the plume or the location of high discharge zones is not provided

- The method assumes that the well or well system fully captures the horizontal and vertical extent of the plume and that the extraction point is far enough down gradient of the source to not induce an increased discharge from the source
- Pumping should continue long enough so that relatively steady state conditions can be achieved
- Complete or near complete capture of the high discharge portions of the plume should be confirmed using groundwater potentiometric surface data or tracers
- This method can integrate flow and concentration, capturing small areas with higher concentration and high transmissivity zones
- Data from an existing pump and treat system that captures the entire plume can be used to estimate mass discharge
- The spatial distribution of mass flux is not determined, unless multiple recovery wells are involved, and
- There are various sources of uncertainty: changes may be induced by pumping, e.g. pumping may draw water from less transmissive zones that do not normally contribute to the mass flux, or different quality water (e.g. oxygenated or containing other electron acceptors) may be drawn into the plume which could lead to mass loss through biodegradation; it may not be clear as to whether all of the plume has been captured; over pumping that may result in dilution and reduced concentrations that are difficult to measure accurately.
- By way of example, Johnston et al. (2013) reports on using source zone pumping to characterise a brominated DNAPL source zone in Western Australia. These researchers used various source-dissolved phase concentration models to model the depletion of the source zone mass, and included a partitioning inter-well tracer test to determine parameters for the various models (such as groundwater travel time), and multi-level groundwater sampling to further characterise the source zone. It was found that all of the models could provide a good fit of the observed data, and similar estimates of the source mass. This work supported the conclusion that source zone pumping can be an effective and relatively simple means for characterising DNAPL source zones.

4.3.2 The integral pump test

The integral pump test (IPT) method uses concentration values measured over the duration of pumping to back-calculate the mass discharge. The IPT method provides a way of obtaining an estimate of contaminant mass flux averaged over a large subsurface volume (Goltz et al. 2007), and can utilise existing wells to avoid the costs of installing new wells. An example of well placement for the IPT method is illustrated in figure 5. In this example Yoon (2006) shows how information from pumping wells aligned perpendicular to groundwater flow and an observation well down gradient of the pumping wells can be used to calculate heads at the origin pumping well and observation well.



$d_{obs[i]}$ = distance from the i^{th} pumping well to the observation well
Δx = (distance to the observation well along the x-axis) – (radius of pumping well at the origin)
q_o = Darcy velocity of uniform regional flow
$d_{w[i]}$ = distance from the i^{th} pumping well to the pumping well at the origin

Figure 5. Example of IPT approach using 3 pumping wells and 1 observation well (reproduced from Yoon 2006, page 16).

A variation of this method is the modified integral pump test (MIPT) method; this uses the average concentration and a direct measure of the Darcy velocity obtained by measuring the head difference between pumping wells and monitoring wells, when the pumping wells are pumped at different flow rates. A study comparing tandem circulating wells (TCW) and MIPT methods concluded that the MIPT method had advantages in being simple and easily implemented, although it may underestimate the mass flux (Goltz et al. 2009).

4.3.3 Tandem circulating wells method

The TCW method is experimental; it proposes that two dual-screened wells are used: one extracting water from a lower depth and pumping it upward to inject at a shallow depth, with the second well operating in the opposite direction. The hydraulic gradient is measured with the pumps turned off, and the hydraulic conductivity is measured by pumping the wells and measuring head changes. The contaminant concentration is measured by sampling the contaminated water as it flows through the wells. This method avoids producing wastewater, although it does involve reinjection. This method has the advantage of measuring mass flux integrated over a large sub-surface volume, without extracting and having to dispose of water (Goltz et al. 2009). This is illustrated in figure 6.

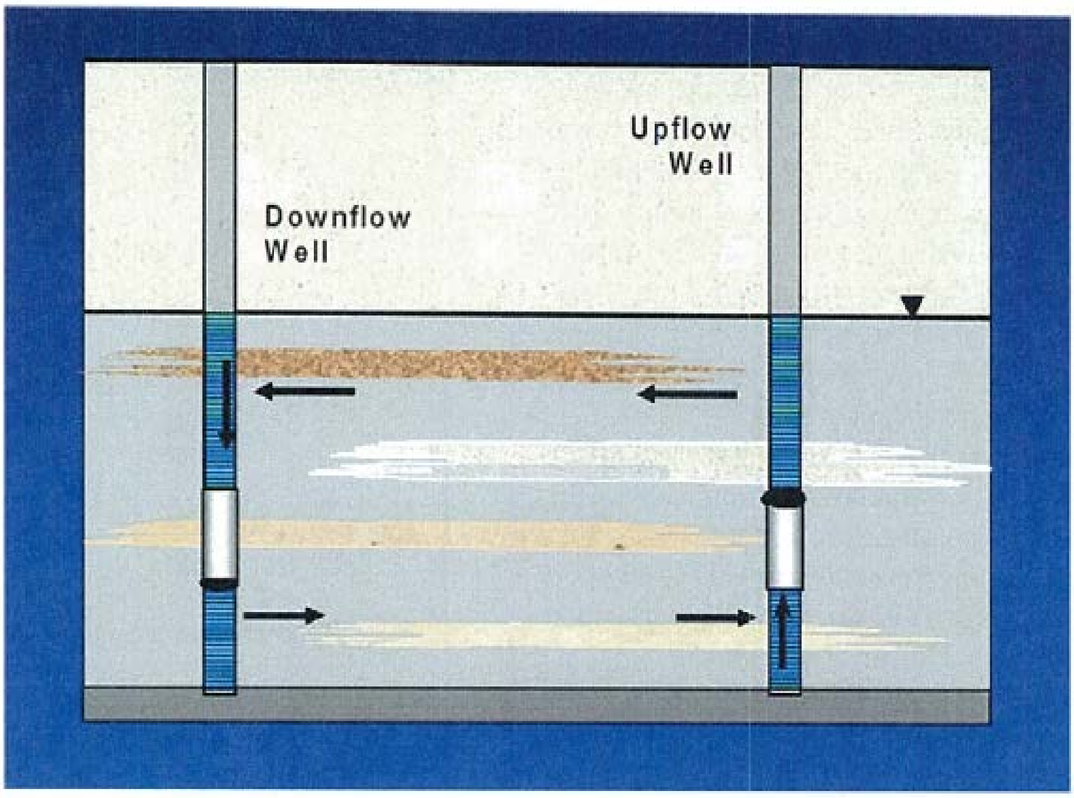


Figure 6. Tandem circulating wells to measure flux (reproduced from Goltz Et Al. 2009, page 53).

The TCW method may be implemented using two different techniques. One technique, the multi-dipole technique, is relatively simple and inexpensive, only requiring measurement of heads, while the second technique requires conducting a tracer test (Goltz et al. 2009). Experiments suggest that the TCW, IPT and MIPT methods can provide good estimates of mass flux (Goltz et al. 2009), and that the TCW method may be more economical for larger areas (Wheeldon 2008).

