Appendix 5A
Irrigation water criteria

1.1 Overview

The derivation of Tier 1 groundwater acceptance criteria for the protection irrigation use has been based on consideration of:

- protection of the health of adults and children that may come in contact with contaminated groundwater during use for irrigation
- protection of the health of residents associated with the inhalation of vapours during use of contaminated groundwater
- protection of the health of residents consuming home grown produce that may have been affected by the use of contaminated groundwater for irrigation
- consideration of aesthetic impacts, including odour.

Walden and Spence (1996) developed a protocol for the development of groundwater acceptance criteria for irrigation use, and this has been used as the basis for the derivation of Tier 1 groundwater acceptance criteria for irrigation. Some modifications have been made to the exposure factors assumed by Walden and Spence in order to retain consistency with exposure factors used in other parts of these guidelines.

A general overview of the approach used in derivation of criteria for the protection of irrigation use is presented, however the reader is referred to Walden and Spence (1996) for further details.

The derivation of irrigation water criteria is discussed in terms of the following:

- shower model (used to estimate volatilisation of contaminants from irrigation water) and exposure via the inhalation of volatiles
- plant uptake and exposure via the consumption of home-grown produce
- dermal exposure
- odour impact.

For details of expressions for estimating exposure refer to Section 5.3 of Module 5(potable use) and Appendix 4C.

1.2 Shower model

The shower model is used to estimate the vapour emissions from the sprayed water and the concentration in water hitting the ground. The shower model was originally developed for estimating exposure to volatile contaminants during showering (Foster and Chrostowski, 1986). In this case the shower model is used to simulate a sprinkler system. The shower model has been modified to reflect the volatilisation from spray irrigation. However given the shower model does not account well for atmospheric dispersion (ie. models dilution of vapours in terms of a defined box and an air exchange rate) it is limited to estimating contaminant concentrations in air within and immediately downgradient of the spray. The concentrations in the air are estimated based on the following assumptions:

- the "shower" is fully mixed for the entire duration (ie. air within the spray area of the sprinkler is fully mixed)
- dilution can be estimated using a simple box model
- two film-model of gas-liquid mass transfer.

Volatilisation is limited by mass transfer rates. The overall mass transfer coefficient is calculated as:

$$K_L = \left[\frac{1}{k_l} + \frac{RT}{Hk_g}\right]^{-1} \tag{A1}$$

where:

K_L = overall mass transfer coefficient (cm/hr)

H = Henry's Law constant for contaminant (atm.m^3 / mol)

R = gas constant (assumed to be 8.2 x 10^{-5}(atm.m^3 / mol.K)

T = absolute temperature (assumed to be (293°K)

k_g = gas phase mass transfer coefficient (cm/hr)

k_l = liquid phase mass transfer coefficient (cm/hr)

The gas and liquid phase mass transfer coefficients for contaminants may be estimated from measure values for CO_2 and H_2O and the following correlations:

$$k_{g(VOC)} = k_{g(H_20)}\left[\frac{18}{MW_{VOC}}\right]^{0.5} \tag{A2}$$

$$k_{l(VOC)} = k_{l(CO_2)}\left[\frac{44}{MW_{VOC}}\right]^{0.5} \tag{A3}$$

where:

$k_{g(H20)}$ = gas phase mass transfer coefficient for water (cm/hr)

=3000 cm/hr

$k_{l(CO2)}$ = liquid phase mass transfer coefficient for carbon dioxide

= 20 cm/hr

18 = molecular weight of water

44 = molecular weight of carbon dioxide

MW_{VOC} = molecular weight of contaminant

The overall mass transfer coefficient must be adjusted for shower temperature and the viscosity of water at the slower temperature.

$$K'_{L(Ts)} = K_L\left[\frac{T_l\mu_S}{T_S\mu_l}\right]^{-0.5} \tag{A4}$$

where:

$K'_{L(Ts)}$ = adjusted overall mass transfer coefficient (cm/hr)

T_l = calibration water temperature of K_L (°K)

T_S = shower water temperature (°K)

m_l = water viscosity at T_l (g/m.s)

m_S = water viscosity at T_S (g/m.s)

Water viscosity may be estimated from the following relationships (T in ^oC):

If $T \leq 20^oC$: $m = 100 \,.\, 10^y$

where:

$$y = \frac{1301}{998.33 + 8.1855(T-20) + 0.00585(T-20)^2} - 3.30233 \qquad \text{(A5)}$$

If $T > 20^oC$: $m = 1.002 \,.\, 10^y$

where:

$$y = \frac{-1.37272(T-20) - 0.001053(T-20)^2}{T+105} \qquad \text{(A6)}$$

Volatilisation is assumed to be a first-order process:

$$C_{sh} = C_o e^{-K'_L t/600d} \qquad \text{(A7)}$$

where:

C_{sh} = concentration of contaminant in shower droplet after time t (mg/L)

C_o = concentration of contaminant in shower water (mg/L)

d = shower droplet diameter (cm)

= 0.2 cm

t = shower droplet drop time (s)

= 10 s (as estimated by Walder and Spence)

C_{sh} is the concentration of the shower drop which enters the soil.

