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Developing risk-based screening guidelines for dioxin management at a Melbourne sewage treatment plant

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Abstract Dioxin is a generic term used to refer to the congeners of polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). The principal source of dioxin production is generally thought to be from unintended by-products of waste incineration, but dioxins are also naturally formed from volcanic activity and forest fires (WHO, 1998). Estimates of dioxin emissions in Australia suggest that approximately 75% of the total PCDD and PCDF emissions derive from prescribed burning and wild bushfires. Currently, no screening guidelines for dioxins within soils are available in Australia. This paper presents the general approach and results of a human health risk-based assessment performed by URS Australia in 2001 to develop site specific reference criteria for remediation of a former sewage treatment plant in Melbourne. Risk-based soil remediation concentrations for dioxins at the sewage treatment plant site were developed using tolerable daily intake values of 4, 2 and 1 pg/kg/day. The potentially significant exposure pathways and processes for exposure to dioxins were identified and risk-based soil concentrations derived in accordance with the general method framework presented in the National Environmental Protection Measure (Assessment of Site Contamination). The derived dioxin reference criteria were used to develop an effective risk management program focussed on those conditions that present the greatest contribution to overall risk to human health.

Keywords Dioxins; risk assessment; risk-based soil concentrations

Introduction

Dioxin is a generic term used to refer to the congeners of polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). The principal source of dioxin production is generally thought to be from unintended by-products of municipal waste incineration and in the manufacture of chlorinated hydrocarbons. Dioxins can also arise from volcanic activity and forest fires (WHO, 1998), and are also present in sewage sludge, discharge from paper mills, automobile exhaust and even cigarettes (Whysner and Williams, 1996). Estimates of dioxin emissions in Australia (Environment Australia, 1998) suggest that approximately 75% of the total PCDD and PCDF emissions derive from prescribed burning and wild bushfires.

Dioxins are highly persistent in the environment, extremely resistant to chemical and physical breakdown and have become a major environmental concern. Dioxins are bioaccumulative, being mainly stored in fatty tissue and can be passed up the food chain from plants to animals to humans (Carlo *et al.*, 1993). Toxic responses attributed to dioxins include dermal toxicity, immunotoxicity, carcinogenicity, and adverse effects on reproduction, development and endocrine functions. The World Health Organisation upgraded dioxin from a "probable" to a "known human carcinogen" in February 1997.

Background of study

The former Dandenong South Sewage Treatment Plant (DTP) was transferred to Melbourne Water Corporation (Melbourne Water) ownership in 1991 and ceased operation in 1996. URS Australia Pty Ltd (URS) was engaged by Melbourne Water in 2001 to undertake a Statutory Environmental Audit of the site. Independent Statutory Environmental Audits are required in Victoria under 1989 amendments to the Environment Protection Act 1970 in all cases where former industrial land is redeveloped for sensitive uses. These include residential use, childcare, kindergartens and primary schools.

The environmental audit includes, as part of the process required by the Environmental Protection Agency of Victoria, an assessment of the risks to human health and to the environment that may be imposed by the site following re-zoning or re-use for more sensitive uses such as residential use. In this case, open space and commercial uses have also been considered by the risk assessment.

The audit process will only be completed once remediation of the site is complete. This paper presents the methodology and findings of a human health risk-based assessment undertaken for the site by the auditor to assess the potential health risks associated with dioxin contamination identified within soils on the site and to establish appropriate risk-based screening criteria for a range of potential beneficial uses. The derived dioxin reference criteria were used by Melbourne Water to develop an effective risk management program focussed on those conditions that present the greatest contribution to the overall risk to human health.

The potentially significant exposure pathways were identified and risk-based soil concentrations derived in accordance with the general method framework presented in the National Environmental Protection Measure (Assessment of Site Contamination) (NEPM, 1999). This framework outlines the general approach which includes: (1) an assessment of the site and data; (2) exposure assessment; (3) toxicity assessment; and (4) calculation of risk-based concentrations.

Site description

The Melbourne Water Sewage Treatment Plant (herein referred to as the site) is located in the outer east Melbourne suburb of Dandenong. From the 1930s to the 1990s, the site received both domestic and trade waste effluent for primary and secondary treatment. Domestic and trade waste sludges and solids were stored in on-site lagoons and disposed on site. From the 1950s to the 1990s treated water from the trade waste treatment plant was flood irrigated onto the surrounding paddocks. The plant ceased operation in 1996 and, today, the majority of the site is secured from the public and is heavily overgrown with grass and patches of shrubs and trees. The western portion of the site is bordered by Dandenong Creek. After the completion of remediation, the site is to be sold and developed for commercial and low-density residential use and will potentially contain public open spaces and wetlands adjacent to Dandenong Creek.