4.4 Passive flux meters

The passive flux meter (PFM) is a developing technology that comprises a permeable sorbent infused with soluble tracers packed in a nylon mesh tube. The device is placed in a borehole or monitoring well for a known exposure period where it intercepts the groundwater flow, causing dissolved contaminants to sorb to the sorbent and the soluble tracers to leach out. The measurements of the contaminants and the remaining resident tracer can then be used to estimate groundwater and contaminant fluxes. By using several passive flux meters across a transect, the average mass flux and total mass discharge through a control plane can be estimated. Patterson et al. (2010) report on the development of an automated on-line instrument to measure groundwater velocity within a groundwater well. Groundwater velocity was measured multiple times a day by delivering a gas tracer to a permeable chamber within a screened well and monitoring reduction of tracer concentrations (Patterson et al. 2010). Field testing results were consistent with those of passive flux meters and site modelling (Patterson et al. 2010).

Key points regarding the method are:

- The capacity of the sorbent should not be exceeded. The passive flux meter should fill the well in which it is installed so that the groundwater is through the meter rather than around it
- The meter may be separated into different vertical zones isolated by impermeable barriers to assess different zones in the aquifer
- The extent to which tracers are leached from the sorbent will depend on the contaminant partitioning between the sorbent and water, which needs to be estimated or measured
- The method may be subject to biostimulation or bioaugmentation; it is possible that the sorbent will trap or degrade contaminants
- The method measures at a point and does not account for contaminants in flow paths not intercepted by the device
- The method relies on horizontal flow, without a significant vertical component, and
- The method is probably not applicable to wells that contain NAPL.

Johnston et al. (2012) reported using PFMs to assess the mass flux from a tetrabromoethane plume in Western Australia. This has been discussed in section 3.3.8.

Other examples in Australia include a TCE plume where PFMs and online probes were compared (Basu et al. 2009). At a landfill site in Perth PFMs were installed to a depth of 65 m to measure groundwater flux variations in a sand and limestone aquifer (Davis et al. 2007).

Martin et al. (2003) compared contaminant concentrations detected with ceramic dosimeters to concentrations determined from conventional pumped groundwater samples collected from a site situated on the foreshore of the Canning River in Perth, Western Australia. Advantages of using ceramic material instead of polymer membranes for the passive sampler include that it is inert and does not swell in contact with organic compounds (Martin et al. 2003). The study found that ceramic dosimeters are suitable devices for monitoring aqueous contaminant concentrations over long time periods with advantages over conventional pumped groundwater samples including time-integrated monitoring during a sampling period, reduced change to hydraulic flow field and reduced volatilisation during sampling (Martin et al. 2003).

In the USA Kavanaugh et al. (2011) reported on using PFMs to estimate the mass and persistence of NAPL, and the potential impact of NAPL source reduction on contaminant mass discharge. Langenbach et al. (2012) reported on the application of PFMs to determine the dissolution rate and lifespan of NAPL.

Basu et al. (2006) reported using the PFM technique for measuring groundwater and contaminant fluxes for a TCE plume; this was referred to in section 3.3.6 of this report. Basu et al. (2006) found that the estimated flux-averaged TCE concentrations compared well with existing groundwater monitoring data, source strength was estimated using TCE mass discharge across the source control plane, and a plume-averaged TCE degradation rate constant was estimated from the mass discharges across multiple down gradient control planes. It was concluded that the mass discharge approach provided a more robust and representative estimate than the centreline approach as it accounted for spatial variability and considered a larger data set (by using all wells in the plume).

Annable et al. (2005) reported on the field testing of PFM for a perchloroethylene plume comparing mass estimates from PFM data with those from an extraction well. Similar results were obtained, supporting the PFM approach as a passive method for obtaining spatially discrete local fluxes that integrate to produce total mass discharge.

Verreydt et al. (2010) discuss the benefits of implementing passive sampling as opposed to active sampling. Concentrations measurements through active sampling are likened to snapshots, where peak concentrations can be missed as shown in figure 7, and it is argued that passive samplers can produce more reliable results in variable field conditions due to their longer term application.

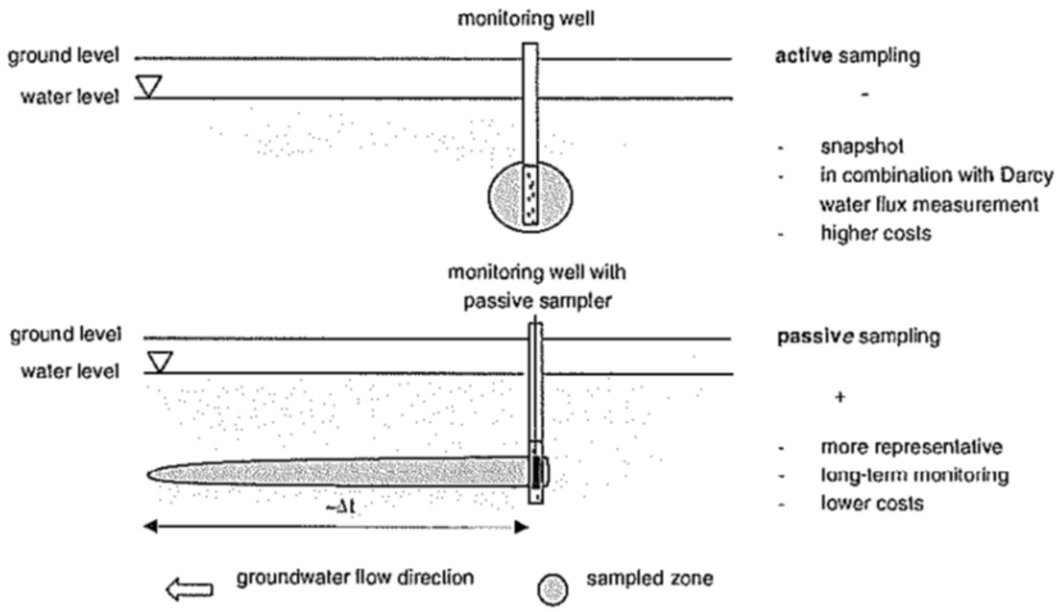


Figure 7. Passive sampling versus active sampling (reproduced from Verreydt et al. 2010, page 115).

Verreydt et al. (2010) screened 18 passive samplers for long term monitoring of volatile organic compound mass fluxes in groundwater and concluded that the only passive sampler proven to effectively measure mass flux was the PFM. The paper noted that PFMs had been applied in near source zones and higher concentration zones, and long term monitoring in lower concentration plume zones would require further investigation.

4.5 Transects based on isocontours

This method involves using concentration data obtained from a monitoring well network to construct a contour map of groundwater concentrations across the plume, and from this to estimate concentrations across particular transects. The method is similar to the Transect method outlined in section 4.2, but uses concentration information that derives from an interpretation of data from wells across the plume, rather than from those that are aligned across a transect.. It is useful to distinguish this method from the Transect method, as it is common to prepare maps of plumes of groundwater contamination, and these maps may already be at hand.