The total amount of contaminant that volatilises is given by:

$$M_{sh} = f_v \,.\, Q \,.\, time_{sh} \,.\, C_o \qquad \text{(A8)}$$

where:

M_{sh} = mass of contaminant volatilised (mg)

f_v = the fraction of contaminant volatilised $(1 - e^{-K'_L t/600d})$ (mg/mg)

Q = the volumetric flow rate of water (L/min)

$time_{sh}$ = the duration for which the shower water is flowing (min)

C_o = the concentration of contaminant in the shower water (mg/L)

The concentration of the shower air can be estimated from:

$$C_{sh} = \frac{M_{sh}}{V_{sh}} \qquad \text{(A9)}$$

where: C_{sh} = air concentration in the shower (mg/m^3)

V_{sh} = volume of air in the shower (m^3)

In order to modify the shower model to reflect conditions occurring during use of a sprinkler, the volume of air in the shower is set equal to the product of the width of the sprinkler area (4 m), the breathing height of the receptor (1.5 m), the wind speed (2 ms^{-1}) and the duration of exposure (0.5 hr or 1800 s for children, and 2 hr or 7200 s for adults) giving a volume of 21,600 m^3 for children and 86,400 m^3 for adults.

1.3 Plant uptake

The uptake of contaminants by plants is a complex series of reactions. For the purpose of this module the following is assumed:

- plants consist of 80% water by fresh weight
- concentration of water in plant is the same as that calculated by the shower model
- no dilution of contaminants by rainfall
- no bioaccumulation of contaminants in the plants.

The modelling of uptake of contaminants from irrigation water differs from that for uptake from soil as it is assumed that water within the plant is the same as calculated by the shower model. Hence no distinction is made between contaminant concentrations in various plant parts reflecting that contaminants may be absorbed through the roots or leaves. This approach is expected to overestimate the uptake of lipophilic compounds such as benzo(a)pyrene (hence a less stringent criterion is adopted, refer Module 5).

The assumption that garden produce contains 80% moisture is expected to be a typical value although some produce may exhibit higher or lower moisture contents.

1.4 Derivation of water criteria based on ingestion of vegetables

This calculation is the same as the calculation for soil criteria (Appendix 4C). The calculation is performed for adults (30 years old), children (six years old) and for the combination (child for first six years followed by adults for next 24 years).

1.5 Dermal exposure

Children get wet playing under the sprinkler. It is assumed that the child's entire body is exposed to the contaminated water and that the concentration of the water is that of the groundwater Cw. The initial water concentration, Co, is used rather than the concentration following volatilisation, as children may contact water as soon as it leaves the sprinkler (this is a conservative assumption).

The average daily dose, ADD (mg/kg.d) is calculated by the equation:

$$ADD = \frac{10^{-3} C_w \times SA \times AAF_{dermal} \times ET \times PC \times EF \times ED}{365\ AT \times BW} \qquad (A10)$$

where:

C_w = concentration of contaminant in groundwater (mg/L)

SA = total skin surface area (cm^2)

AAF = chemical specific adsorption adjustment factor

ET = activity duration (hr/day)

PC = chemical specific skin permeability coefficient (cm/hr)

EF = exposure frequency for playing/gardening (d/yr)

ED = exposure duration (yr)

AT = averaging time (yr)

= 70 yr for carcinogenic contaminants

= ED for non-carcinogenic contaminants

BW = body weight (kg)

The USEPA (Dermal Exposure Assessment: Principles and Applications, 1992) have estimates of permeability coefficients. These are estimated by the following equation:

$$\log K_p = -2.72 + 0.71 \log K_{o/w} - 0.0061\ MW \quad \text{(A11)}$$

where:

K_p = permeability coefficient (cm/hr)

$K_{o/w}$ = Octanol Water Partition Coefficient

MW = Molecular weight (g/mol)

Table 5A1 shows the permeability coefficients used in the model.