The site and surrounding area is underlain by tertiary age Baxter formation comprising ferruginous sandstone, sand, sandy clay and occasional gravels. Quaternary age swamp deposits of peat and peaty clay overlie the Baxter formation with silty clay, sandy clay and sandy topsoils. Some localised fill materials have been noted on the site, comprising silty clay, clay-sand and trace amounts of quartz gravel.

Nature and extent of site contamination

The assessment of the extent of contamination included the collection of soil, sludge and groundwater samples from a number of areas primarily targeted at where contamination was expected. Dioxins in soils and sludges were identified as the predominant site contaminant of potential concern. Dioxins in groundwater were not assessed as a significant exposure pathway for two reasons: (1) data collected on the biannual sampling of groundwater conditions both on and off the site have not shown significant concentrations of dioxins; and (2) dioxins are hydrophobic compounds and are expected to readily adsorb in sediments and thereby have limited mobility in soils and limited potential to leach into groundwater (Alcock and Jones, 1996).

Although other contaminants may be present on the site, the dioxins are most likely to influence management decisions. For other contaminants, Tier 1 criteria such as those provided in Schedule B1 of the Australian National Environment Protection Measure (NEPM, 1999) (Assessment of Site Contamination), are considered sufficient for appropriate site management decisions as they provide acceptable health and ecological protection.

Exposure assessment

The exposure assessment identifies the human populations (receptors) who may be exposed to dioxins on the site, outlines the mechanisms (pathways) by which these populations may be exposed and provides a quantitative estimate of exposure and chemical intake.

Potential human receptors

Residential areas are located to the north of the site, whilst industrial areas are located to the east and south of the site. Given these uses of the site and surrounding area, the groups of people (receptors) who may be exposed to the dioxins include:

- on-site construction workers who may be involved in the construction of the residential and commercial developments;
- on-site commercial employees who may be employed within the proposed commercial areas on the site;
- on-site residents who may live within low- or medium-density residential areas proposed on parts of the site;
- off-site residents in areas surrounding the site who may be exposed to site-related dioxins via off-site migration;
- recreational users of the proposed open space and wetland areas.

Potential exposure pathways

Exposure pathways are the means or routes by which people or receptors may be exposed to the dioxins on the site. The following pathways were considered to be relevant for the site and surrounding areas (Figure 1).

Toxicity assessment

The objective of the toxicity assessment is to identify toxicity values for dioxins that can be used to quantify potential risks to human health associated with a calculated intake. Toxicity can be defined as "the quality or degree of being poisonous or harmful to plant, animal or human life" (NEPM, 1999).

Congeners containing 1, 2 or 3 chlorine atoms are thought to be of no toxicological significance to humans. Increasing substitution from 4–8 chlorine atoms generally leads to a decrease in toxicity. The dioxin congener 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD) is considered to be the most toxic to humans. In environmental situations, the PCDDs and PCDFs occur as a complex mixture of congeners. To enable a complex, multivariate set of data to be reduced to a single number, a system of toxicity equivalents (TEQ) has been developed. The assessment of dioxins follows the methodology outlined by WHO (1997) and NATO (1998). This methodology references the toxicity of dioxins to 2,3,7,8-TCDD using toxicity equivalency factors (TEF). Multiplication of the concentration of a PCDD or PCDF congener by the TEF gives a corresponding 2,3,7,8-TCDD TEQ concentration. The toxicity of a mixture of PCDDs and PCDFs, expressed as 2,3,7,8-TCDD TEQ, is derived by the summation of the individual TEQ concentrations and reported as the total TEQ for a mixture.