Key points regarding this method are:

- Information from the monitoring well network may not consider the site-specific geology and preferential pathways that exist.
- The method will be more accurate when the well network is dense, the network intercepts all or a large fraction of the contaminated plume thickness, and when the sample that is collected represents a flow-weighted average concentration. Low flow sampling may not provide a flow-weighted average concentration if the sample is not collecting water from the entire screened interval. Long screened wells can provide appropriate flow weighted concentration measurements, as vertical samples are not needed. Note that such samples will not necessarily record the maximum concentration at the monitoring point due to the vertical averaging.

4.6 Solute transport models

Solute transport models process input data relating to groundwater and contaminants, and mass flux data can usually be obtained from the model outputs through the use of an external spread sheet or, in some cases, solute transport models have dedicated routines to calculate mass flux. For example, the following solute transport models can be used to prepare mass flux estimates: BIOSCREEN, BIOCHLOR, BIOBALANCE, MODFLOW/RT3DMS, and REMChlor.

Key points regarding this method are:

- The accuracy of the mass flux estimates will depend on the accuracy and amount of the input data for flow and contaminant concentrations, and the parameters relating to the local geology and hydrogeology, and
- The accuracy and data requirements will vary depending on the type of model; analytical models make use of simplifying assumptions and can be more appropriate for screening or planning purposes, whereas numerical models based on a large amount of data may be more appropriate where mass flux information is to be used in remedial design.

4.7 Comparison of various mass flux measurement methods

A number of studies have been undertaken where two or more methods for measuring mass flux have been employed and the results compared. These comparisons distinguish methods based on measurements at individual points to determine mass flux (referred to as point scale measurement methods) and methods which involve pumping to provide an integrated estimate of mass flux (integral investigation methods). These include:

- A field comparison of the IPT and point scale measurement methods (Dietze & Dietrich 2011)
- Comparison of the TCW and MIPT methods (Goltz et al. 2009), and
- A comparison of results from point scale and integral investigation methods (Bockelmann et al. 2003).

Dietze and Dietrich (2011) report on a field comparison of the integral pump test and point scale measurement methods. The study compared benzene, toluene, ethylbenzene and xylene mass flow rates obtained from point scale data and integral pumping tests. While it was reported that a combination of both methods was optimal to decrease uncertainty, the difference between benzene and groundwater flow rate estimates were between 6 and 7% and it was concluded that the study demonstrated both methods were applicable at the site. The integral pumping test method was found to provide more reliable results where the monitoring network is sparse. Reliable results can be obtained from point scale measurements when the contaminant plume is of homogeneous shape and an adequate sampling grid is used. The contaminant plume in the study was a homogenous shape. The study concluded that using integral pumping tests is generally more accurate for heterogeneously developed plumes when used down the gradient of a contaminant source on a control cross section.

The TCW and MIPT were compared by Goltz et al. (2009). The TCW method was found to have the advantage of being able to interrogate a large subsurface volume without extracting large volumes of contaminated water. The MIPT directly measured groundwater Darcy flux which is multiplied by an average concentration to calculate mass flux, and is considerable simpler to implement than the IPT as it does not require separate measurements of hydraulic conductivity and hydraulic gradient. The results of the study indicated that the MIPT method was not as accurate as the TCW method; however the accuracy of the results of the TCW was questioned, with a possibility of errors due to well screen losses being offset by other errors. Further studies were recommended.

Bockelmann et al. (2003) reported on the use of point scale and integral investigation methods at a former manufactured gas plant in Germany. It was concluded that where the monitoring network is sparse, results of point scale methods could be highly unreliable and subject to a large degree of uncertainty, and an integral site investigation is an alternative method of investigating contaminant mass fluxes and natural attenuation rates. The integral investigation method investigated can yield adequate results under sparse monitoring conditions for the quantification of contaminant mass fluxes.

A qualitative comparison of the various mass flux measurement methods is provided in table 4. This has been drawn from a comparison reported by Goltz et al. (2007) and reported in ITRC (2010). Wheeldon (2008) also reports on a comparison of various flux measurement methods, and compares the relative cost of various methods. The comparison carried out by Goltz et al. (2007) has been based on the following factors:

- Implementability – how straightforward and simple it is to apply.
- Regulatory – whether the regulatory agency may have concern regarding implementation of the method (e.g. this might involve concern regarding the injection of material into an aquifer (e.g. of tracers), sub-surface circulation of

groundwater and spreading of groundwater contamination, or extraction and disposal (or use) of groundwater).

- Availability – the degree to which a method is understood and has been applied in the field, or is developmental and requires specialist knowledge to implement.
- Cost – the cost of acquiring mass flux information, although this has to be off set against the benefits that the information may provide.

Table 4. Comparison of mass flux measurement methods (adapted from ITRC 2010).

Method		Implementability	Regulatory considerations	Availability	Cost	Ranking
Point	Transect (TM)	1	1	1	4	7
	Passive flux meter (PFM)	3	2	2	4	11
Integral	Integral pump test (IPT)	4	3	2	2	11
	Modified integral pumping test (MIPT)	2	3	2	2	9
	Tandem circulation wells (TCW)	4	3	4	1	12
Analytical	Isocontour	2	1	2	1	6
	Solute transport models	1	1	2	1	5

Note: 1 = best, 4 = worst.

In making the comparison, it was noted (Goltz et al. 2007):

- The transect method (TM), MIPT and analytical methods were simple to implement while PFM, IPT and TCW were more complex
- The TM was well understood and available, while other methods were in some stage of development, and
- The TCW and the analytical methods were the least expensive, while the transect and PFM methods were the most expensive

Wheeldon (2008) also carried out a comparison of flux measurement methods, and concluded:

- The point methods assessed (TM and PFM) were less expensive for smaller areas of contamination, whereas pumping methods (MIPT and TCW) were more economical for larger areas
- Characterisation of heterogeneous systems or design of remediation may require high resolution sampling, therefore the pumping methods are not suitable
- The PFM method is more economical than the TM when high resolution investigation is required, and

- The accuracy of newer methods was demonstrated to be as good or better than that of the TM.

The Wheeldon (2008) study also provided a decision tree as a qualitative method of deciding what flux measurement technology might be most suitable, taking into account site conditions and management objectives.

4.8 Mass flux measurements for non-aqueous phase liquids

Johnston (2010b) published an authoritative guidance paper on the metrics, performance indicators and measurement techniques for characterising petroleum LNAPL movement and recovery in aquifers, and in determining the clean up that is required. In particular, the paper outlines the factors that need to be considered when characterising the presence, mass, mobility, spreading and recovery of LNAPL in an aquifer.

In Australia there are regulatory requirements for removal of NAPL where present. For example, the *State Environment Protection Policy Groundwaters of Victoria 1997* requires NAPL removal, with the extent to which clean up of the NAPL and associated dissolved phase is required being dependent on the risk posed by the NAPL and practicability of clean up. While full clean up of NAPL is often not practicable, it is important to recover NAPL as far as is practicable. In such situations, the characterisation of the NAPL in terms of mobility and recoverability is an important consideration, although there are many factors that need to be considered when deciding on a remediation response.