Table 5A1 Permeability coefficients for dermal exposure

Contaminant	Permeability Coefficient Kp (cm/hr)
C_7- C_9	0.205
C_{10}-C_{14}	1.53
C_{15}-C_{38}	2.40
Toluene	0.045
Ethylbenzene	0.074
Xylene	0.080
Naphthalene	0.069
Pyrene	0.32
Benzo(a)pyrene	1.2

Table 5A2 Exposure parameters for irrigation model

Parameter	Child	Adult
Water ingestion rate (L/day)	0.25	-
Vapour inhalation rate (m^3/hr)	0.83	0.83
Dermal AAF - Benzene	2.13	2.13
Dermal AAF - Toluene	2.0	2.0
Dermal AAF - Ethylbenzene	1.0	1.0
Dermal AAF - Xylene	1.1	1.1
Dermal AAF - other	1.0	1.0
Gardening/play activity duration (hr/d)	0.5	2
Gardening/play exposure frequency (d/yr)	54	54
Gardening exposure duration (yr)	6	30
Vegetable ingestion exposure freq (d/y)	350	350
Vegetable ing. exposure duration (yr)	6	30
Vegetable ingestion rate (g/day)	130	450
Fraction of vegetables homegrown	0.10	0.10
Vegetable water retention (%)	80	80
Skin surface area (cm^2)	6800	-
Wind speed (m/s)	2	2
Inhalation “box” volume (m^3)	21,600	86,400
Sprinkler flow rate (L/min)	30	30
Water temperature (^oC)	25	25
Lifetime (yr)	70	70
Body weight (kg)	15	70

1.6 Odour-based criteria

Odour-based criteria were determined using threshold values obtained from literature and air concentration values calculated from the shower model. Shower air concentrations were calculated for a water concentration of one milligram per litre. A proportional relationship was used to allow the calculation of the water concentration, which would produce a shower air concentration equal to the odour threshold.

Odour threshold air concentrations were obtained from Walden and Spence, 1996, and AIHA, 1989.

1.7 References

AIHA. 1989. **Odour Thresholds for Chemicals with Established Occupational Health Standard**, American Industrial Hygiene Association.

Foster S.A., and Chrostowski P.C. 1986. **Integrated Household Exposure Model for use of Tap Water Contaminated with Volatile Organic Chemicals,** Proc. 79th Ann. Meeting of Air Pollution Control Association, Minneapolis.

Walden and L. Spence. 1996. **Risk-Based BTEX Cleanup Goals in Groundwater for Irrigation Scenarios,** BP Oil Internal Report.

USEPA. 1992. **Dermal Exposure Assessment: Principles and Applications**.

Table 5A1 Preliminary Health Risk Based Acceptance Criteria *Residential Site Use* Estimation of Target Groundwater Concentrations:- Produce Based

Site Use:	Residential	Expo. Dur. (child):	6	yrs	garden dur.(child)	0.5	hr/d	Prod Ing. (child):	0.13	kg/d
Receptor:	Children residents on site for up to 30 yrs	Expo. Dur. (adult):	30	yrs	(adult)	2	hr/d	Prod Ing. (adult):	0.45	kg/d
		Expo. Dur. (ad,com):	24	yrs	garden exp. freq.	54	d/yr	Prop homegrown	0.1	
		Ave. Time (carc):	70	yrs	Inhale rate (child)	20	m3/d	Prod Expo.Freq.	350	d/yr
Target Risk:	0.00001	(non-carc, child):	6	yrs	Inhale rate (adult)	20	m3/d	Skin area (child)	6800	cm2
Target HI:	1	(non-carc, adult)	30	yrs	Water Ing (child)	0.25	L/d			
		Body Weight (child)	15	kg	Water Ing (adult)	0	L/d			
		(adult)	70	kg						

