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FOCUS

Irrigating horticultural crops with recycled water: an Australian perspective

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ABSTRACT

Access to water has been identified as one of the most limiting factors in economic growth of Australia's horticultural sector. Water reclaimed from wastewater (sewage) is being increasingly recognized as an important resource and agricultural sector is currently the largest consumer of this resource. An overview of the Australian experience of using reclaimed wastewater to grow horticultural crops is presented in this paper: from regulations governing it and treatment processes, to management and risk-minimization practices that ensure this resource is used in a sustainable manner, not impacting adversely human health or environment. A case study covering socio-economic and environmental implications of recycled-water irrigation is also presented.

Key words: Irrigation, water recycling, water treatment, nutrients, sodicity, salinity

INTRODUCTION

Interaction between water resources and agriculture in Australia

Australian annual water use is approximately 920 kilolitres (KL) per capita, 60KL above the OECD average. Yet, it is the driest continent, second only to Antarctica (ABS, 2010a,b). Rainfall distribution across the continent is not uniform (Figure 1). Up to two thirds of the continent is arid or semi-arid (ABS, 2010c); the northern region is relatively wet and receives heavy summer rainfall, while in the south, the climate is more Mediterranean and experiences long, dry periods particularly, in summer. Rainfall also varies greatly from year to year, more so than in any other continental region (ABS, 2010a).

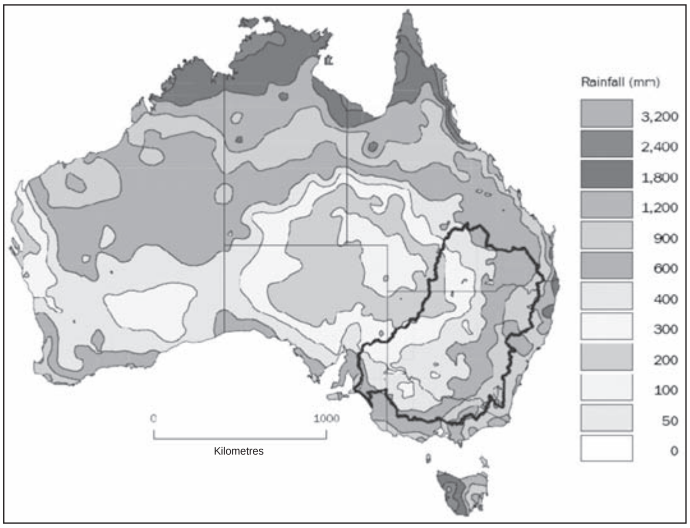

Fig 1. Australia's Total Rainfall 2005-2006 (including an outline of Murray Darling Basin)
Source: Australian Bureau of Statistics, 2010c

Prior to European colonization, Australian native plants thrived-with their adaptations to this somewhat harsh and changing climate. But, with colonization, came widespread clearing of indigenous vegetation, and a strong economy developed built on farming-introduced crop species. While agriculture no longer dominates the Australian economy, it continues to contribute substantial export income to the national account and plays a crucial role in feeding the nation and in sustaining rural populations (DSEWPC, 2008). To support production of crops whose water requirements are higher than natural rainfall, storage of water, diversion of, and extractions from natural water bodies, have become standard farming practices in a large area of Australia.

The agricultural sector occupies approximately 54% of the land (ABS, 2010c) and is the largest consumer of water in Australia (Table 1). In 2008-9, the total water-use by the agricultural sector was 6696 GL, 47% of the total for Australia. A majority of the water used was either self-extracted (52%), or distributed by water suppliers (47%). Table 2 outlines the extent of water use by various types of agriculture in each state and territory. In the northern regions-

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where rainfall is more reliable-the predominant enterprises are beef cattle grazing, sugar and tropical fruit farming (ABS 2010c). In the south, where summers are generally dry, dryland cereal farming, sheep grazing and dairy farming (in areas of higher rainfall) predominate (ABS, 2010c).