A metric that is now widely proposed for measuring petroleum LNAPL spreading and mobility in plumes is LNAPL transmissivity. Determining the transmissivity of LNAPL is more complex than that for groundwater (Johnston 2010b): it is an integration of the depth-distribution of LNAPL conductivity which is the product of relative permeability and intrinsic permeability of the aquifer materials over the depth interval of mobile LNAPL. The transmissivity can be sensitive to fine-scale variability and vertical moment of LNAPL in the profile due to varying water tables.

There are various methods for measuring LNAPL transmissivity (such as those discussed in Cho (2010) and Johnston (2010b)); these include:

- LNAPL bail down tests (such as those discussed in Charbeneau, Kirkman and Rangaramanuiam (2012)). This requires a well with considerable LNAPL thickness (> 300 mm), trained field staff, the well to return to equilibrium, understanding of LNAPL distributions, and competent data analysis

- A tracer dilution method developed by Sale et al. (2007) to directly measure the flow rate of LNAPL through a screened well. This method can yield estimates of the rate of flow within the LNAPL plume by use of appropriate factors for the convergence of LNAPL flow through the well. LNAPL transmissivity in the aquifer can be inferred from these flow rates where LNAPL pressure gradients are known

- Modeling from LNAPL saturation data. This requires high density LNAPL saturation or total petroleum hydrocarbon data (ie greater than one sample per 100 mm vertical), multiple borings, and use of relative permeability and capillary pressure algorithms calibrated to soil core data (Charbeneau 2008), and

- Review of LNAPL recovery system data. This requires a well operated LNAPL recovery system, recovery data for volumes of LNAPL and water recovered, understanding of hydraulic conductivity and LNAPL distribution and thickness (for example Volume 1 of Charbeneau (2008)).

The ASTM has recently developed a standard on determining LNAPL transmissivity (E2856-13). This provides information on data collection and analysis methodologies for LNAPL bail down tests, LNAPL tracer tests, soil core information, and recovery systems data (e.g. from skimming, vacuum enhanced skimming, multiphase extraction, trench recovery, and periodic removal events). This standard should increase the accuracy and consistency of estimates of transmissivity.

4.9 Managing uncertainty

Mass flux and mass discharge estimates have considerable uncertainty. Whether the level of uncertainty is acceptable will depend on the intended use of the information, and how the uncertainty will be managed.

The range of variation in mass flux and mass discharge estimates can be very large; hydraulic conductivity values can range over 6 or 7 orders of magnitude, and contaminant concentrations can similarly vary greatly. Sometimes orders of magnitude variations in these parameters will occur in the aquifer over very short distances (only a metre or two). Because of this, it is quite possible that estimates of mass flux and mass discharge will have a level of uncertainty in the order of one or two orders of magnitude, depending on the homogeneity of the site, the density of sample information, and the method used for estimation. It is important to understand uncertainty when mass discharge or mass flux is being considered as a possible metric, because if the level of uncertainty in mass flux or mass discharge is high it might not be possible to establish a quantitative metric, and it may only be possible to indicate relative changes in the metric or indicative values.

In particular:

- In highly heterogeneous environments where groundwater velocities may vary by many orders of magnitude across small distances, it may not be cost effective or physically possible to collect enough samples to obtain a sound estimate of mass flux or mass discharge. This can be contrasted with concentration, which if the plume is in equilibrium may be relatively uniformly distributed and therefore able to be characterised with a much lesser number of samples.

- Where mass flux across parallel planes is being used as a measure of mass loss (e.g. in natural attenuation or treatment), then very closely spaced wells may be required to gain the resolution required to indicate whether mass loss is occurring or not. In the author’s experience with a large nitrate plume at an explosives factory, several wells along each parallel transect across a plume width of 50–100 m were not nearly enough, and did not result in sensible mass flux information. To have well spacing of less than a few metres and multiple depths would have involved a large number of wells and was deemed to not be practicable. This suggests that alternative flux measurement methods such as plume capture, which are less dependent on high resolution information, or perhaps numerical modelling that smooths out data and provides a broader perspective on concentration and flow, would be preferred for consideration.

- There are similar examples in the literature. For example, Bockelmann et al. (2003) reported on a groundwater investigation at a former manufactured gas plant in Germany where site conditions limited the number of groundwater wells that could be installed. The investigation concluded that mass flux estimations can be highly unreliable when based on sparse point scale data and that there can be a large degree of uncertainty with results of such an investigation. It was concluded that research was needed to increase understanding of the limitations of field methods under different geological and contaminant source conditions. Chen et al. (2012) compared pumping methods with point measurement methods, and concluded that uncertainty in mass discharge estimates based on pumping methods was less than point measurement methods, and that a sequential pumping approached resulted in less uncertainty than a concurrent pumping approach. However, with the addition of a limited number of wells, the uncertainty of the point measurement technique was comparable to the pumping methods. Quinnan et al. (2012) carried out analyses to show that when conventional investigation methods are used, mass flux and mass discharge estimates are typically performed using overly simplified conceptualisations of geology with average hydraulic conductivity estimates for an entire cross-section or hydrostratigraphic unit. Because aquifers often exhibit orders of magnitude variation in permeability both laterally and vertically, this can lead to significant errors in estimation. Quinnan et al. (2012) encourage detailed characterisation methods, such as direct push injection logging tools like the Geoprobe® Hydraulic Profiling Tool or the Waterloo Advanced Profiling System™ (Waterloo APS).

- Direct measurement of mass discharge, for example in extraction wells or in a receiving water body may also avoid the need for high resolution information. However, even this type of information will have uncertainty – measuring contaminant concentrations in receiving water such as at a shoreline of a sea or river can also be highly variable depending on the method used to measure the level of contamination that results. For example, measuring seeps can be very problematic, or measuring the resulting concentration in the receiving water can be difficult depending on the existence of shoreline boundary currents and turbulence.

- In the case of LNAPL, there can also be significant uncertainty in measurements of transmissivity, for example, if this is the metric that is to be used, depending on the heterogeneity of the aquifer and disposition of LNAPL. However, information from a number of wells that cover the range of conditions expected might be helpful in understanding the recovery that might be possible and hence practicability of LNAPL recovery, and might form a useful line of evidence regarding LNAPL recovery or mobility.

It is concluded that, because of the high level of uncertainty that can be involved, understanding uncertainty is an essential aspect of applying mass flux and mass discharge concepts in contamination assessment and remediation. A big picture view is required; with a realistic assessment of the level of uncertainty that is likely to result, and whether this level of uncertainty will be acceptable and not negate the desired use of the information.

4.10 Methods of measurement and potential for further work

A summary of where particular methods of measurement of mass flux and mass discharge might be improved, together with preliminary recommendations for the nature of further work, is provided in table 5.