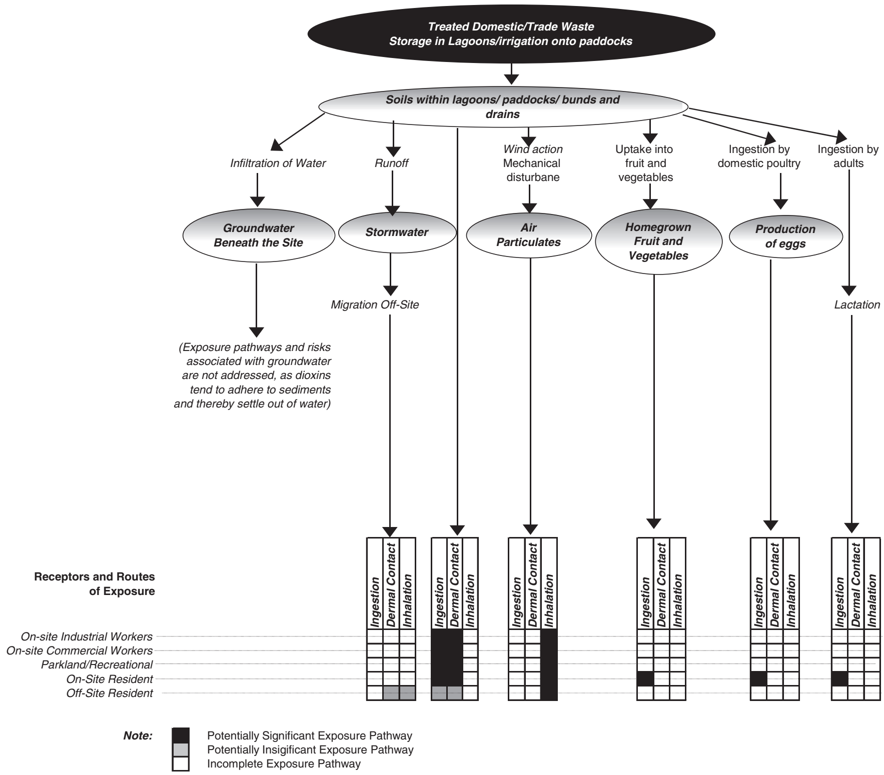

Figure 1 Dioxin exposure pathways

Tolerable daily intake for dioxins

A tolerable daily intake (TDI) is an estimate of the average daily intake of a contaminant that can be taken into a body (via ingestion, inhalation and dermal absorption) over a lifetime without any appreciable health risk.

In 1990 the World Health Organisation (WHO) proposed a TDI of 10 pg/kg/day for 2,3,7,8-TCDD. This was based on a study in which the inhibition of body weight gain and liver damage were observed when low doses of TCDD were administered to rats over a two year period (Kociba *et al*., 1978). This study found that 1 ng/kg/day lead to no manifestation of toxicity. Applying an uncertainty factor of 100 resulted in the proposed TDI of 10 pg/kg/day (WHO, 1991).

WHO European Centre for Environmental and Health (WHO-ECEN) and International Program on Chemical Safety (IPCS) held an expert consultation in Geneva in 1998 to review the TDI for dioxins based on new scientific information which had accumulated since 1990. As a result of new research on the health effects of dioxins and related compounds, the approach of using body burden rather than the exposure dose in extrapolating the results of toxicity data from animal studies to humans was introduced *(*body burden is a more appropriate measure than daily intake when discussing the relationship between substances and their effects, for substances known to bioaccumulate, and to exhibit large differences among species in the degree of bioaccumulation). In this approach, the lowest observable adverse effect level (LOAEL) for humans was determined by the lowest body burden at which adverse effects were observed in animals. This dose was multiplied by an uncertainty factor of 10 to give a TDI for dioxins in the range of 1–4 pg TEQ/kg/day.

The Australian Therapeutic Goods Administration (2000) has also reviewed the TDI for dioxins and has set the WHO value as a provisional TDI. The executive summary of the

WHO final report concludes that this value for TDI is considered to be the provisional tolerable value in view of the fact that current background exposure levels of dioxins in industrialised countries is considered to be in the range 2–6 pg TEQ/kg/day. Although subtle effects may occur at these exposure levels, no confirmed manifestations of toxic effects have yet been reported. Whilst WHO considered the upper range of 4 pg TEQ/kg/day to be the "maximum tolerable intake on a provisional basis", it stressed that the ultimate goal should also be to reduce potential human intake to less than 1 pg TEQ/kg/day.

The development of risk-based soil concentrations (RBSCs) for dioxins at the Dandenong site has been undertaken using TDI values of 4, 2 and 1 pg/kg/day (WHO, 1998). The TDI represents the daily intake allowable from all routes of exposure, which include ingestion, dermal absorption and inhalation.

It is accepted that toxicological data has some uncertainties. However, the approaches adopted by the different regulatory bodies in determining the relevant toxicological values are also considered to be conservative and likely to overestimate the risks due to the inclusion of safety factors.

Estimation of potential intake

Quantitative assessment of exposure to dioxins involves the estimation of potential intake for the defined receptor groups and pathways identified in the conceptual site model. A conservative measure of exposure, the reasonable maximum exposure (RME), has been defined in the assessment. This method follows ANZECC/NHMRC guidance incorporated in the 1999 NEPM, supplemented by USEPA guidance (USEPA, 1989a). The RME is usually estimated by using intake variables and chemical concentrations that define the highest exposure that is reasonably likely to occur at a site. The RME is likely to provide an overestimate of total exposure.

Calculation of intake factors

An intake factor is a site and receptor specific value which, when multiplied by the concentration, provides an estimate of the daily chemical intake of dioxins for each receptor and pathway. The magnitude of the intake or exposure is a function of a number of variables, which describe the physical and behavioural parameters of the potentially exposed population. Examples include contact rate, exposure frequency and duration, and body weight based on values suggested by Langley (CSMS, 1996).