Contaminant	Skin Absorption	SF (1/(mg/kg/d))	RfD (mg/kg/d)	SF (1/(mg/kg/d))	RfD (mg/kg/d)	Acceptable CDI (mg/kg/d)						Risk Based Screening Level (mg/L-H2O)		
						Carcinogenic			Non-carcinogenic			Child	Adult	Child->Adult
	cm/hr	Oral	Oral	Inhalation	Inhalation	Oral	Dermal	Inhalation	Oral	Dermal	Inhalation			(carc. only)
Alkanes														
C7-C9	2.05E-01		5.00E+00		5.00E+00				5.00E+00	5.00E+00	5.00E+00	5.15E+02	1.78E+04	
C10-C14	1.53E+00		1.00E-01		3.00E-01				1.00E-01	1.00E-01	3.00E-01	1.85E+00	3.90E+02	
C15-C36	2.40E+00		1.50E+00		1.50E+00				1.50E+00	1.50E+00	1.50E+00	1.80E+01	4.60E+03	
MAHs														
benzene	4.47E-02	2.90E-02		2.90E-02		3.45E-04	3.45E-04	3.45E-04				9.36E-01	3.09E+00	7.54E-01
toluene	9.00E-02		2.00E-01		1.10E-01				2.00E-01	2.00E-01	1.10E-01	3.38E+01	5.76E+02	
ethylbenzene	7.40E-02		1.00E-01		2.90E-02				1.00E-01	1.00E-01	2.90E-02	1.80E+01	2.00E+02	
xylene	8.80E-02		1.80E-01		9.00E-02				1.80E-01	1.80E-01	9.00E-02	3.06E+01	4.87E+02	
PAHs														
naphthalene	6.90E-02		4.00E-03		4.00E-03				4.00E-03	4.00E-03	4.00E-03	7.72E-01	1.29E+01	
pyrene	3.20E-01		3.00E-02		3.00E-02				3.00E-02	3.00E-02	3.00E-02	2.17E+00	6.15E+01	
benzo(a)pyrene	1.20E+00	7.30E+00		7.30E+00		1.37E-06	1.37E-06	1.37E-06				3.68E-04	6.49E-03	3.52E-04

Contaminant	Pathway Contribution to Risk											
	Child				Adult				Child->Adult			
	Inhalation	Produce Ingestion	Water Ingestion	Skin Absorption	Inhalation	Produce Ingestion	Water Ingestion	Skin Absorption	Inhalation	Produce Ingestion	Water Ingestion	Skin Absorption
Alkanes												
C7-C9	1.08%	2.67%	25.41%	70.84%	31.82%	68.18%	0.00%	0.00%	-	-	-	-
C10-C14	0.06%	0.58%	4.57%	94.80%	10.14%	89.86%	0.00%	0.00%	-	-	-	-
C15-C36	0.10%	0.41%	2.95%	96.54%	21.77%	78.23%	0.00%	0.00%	-	-	-	-
MAHs												
benzene	2.68%	5.06%	57.37%	34.90%	38.00%	62.00%	0.00%	0.00%	9.56%	16.15%	46.19%	28.10%
toluene	3.39%	3.98%	41.65%	50.98%	49.59%	50.41%	0.00%	0.00%	-	-	-	-
ethylbenzene	6.59%	4.52%	44.30%	44.58%	62.76%	37.24%	0.00%	0.00%	-	-	-	-
xylene	3.61%	4.29%	41.92%	50.17%	49.31%	50.69%	0.00%	0.00%	-	-	-	-
PAHs												
naphthalene	1.75%	6.03%	47.58%	44.64%	25.12%	74.88%	0.00%	0.00%	-	-	-	-
pyrene	0.02%	4.73%	17.80%	77.46%	0.46%	99.54%	0.00%	0.00%	-	-	-	-
benzo(a)pyrene	0.00%	1.53%	5.69%	92.78%	0.04%	99.96%	0.00%	0.00%	0.00%	5.81%	5.44%	88.75%

Table 5A2 A*gricultural Criteria Calculation* Shower Model

water conc:			1 mg/L								
viscosity:	T			25 C	drop diameter:	0.2 cm	gardening exposure time:				
	if T<20				drop time:	10 s		adult:	2 hr		
		y	-2.050650852					child:	0.5 hr		
		u	0.889916272		wind speed	2 m/s					
	if T>=20				sprinkler dia.	4 m	Box volume	adult:	86400 m3		
		y	-0.051248654		receptor height	1.5 m		child:	21600 m3		
		u	0.890469539		flowrate	30 L/min	Fraction of water in produce:		0.8		
	u=		0.890469539 g/m.s								