This table was prepared through consultation with end users, and involved auditors with both accreditation and experience in groundwater contamination assessment in New South Wales, Victoria, Western Australia, South Australia and Queensland, and a specialist in Australian groundwater contaminant assessment, modelling and remediation.

Table 5. Methods of measurement and potential for further work.

Method		Need	Recommendation
Point	Transect	Increased level of understanding in the industry on how to implement – particularly the use of single screened pumping wells where high resolution characterisation is not feasible. Explain the uncertainty and demanding requirements for this.	Provide guidance and training on this method of determining mass flux and mass discharge, and the application of these concepts.
	Passive flux meter	If PFMs are to be used in preference to other methods, then need to make the method and its interpretation easier, and to significantly reduce cost of implementation. Note: likely to be challenging to develop PFMs to the point where they can be used to advantage over other methods. Lower priority for work.	Consider potential to develop low cost PFMs and to provide simple guidance on the application of the method.
Integral	Integral pump test	Increased level of understanding in the industry on the method and its use.	Provide guidance and training on this method of determining mass flux and mass discharge, and the application of these concepts. Consider development of tool (software) to simplify application.
	Modified integral pumping test	Increased level of understanding in the industry on the method and its use.	Provide guidance and training on this method of determining mass flux and mass discharge, and the application of these concepts. Consider development of tool (software) to simplify the application of this method.
	Tandem circulation wells	This method is more complex and there are potential problems in implementation; need to resolve whether method will gain regulatory acceptance. Lower priority for further work.	Low priority for further work on this topic at this time.
Analytical	Isocontour	Increased level of understanding in the industry on the method and its use.	Provide guidance and training on this method of determining mass flux and mass discharge, and the application of these concepts. Consider development of tool (software) to simplify the application of this method.
	Solute transport models	Increased level of understanding in the industry on the method and its use.	Provide guidance and training on this method of determining mass flux and mass discharge, and the application of these concepts.
General	Uncertainty	Better quantification of uncertainty and its significance in applying mass discharge and mass flux concepts.	Undertake research to better quantify uncertainty and its significance with respect to each of the methods, and therefore the limitations on their application and the conclusions that can be drawn.

5. How mass flux or mass discharge may be applied or adopted in Australia

5.1 Realising opportunities—general considerations

The considerations in the previous sections indicate that there can be significant benefit in the application of mass flux and mass discharge methods in the assessment, remediation and closure of contaminated sites, including assessing risk to potential receptors and in setting remediation goals for site closure. More specific suggestions and recommendations are provided in the following sections.

Similarly to the previous section, the recommendations and priorities for further work were prepared through consultation with end users, particularly involving auditors with both accreditation and experience in groundwater contamination assessment in New South Wales, Victoria, Western Australia, South Australia and Queensland, and a specialist in Australian groundwater contaminant assessment, modelling and remediation. In the application of mass flux and mass discharge methods, there are several key areas where further development is required, if these methods and concepts are to be applied more usefully in Australia. These are:

- Development of guidance and training packages that provide a better understanding of the concepts and how they can be applied within the existing Australian regulatory context and industry knowhow. This should include method-specific application guidance, and information on the various methods of measurement and their relevance to regulatory requirements.
- Analysis of how the concepts can be introduced and applied in Australian regulations pertaining to contaminated sites; particularly with respect to providing a measure related to determining whether remediation is required, and when an acceptable endpoint has been achieved. In this, consideration should be given to:
  - The approach being taken in Europe (e.g. in Austria)
  - Relating mass flux and mass discharge to concentration and risk to particular beneficial uses of groundwater
  - How mass flux and mass discharge should be measured to achieve measures that are relevant to regulatory requirements, and
  - Relating mass flux and mass discharge to the performance of remedial methods, the requirements for closure, and the concepts of significance, CUTEP, and sustainability.
- Guidance on the uncertainty associated with the measurement and application of mass flux and mass discharge concepts and measurements. Consideration should be given to the development and application of statistical methods and models that allow for cost-effective estimation of mass flux and mass discharge and quantifying the level of uncertainty.
- Consideration of the existing methods of measurement and estimation of mass flux and mass discharge, and how these methods can be improved to make their application simpler, more reliable, and less costly.

- Carrying out demonstration projects to illustrate, compare and encourage the application of mass flux and mass discharge methods.
- Comparison of two dimensional (long-screened well information) with three-dimensional analysis, and integrated methods with high resolution methods (such as MIPT, multipoint samplers and advanced piezocone), in terms of uncertainty, relative accuracy, and potential to reach erroneous conclusions.
- Consideration of the relation between mass flux to geological and hydrogeological parameters, and hence to the application, decision making and performance of remedial methods, including characterising matrix diffusion.

5.2 Application of mass flux concepts to specific site contamination issues

5.2.1 Overview of areas for application

A summary of where mass flux and mass discharge concepts might be applied to assist in dealing with specific site contamination issues is provided in table 6. The potential for cost saving was used to determine the priority for particular areas of application and where further work might be best directed; the priorities were determined through discussion with end users, in particular persons with broad experience in the auditing, assessment and remediation of groundwater contamination in Australia. A preliminary set of recommendations from this work is included; these should be considered together with the listing of general areas where improvement is required in the previous section.

5.2.2 Formulating metrics

Three areas have been identified in table 6 where there can be a high cost saving to the industry, and where it can be valuable if metrics were to be developed. These include:

- Determining when remediation is required
- Assessing the performance of remedial measures, and
- Providing a compliance measure, or determining when closure has been achieved.

These situations are related: for example, the situation that determines whether remediation is required (the trigger level for remediation) could also form a compliance measure if the objective is to avoid an unacceptable situation. However, it is possible that the trigger for requiring remediation could be set at a greater level of impact than the objective for remediation, if it is accepted that the intervention level can be greater than the target level. This would seem to be a sensible approach, as it could be considered that a minor exceedence of an objective should not necessarily trigger clean up. If this principle is accepted, then it becomes necessary to determine what level of exceedence (or impact) can be tolerated before remediation is necessary.

Table 6. Application of mass flux concepts.