Derivation of risk-based soil concentrations (RBSCs)

The derivation of RBSCs involves the incorporation of the exposure assessment and toxicity assessment along with the use of a target risk value to provide a quantitative assessment of threshold health effects. The aim of the assessment is to identify the maximum concentrations of dioxins within the soil on the site, which are protective of long-term exposure by all relevant receptor groups (including workers and residents).

Target hazard index for threshold effects

The potential for adverse threshold effects, resulting from exposure to dioxins, can be evaluated by comparing an exposure level (intake), with the acceptable or tolerable daily intake (ADI/TDI). The resulting ratio is referred to by the USEPA as the hazard quotient (USEPA, 1989a) and is derived in the following manner:

$$\text{Hazard quotient} = \frac{\text{Exposure Level}}{\text{Tolerable Daily Intake}} \qquad (1)$$

In order to derive a RBSC for dioxins (as TEQ), the target hazard quotient was set equal to 1.

The RBSC for dioxins in soil could then be evaluated using the following equation:

$$\text{RBSC} = \frac{\text{Target HI} \times \text{TDI}}{\sum_{\text{All Pathways}} \text{Intake Factor}} \tag{2}$$

Risk-based soil concentrations

Table 1 presents a summary of the RBSC that have been calculated using the process described above, for construction and commercial workers and recreational and child residents on the DTP site. Children (typically aged 0 to 5 years) are expected to be the most sensitive receptors in the residential and recreational receptor groups as they have a lower body weight than adults, resulting in a higher potential intake of dioxins per unit body weight.

Of the human health RBSC derived, the following values have been recommended:

- the RBSC for *low density residential* areas of the site be 100 TEQ ng/kg;
- the RBSC for *open space/recreational* area of the site be 370 TEQ ng/kg;
- the RBSC for *commercial/industrial* areas of the site also be 370 TEQ ng/kg.

The figure of 100 ng/kg was suggested for low density residential land use as it falls within the range of acceptable concentrations based on the WHO allowable range of 1–4 pg/kg/day, and allows for the presence of background concentrations of dioxins exceeding 50 ng/kg present in the surface soils on the site, that appear unrelated to effluent disposal.

A higher figure of 1,625 TEQ ng/kg (construction workers) and 20,000 TEQ ng/kg (commercial workers) would appear to be acceptable in terms of potential risks in these areas for completed developments. However, a lower criteria was suggested to be protective of all users of these areas that may remain as default open space for considerable time and to cater for construction workers in phases subsequent to the main remediation phase on the site. It would also cater for future soil disposal to controlled landfills once proposed on-site containments developed to accept the dioxin contaminated sludges, have been closed.

Risk management program

Although this paper is primarily aimed at development of risk-based soil criteria for remediation of a closed facility, it has implications for the management of existing effluent

Table 1 Human health risk based soil concentrations

Chemical of potential concern	Potential receptor	Risk based concentration range (TEQ ng/kg)			Notes
		Threshold effects with target hazard quotient of 1			
Dioxin	TDI (pg/kg/day)	1	2	4	Key exposure pathways to dioxins are the potential ingestion and direct contact with soil.
	Commercial worker	20,000	40,000	80,000	
	Construction worker	1,625	3,250	7,500	
	Child recreational (open space)	370	740	1,480	
	Child on-site resident	38	76	152	Key exposure pathway to dioxins are the potential ingestion (soil, homegrown fruit and vegetable, eggs, human breast milk) and direct contact with the soil. It is assumed that homegrown produce contributes more than 10% of intake.

treatment plants, in particular those accepting industrial effluents, the likely source of the dioxins encountered at the DTP.

Management procedures put in place by Melbourne Water to prevent future issues of a similar nature involve the quarterly monitoring for dioxins (and furans) of raw sewage and trade waste effluents entering the treatment plants in accordance with Melbourne Water Trade Waste Standards summarised as follows.

- An occupier must not discharge trade waste containing any of the full range of chlorodibenzo-*p*-dioxin and chlorodibenzo-furan congeners in a concentration greater than the NATO total toxic equivalent of 40.0 ng/L with the option for Melbourne Water to reduce this concentration to 20 ng/L at their discretion.
- An occupier must not discharge trade waste containing any 2,3,7 or 8 tetrachlorodibenzo-*p*-dioxin congeners in a concentration greater than the NATO total toxic equivalent of 20 ng/L with option for Melbourne Water to reduce this concentration to 5 ng/L at their discretion.

Conclusion

Site specific risk-based soil guidelines for dioxins (TEQ) were developed for a range of land uses at the former DTP site. These guidelines were generally established as 100 TEQ ng/kg for residential areas, 370 TEQ ng/kg for public open space areas, and 1,625 TEQ ng/kg for construction workers on industrial commercial lots. These guidelines were moderated by potential future disposal considerations for surplus soils off-site.

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