Chemical	MW g/mol	H @ 20oC L-H20/L-air	H atm.m3/mol	kg cm/hr	kl cm/hr	Kl cm/hr	Kl' cm/hr	Cirrigation mg/L	Cshower mg/L	Mass vol (mg) adult	Csh (mg/m3) adult	Cplant g/g	Odour threshold mg/m3	Odour based Criteria (mg/L)
C_7-C_9	120	1.2E+02	2.93E+00	1161.895004	12.11060142	12.10956795	11.31957183	0.389341802	0.610658198	2198.369512	0.025444092	3.11473E-07	-	-
C_{10}-C_{14}	185	1.6E+02	3.91E+00	935.7754408	9.753724167	9.753099898	9.116833509	0.467789848	0.532210152	1915.956546	0.022175423	3.74232E-07	-	-
C_{15}-C_{36}	245	1.4E+02	3.30E+00	813.1571126	8.475655414	8.475012496	7.922125141	0.516759811	0.483240189	1739.664681	0.020135008	4.13408E-07	-	-
benzene	78	2.2E-01	5.38E-03	1441.153384	15.02135232	14.35320032	13.41683557	0.326910243	0.673089757	2423.123124	0.028045407	2.61528E-07	4.5	160.5
toluene	92.1	2.6E-01	6.36E-03	1326.257009	13.82377062	13.29989977	12.43224956	0.354863952	0.645136048	2322.489772	0.026880669	2.83891E-07	8	297.6
ethylbenzene	106.2	3.2E-01	7.82E-03	1235.080454	12.87342406	12.47420425	11.66042023	0.378438507	0.621561493	2237.621376	0.025898396	3.02751E-07	8.7	335.9
xylene	106.2	2.9E-01	7.09E-03	1235.080454	12.87342406	12.43431434	11.62313262	0.379616257	0.620383743	2233.381473	0.025849323	3.03693E-07	0.35	13.54
naphthalene	128.2	4.9E-02	1.20E-03	1124.122122	11.71688915	9.691362472	9.059123669	0.47004494	0.52995506	1907.838217	0.022081461	3.76036E-07	0.20	9.06
pyrene	202.3	2.2E-04	5.38E-06	894.8692109	9.327352555	0.196155807	0.183359122	0.984836219	0.015163781	54.58961195	0.000631824	7.87869E-07	-	-
benzo(a)pyrene	252.3	2.0E-05	4.89E-07	801.3068992	8.352138908	0.01627913	0.015217122	0.99873271	0.00126729	4.562243458	5.28037E-05	7.98986E-07	-	-

adult Chemical	risk/HI inhalation	risk/HI produce	risk/HI total
C_7-C_9	1.79E-05	3.84E-05	5.63E-05
C_{10}-C_{14}	2.60E-04	2.31E-03	2.57E-03
C_{15}-C_{36}	4.73E-05	1.70E-04	2.17E-04
benzene	1.23E-06	2.00E-06	3.23E-06
toluene	8.61E-04	8.75E-04	1.74E-03
ethylbenzene	3.15E-03	1.87E-03	5.01E-03
xylene	1.01E-03	1.04E-03	2.05E-03
naphthalene	1.94E-02	5.80E-02	7.74E-02
pyrene	7.42E-05	1.62E-02	1.63E-02
benzo(a)pyrene	5.82E-07	1.54E-03	1.54E-03

child Chemical	risk/HI inhalation	risk/HI vegetation	risk/HI water ing.	risk/HI dermal	risk/HI total
C_7-C_9	2.09E-05	5.18E-05	4.93E-04	1.37E-03	1.94E-03
C_{10}-C_{14}	3.04E-04	3.11E-03	2.47E-02	5.12E-01	5.40E-01
C_{15}-C_{36}	5.52E-05	2.29E-04	1.64E-03	5.37E-02	5.56E-02
benzene	2.86E-07	5.40E-07	6.13E-06	3.73E-06	1.07E-05
toluene	1.00E-03	1.18E-03	1.23E-02	1.51E-02	2.96E-02
ethylbenzene	3.67E-03	2.52E-03	2.47E-02	2.48E-02	5.57E-02
xylene	1.18E-03	1.40E-03	1.37E-02	1.64E-02	3.27E-02
naphthalene	2.27E-02	7.81E-02	6.16E-01	5.78E-01	1.30E+00
pyrene	8.66E-05	2.18E-02	8.22E-02	3.58E-01	4.62E-01
benzo(a)pyrene	1.36E-07	4.15E-04	1.54E-03	2.52E-02	2.71E-02

adult(com) Chemical	risk/HI inhalation	risk/HI produce
C_7-C_9		
C_{10}-C_{14}		
C_{15}-C_{36}		
benzene	9.82E-07	1.60E-06
toluene		
ethylbenzene		
xylene		
naphthalene		
pyrene		
benzo(a)pyrene	4.66E-07	1.23E-03

child->adult Chemical	risk/HI inhalation	risk/HI vegetation	risk/HI water ing.	risk/HI dermal	risk/HI total
C_7-C_9					
C_{10}-C_{14}					
C_{15}-C_{36}					
benzene	1.27E-06	2.14E-06	6.13E-06	3.73E-06	1.33E-05
toluene					
ethylbenzene					
xylene					
naphthalene					
pyrene					
benzo(a)pyrene	6.01E-07	1.65E-03	1.54E-03	2.52E-02	2.84E-02