Aspect	Current role of mass flux and mass discharge in regulatory decision making	Cost saving to the industry	Recommendation
Conceptual Site Model	Mass flux and mass discharge concepts are sometimes applied to assist in understanding contamination, its movement and potential for impact. Generally mass flux and mass discharge are not primary measures.	Low. Important in understanding, but not a primary cost determinant.	Provide guidance and training on the application of mass flux and mass discharge concepts in developing a Site Conceptual Model.
Variation of plumes with time	Mass flux is sometimes used to assist in understanding the variation in extent of plumes, whether they are increasing or decreasing in extent, whether plumes will migrate off site. Generally mass flux and mass discharge are not primary measures.	Medium. May be important in determining CUTEP, and may have a significant bearing on cost for some sites.	Provide guidance and training on the application of mass flux and mass discharge concepts in understanding the variation over time of plumes.
Requirement for remediation or management	Mass flux is sometimes used to assist in decision making as to whether remediation or management is required.	High. Could be important in deciding whether remediation is or is not necessary, with significant bearing on cost for some sites.	Develop suggestions for specific metrics as to the remedial response that should apply (refer Section 5.2.2). Illustrate the application of these concepts and metrics with demonstration projects.
Selecting Remediation Methods	Mass flux concepts are considered when assessing the effectiveness of particular remedial methods in removing source material and restoring beneficial uses. Generally mass flux will be only one of a number of measures that are used to decide whether a remedial method should be selected.	Medium. Important in assessing and selecting remedial strategies. Can have a significant bearing on cost of remediation.	Provide guidance and training on the application of mass flux and mass discharge concepts in understanding source areas, risk, and how certain remediation methods may assist in dealing with the contamination.
Assisting in the design of a remedial method	Mass flux measurements are considered in the design of remedial methods.	Medium. Important in designing a remedial method. Can have a significant bearing on cost of remediation.	Encourage consideration of mass flux measurements for source characterisation.
Assisting in assessing the	Mass flux and mass discharge measures are sometimes considered when assessing the performance of remediation	High.	Provide guidance on how mass flux and mass discharge concepts can assist in assessing the

Performance of Remediation Methods	methods, although usually not as an explicit measure.	Can be important in determining the end point of a remedial method, and CUTEP. May have a significant bearing on cost for some sites.	significance and risk of plumes, and the performance of remediation methods in reaching CUTEP. Develop suggestions regarding specific metrics for decision making (refer Section 5.2.2). Illustrate the application of these using demonstration projects.
Providing a compliance measure, and a measure for closure	Mass flux and mass discharge can be important measures in deciding whether compliance with regulatory requirements has been achieved, although current practice usually will not refer to these measures explicitly. An example of this is in deciding whether CUTEP has been achieved. In the case of NAPL recovery, measures related to mass flux such as transmissivity are being proposed as a primary measure of compliance, but a specific value for transmissivity has not yet been accepted. In some situations mass flux or mass discharge can be linked to restoration of beneficial uses (ie achieving certain contaminant concentrations) and could be used as a primary measure of compliance; however this does not appear to have been applied to date.	High. May be important in determining the end point of a remedial method, and CUTEP and closure. Application of flux-based endpoints could have a significant bearing on cost for some sites.	Develop information on how mass flux and mass discharge may be used as a compliance and closure measure, perhaps related to CUTEP and sustainability, with examples, so that the concepts may be included in the National Remediation Framework. Develop suggestions regarding specific metrics for decision making (refer Section 5.2.2). Illustrate the application of these using demonstration projects.

Several examples where mass flux or mass discharge might be adopted as criteria for determining when clean up is necessary, or as a remedial objective are presented in the following sections.

5.2.3 Setting a trigger for remediation, or a measure for compliance or closure

In some situations, the concentrations of contaminants in groundwater may exceed the criteria for protection of beneficial uses, but the load of contaminants and extent of contamination that results is such that it will not materially affect the use. This situation may form the basis for accepting that remediation may not be required, or it may be set as the objective for remediation. This contrasts with the situation that any exceedence of the concentration criterion cannot be tolerated, even if it is just a small localised area that is not material to the use.

Basing decision making on whether contamination will or will not materially affect the use has a parallel with the approach adopted in Austria, where contamination may be tolerated where the mass flux is small in the context of use (e.g. for pumping for potable use).

Several situations and metrics relating to flux can be distinguished; these (or some multiple or fraction of them) may form either a trigger for remediation, or a compliance objective if remediation is undertaken:

a) Use of groundwater

If the use of groundwater involves pumping a certain minimum extraction rate (for example for potable, irrigation, stock, swimming pool make up, or industrial use), localised contamination that exceeds the use criterion may be able to be accepted if the source flux rate and contaminant load is such that the use criteria will not be exceeded when the extraction rate is taken into account.

In this case the metric for the maximum acceptable flux could be based on:

Mass flux < (concentration criterion for use) x extraction rate

b) Impact on receiving water body

If groundwater is discharged to a receiving water body, contamination that exceeds the criterion for protection of the receiving water body may be able to be accepted if the mass discharge is low (e.g. perhaps indistinguishable from that occurring naturally) and the water quality criterion will not be exceeded in the receiving water body.

In this case the metric for maximum allowable mass discharge might be based on:

Mass discharge < (concentration criterion for receiving water) x (flowrate of receiving water)

This concept may be able to be extended to determine the effective area of a mixing zone, as is often applied when licensing discharges to receiving water. In this case the metric for maximum allowable mass discharge could be expressed in terms of the receiving water flow through the area where mixing with the receiving water will take place:

Mass discharge < (concentration criterion at boundary of mixing zone) x (flowrate through mixing zone)

Note that in assessing such situations, if the contaminants are such that they might give rise to bioaccumulation, consideration should also be given to possible effects of bioaccumulation in the ecosystem, as provided for in the Australia and New Zealand Environment Conservation Council (ANZECC) *Water Quality Guidelines for Fresh and Marine Waters*.

c) Impact on a shoreline

Risk to human health

If groundwater discharges through an area where at risk of impact (such as a shoreline), contamination may be accepted if the areal extent of exceedence does not result in an unacceptable effect on human health. Whether the effect is acceptable or not may be determined, for example, by the application of the process of human health risk assessment as outlined in the NEPM (Schedule B4).

In such an assessment the areal extent of exceedence relevant for determining exposure can vary. For example, in the case of health risk assessment it can be appropriate to average the contaminant concentration over the exposure area of interest (this might be 50 m x 50 m in the case of passive recreation, or perhaps 7 m x 7 m in the case where there is a relatively intense and continuing use) and the discharge may be accepted if the concentration averaged over this area will not give rise to unacceptable exposure. Assuming we are dealing with a dissolved contaminant, exposure will depend on concentration passing through the surface and can be quantified in terms of flux through the area of interest.

In this case, the metric for the maximum allowable mass flux across the area over which exposure occurs could be based on:

Mass flux < (average concentration over exposure area) x (flow rate through the exposure area)

Risk to ecosystems

It is possible that this concept can be extended to determining when the impact on a shoreline ecosystem is unacceptable, although this will depend on whether and how the effect varies with concentration, which may not be readily quantifiable. For example, effect will commence occurring when the concentration exceeds the effect criterion as indicated for example in the ANZECC *Water Quality Guidelines for Fresh and Marine Waters* (section 3.1). If the concentration exceedence is small, then it may be that only some species will be affected, whereas if the exceedence is large many species will be affected. As such, as the flux increases over an area that is significant, the impact may become significant in terms of the overall ecosystem. As noted in section 3.1.4.3 of the ANZECC Guidelines, the area of interest may vary in size from a few square metres, as in the case of a stretch of an upland stream, to a few square kilometres, as in the case of a large seagrass bed.

In this case, the metric for the groundwater discharge giving rise to a significant effect on an ecosystem may be able to be characterised in terms of an equation such as:

Mass flux < (concentration criterion for ecosystem effect) x (flow through the area of significance)

As noted in the previous case, consideration should also be given to possible effects of bioaccumulation in the ecosystem where relevant.

d) NAPL treatment or recovery, and closure

Australian regulatory guidance allows for NAPL treatment or recovery to cease where the risk is shown to be acceptable, and recovery is not practicable (e.g. *State Environment Protection Policy Groundwaters of Victoria 1997* (Victorian Government 1997)). In situations where NAPL is present and the risk is acceptable, determining whether NAPL should be treated or recovered, or when treatment or recovery can cease, can be key issues. Often it is difficult to treat or recover NAPL, particularly where treatment or recovery has already taken place, there is little NAPL present, or the NAPL is located within a low permeability material or material that precludes methods such as excavation.

In situations where excavation and in-situ treatment is not practical, recovery by methods that involve extraction via wells (such as total fluids pumping, multiphase extraction, or skimming) are often seen as alternatives that may be practicable. However, if the quantity of NAPL that will enter a well is very small, then such methods may be considered to not be practicable and recovery may not then be required (this would, however, require that the risk be acceptable).

It is generally recognised that petroleum LNAPL thickness in wells does not provide a good measure of the potential for LNAPL recovery. Instead, it is recognised that transmissivity provides a better measure in this regard, in providing a measure of the rate at which NAPL will enter a well. If the transmissivity is very low, it can be concluded that very little NAPL will be able to be recovered using well methods, and NAPL recovery is not practicable, ie the metric at which recovery is not practicable would be:

Transmissivity < agreed value

In terms of setting an agreed value, there have been a number of proposals for such a value. For example, it has been suggested that a transmissivity less than 0.0013 m^2/day (0.014 ft^2/day) constitutes a very low value below which the costs and resources required for recovery make recovery not practicable (ASTM International 2007, Beckett and Lundegard 1997). Beckett and Lundegard (1997) suggest that with a transmissivity less than this value, it is unlikely that a recovery well will recover more than a few hundred litres of LNAPL over its lifetime. ITRC (2009) suggests that a range of 0.009 m^2/day (0.1 ft^2/day) to 0.07 m^2/day (0.8 ft^2/day) (higher than that suggested by Beckett and Lundegard (1997)) corresponds to a practicable level of hydraulic recovery, based on observations at various sites. It notes that sites in state regulatory programs in California, Kentucky, Florida and Virginia have been closed or granted no further action, where the transmissivity values were in this range. ITRC (2009) notes that lower transmissivity values can potentially be achieved, but technologies other than hydraulic and pneumatic recovery technologies typically need to be employed to recover additional LNAPL. Further recovery of LNAPL resulting in a lower transmissivity is difficult and can be inefficient, and may not offer a useful benefit in terms of reduction of LNAPL mass, migration potential, risk, or longevity.

There has not been regulatory acceptance in Australia that such a value can provide a standalone measure that a practicable endpoint has been reached; however, it can be expected that this measure together with other measures such as relating this to the

NAPL or adsorbed phase[7] present and likely to be recovered, and the amount being reduced through natural mass loss processes, may well provide a basis for accepting that a practicable endpoint has been reached. In this, the risk posed by the contamination both on site and off site and the time over which the site and resulting contamination will need to be managed are important considerations.

The relationships and measures listed above relate to determining when remediation is required, or in setting a performance objective for remediation. As such, they generally will relate to mass flux arising from a source area, or mass flux or mass discharge at a point where impact can occur.

Mass flux and mass discharge can vary with location if contaminant is being removed from the system, either through treatment or through natural processes. Mass flux across a plane may also vary if a contaminant plume changes direction, such as can occur during remediation. In such situations, the measures outlined above might or might not relate to the contaminant flux from a source area, and might or might not form a measure as to whether the source area requires remediation or not. Understanding such factors is clearly essential in using mass flux and mass discharge as criteria for initiating remediation or as a performance measure.

5.2.4 Plume stability metrics

Plume stability can also be a key determinant whether remediation is required, and achieving a stable or reducing plume can also be a key objective. Concentration measurements at key wells are likely to provide the primary measure of whether a plume is stable or increasing or decreasing; however, flux measurements can assist in better understanding the processes involved (such as the role of natural attenuation) and what can be expected in the future in terms of plume extent.

Because of the range of situations that can be encountered it is difficult to suggest a general set of metrics. Instead, metrics should be developed that are appropriate for each particular situation.

5.2.5 Remedial method performance metrics

In terms of assessing the performance of remedial methods, when it has been decided that a particular remedial method is to be applied (or has been applied), the measures outlined in section 5.2.3 can also form the basis for assessing the performance of the remedial method.

For example, if one of the measures suggested above has been selected as the objective for clean up, then it may be appropriate to establish the degree to which the objective has been achieved (or is likely to be achieved) as being the performance measure. This might be expressed in terms of a percentage at a point in time, or in terms of a graph of percentage over time. The latter may be useful in terms of understanding when improvement is plateauing and further remedial effort might not be warranted or an alternative method should be sought.

[7] Contamination such as hydrocarbon liquid that is adsorbed or entrapped within the soil matrix and does not migrate under natural conditions and therefore is not considered a free phase, although it may separate and release under some conditions (e.g. with the application of heat).

5.3 Considerations in the further development of metrics

The preceding sections have suggested possible metrics that can be useful in regulatory decision making. In further developing and applying these metrics, regulatory agencies are likely to consider the reliability of a metric and the resulting risk if applied. Examples of the considerations that the agencies may take into account are listed in table 7.

Table 7. Application of metrics: examples of issues which may be important to regulatory agencies.

Metric	Some issues for consideration
Use of groundwater: Mass flux < (concentration criterion for use) x extraction rate	• What confidence do we have that applying this approach will protect users of groundwater? • How will this be managed? • Might there be other users who will extract groundwater at a lower rate, with higher contaminant concentrations? • How accurate and reliable is the measurement of mass flux and the prediction of contaminant concentration, noting that hydraulic conductivity and contaminant concentrations may range over 6 -7 orders of magnitude? • How much additional work is required to be confident regarding the resulting concentrations?
Impacts on receiving water bodies: Mass discharge < (concentration criterion at boundary of mixing zone) x (flow rate through mixing zone)	• Issues as for the preceding metric • Is the contaminant bioaccumulative, and would this result in additional impact over that indicated by the estimated concentration? • Is the impact on the shoreline a limiting issue? (see next point)
Impact on shoreline: Mass discharge < (concentration criterion for ecosystem effect) x (flow through the area of significance)	• Issues as for the preceding metrics • Is the impact localized or more extensive, and is this being taken into account in assessing the risk to the shoreline ecosystem. • Are there any threatened or endangered species present that require protection?

6. Findings and recommendations

This project was the first stage in a program of work related to mass flux-based assessment of dissolved phase and free phase (e.g. NAPL) groundwater contamination. The project included:

- A review of national and international policy, regulation and practice
- A review of the technical options and techniques for measurement of groundwater mass flux and mass discharge
- Identification and recommendation of technology options for evaluation and adoption in consultation with end users, and
- Conceptualisation of how a mass flux or mass discharge approach might be applied and adopted in Australia.

The concepts of mass flux and mass discharge of contaminants are recognised in Australian regulation as being useful in understanding the significance of contamination and in determining the requirements for clean up and management.

Examples of how flux is or can be used include:

- Contributing to the site conceptual model and understanding risk
- Better understanding how concentrations of contaminants may vary in the future
- Assisting in determining whether remediation is required
- Assisting in selecting remediation methods
- Assisting in the design of a remedial method
- Assisting in assessing the performance of remediation methods, and
- Providing a compliance measure and a measure for closure.

Various methods have been developed for the measurement of mass flux. These include point, integral and analytical methods. Recommendations for further work on these methods are summarised in table 8. An investigation of how mass flux or mass discharge may be applied or adopted in Australia was also carried out; the findings of this are summarised in table 9. The recommendations and priorities for further work were determined through discussion with end users, in particular persons with broad experience in the auditing, assessment and remediation of groundwater contamination in Australia.

Further considerations relating to formulating metrics are provided in the report; in particular this includes considerations relating to:

- Determining when remediation is required
- Assessing the performance of remedial measures
- Determining measures for compliance and closure, and
- Assessing plume stability.

The intention of this report is not to provide a final position on these matters, but to provide commentary on the issues and to suggest areas for application and further work, facilitating understanding and providing a focus for further consideration.

Table 8. Methods of measurement and potential for further work.

Method		Need	Recommendation
Point	Transect	Increased level of understanding in the industry on how to implement – particularly the use of single screened pumping wells where high resolution characterisation is not feasible. Explain the uncertainty and demanding requirements for this.	Provide guidance and training on this method of determining mass flux and mass discharge, and the application of these concepts.
	Passive flux meter	If PFMs are to be used in preference to other methods, then need to make the method and its interpretation easier, and to significantly reduce cost of implementation. Note: likely to be challenging to develop PFMs to the point where they can be used to advantage over other methods. Lower priority for work.	Consider potential to develop low cost PFMs and to provide simple guidance on the application of the method.
Integral	Integral pump test	Increased level of understanding in the industry on the application of the method and its use.	Provide guidance and training on this method of determining mass flux and mass discharge, and the application of these concepts. Consider development of tool (software) to simplify application.
	Modified integral pumping test	Increased level of understanding in the industry on the method and its use.	Provide guidance and training on this method of determining mass flux and mass discharge, and the application of these concepts. Consider development of tool (software) to simplify the application of this method.
	Tandem circulation wells	This method is more complex and there are potential problems in implementation; need to resolve whether method will gain regulatory acceptance. Lower priority for further work.	Low priority for further work on this topic at this time.

Analytical	Isocontour	Increased level of understanding in the industry on the method and its use.	Provide guidance and training on this method of determining mass flux and mass discharge, and the application of these concepts. Consider development of tool (software) to simplify the application of this method.
	Solute transport models	Increased level of understanding in the industry on the method and its use.	Provide guidance and training on this method of determining mass flux and mass discharge, and the application of these concepts.
General	Uncertainty	Better quantification of uncertainty and its significance in applying mass discharge and mass flux concepts.	Undertake research to better quantify uncertainty and its significance with respect to each of the methods, and therefore the limitations on their application and the conclusions that can be drawn.

Table 9. Application of mass flux concepts.

Aspect	Current role of mass flux and mass discharge in regulatory decision making	Cost saving to the industry	Recommendation
Conceptual Site Model	Mass flux and mass discharge concepts are sometimes applied to assist in understanding contamination, its movement and potential for impact. Generally mass flux and mass discharge are not primary measures.	Low. Important in understanding, but not a primary cost determinant.	Provide guidance and training on the application of mass flux and mass discharge concepts in developing a Site Conceptual Model.
Variation of plumes with time	Mass flux is sometimes used to assist in understanding the variation in extent of plumes, whether they are increasing or decreasing in extent, whether plumes will migrate off site. Generally mass flux and mass discharge are not primary measures.	Medium. May be important in determining CUTEP, and may have a significant bearing on cost for some sites.	Provide guidance and training on the application of mass flux and mass discharge concepts in understanding the variation over time of plumes.
Requirement for remediation or management	Mass flux is sometimes used to assist in decision making as to whether remediation or management is required.	High. Could be important in deciding whether remediation is or is not necessary, with significant bearing on cost for some sites.	Develop suggestions for specific metrics as to the remedial response that should apply (refer Section 5.2.2). Illustrate the application of these concepts and metrics with demonstration projects.
Selecting Remediation Methods	Mass flux concepts are considered when assessing the effectiveness of particular remedial methods in removing source material and restoring beneficial uses. Generally mass flux will be only one of a number of measures that are used to decide whether a remedial method should be selected.	Medium. Important in assessing and selecting remedial strategies. Can have a significant bearing on cost of remediation	Provide guidance and training on the application of mass flux and mass discharge concepts in understanding source areas, risk, and how certain remediation methods may assist in dealing with the contamination
Assisting in the design of a remedial method	Mass flux measurements are considered in the design of remedial methods.	Medium. Important in designing a remedial method. Can have a significant	Encourage consideration of mass flux measurements and high resolution source characterisation.

		bearing on cost of remediation.	
Assisting in assessing the Performance of Remediation Methods	Mass flux and mass discharge measures are sometimes considered when assessing the performance of remediation methods, although usually not as an explicit measure.	High. May be important in determining the end point of a remedial method, and CUTEP. May have a significant bearing on cost for some sites.	Provide guidance on how mass flux and mass discharge concepts can assist in assessing the significance and risk of plumes, and the performance of remediation methods in reaching CUTEP. Develop suggestions regarding specific metrics for decision making (refer Section 5.2.2). Illustrate the application of these using demonstration projects.
Providing a compliance measure and a measure for closure	Mass flux and mass discharge can be important measures in deciding whether compliance with regulatory requirements has been achieved, although current practice usually will not refer to these measures explicitly. An example of this is in deciding whether CUTEP has been achieved. In the case of NAPL recovery, measures related to mass flux such as transmissivity are being proposed as a primary measure of compliance, but a specific value for transmissivity has not yet been accepted. In some situations mass flux or mass discharge can be linked to restoration of beneficial uses (ie achieving certain contaminant concentrations) and could be used as a primary measure of compliance; however this does not appear to have been applied to date.	High. May be important in determining the end point of a remedial method, and CUTEP and closure. Application of flux-based endpoints could have a significant bearing on cost for some sites.	Develop information on how mass flux and mass discharge may be used as a compliance and closure measure, perhaps related to CUTEP and sustainability, with examples, so that the concepts may be included in the National Remediation Framework. Develop suggestions regarding specific metrics for decision making (refer Section 5.2.2). Illustrate the application of these using demonstration projects.

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