In 2007-08, 28% of all agricultural establishments reported some irrigation activity; grapes, vegetables, cotton and nurseries/cut flowers/cultivated turf are some of the most intensively irrigated with 96, 93, 85 and 83%, respectively, of their growing areas under irrigation (ABS, 2010c). While the gross value of irrigated agricultural production in 2006-07 was 34% of the total gross agricultural production, irrigated farmland represents only 1% of the total land used for agriculture, most of which is within the confines of Murray Darling Basin (MDB) (ABS, 2010c).

Known as Australia's 'food bowl', the MDB catchment covers an area of over 100 million ha and contains Australia's three longest rivers; a majority of the land is either dedicated to agriculture (67%) or has been conserved as native forest (32%) (ABS, 2010c). Extractions from the rivers within the MBD are a major irrigation source in the region and, historically, water allocation has not been well-managed; over-extraction has driven a decline in health of the river systems.

Policy changes to return environmental flows to the rivers, coupled with 8-10 years of drought have seen water allocation decline, placing an increasing pressure on irrigators. Despite water conservation steps taken across several states which have seen 43% reduction in water consumption throughout the country over a period of drought (from 24,909 GL in 2000-01 to 14,101 GL in 2008-09), irrigators are still challenged with ongoing reduction in water allocation (ABS, 2010a). In the face of these shortages, water reclaimed from wastewater (sewage) is being increasingly recognized as an important resource and provides benefits for the community and the environment by: increasing available water resources, returning critical environmental flows to failing waterways, and decreasing nutrient and contaminant load pumped to surface and coastal waters.

Table 1. Water consumption (GL) in Australian major sectors and States/Territories 2008-09

State or Territory		Agriculture	Forestry and fishing	Mining	Manufacturing	Electricity and gas	Water supply and waste	Other industries	Household
2008-09	NSW	2 001	1	66	150	92	1 329	387	536
	Vic.	1 435	1	6	158	123	558	367	342
	Qld.	2 144	6	118	148	82	297	249	308
	SA	788	2	22	88	2	64	79	122
	WA	325	89	257	61	27	111	176	326
	Tas.	264	3	18	50	-	22	30	69
	NT.	35	-	21	22	1	9	27	39
	ACT	2	-	-	-	-	7	11	27
Aust.	2000-01	14 989	40	321	549	255	2 165	1 106	2 278
	2004-05	12 191	47	413	589	271	2 083	1 063	2 108
	2008-09	6 996	101	508	677	328	2 396	2 108	1 768

Source: Australian Bureau of Statistics (ABS), 2010a

Table 2. Water consumption in the Australian agriculture industry 2008-09

	NSW ML	Vic. ML	Qld. ML	SA ML	WA ML	Tas. ML	NT ML	ACT ML	Total ML
Nursery & Floriculture	16 584	14 345	10 358	3 819	10 658	1 249	373	1 104	58 490
Mushroom & vegetable growing	70 001	81 787	87 878	95 621	61 397	30 896	4 175	26	431 782
Fruit and tree nut growing	229 944	329 071	147 374	270 544	55 592	7 176	7 755	154	1 047 610
Sheep, beef cattle and grains	848 754	291 778	539 343	260 247	112 964	100 911	22 621	246	2 176 863
Other crop growing	618 967	17 324	1 229 013	17 648	15 273	1 989	417	233	1 900 863
Dairy cattle farming	178 627	672 686	104 898	125 023	62 594	119 048	-	3	1 262 879
Poultry farming	11 297	4322	4 538	1 897	1 497	360	4	26	23 940
Deer farming	13	327	-	201	52	35	-	-	630
Other livestock farming	27 275	23 761	20 798	13 324	4 744	2 783	36	2	92 724
Total	2 001 462	1 435 401	2 144 201	788 326	324 771	264 446	35 380	1 793	6 995 781

Source: Australian Bureau of Statistics (ABS), 2010a

Table 3. Effluent generated and reused in Australia

Region	2001-02			2004-05		
	Effluent GL/year	Reuse GL/year	% Reuse	Waste water discharged GL/year	Water collected for reuse GL/yr	% Reuse
NSW	694	61.5	8.9	636	53	7.7
Vic.	448	30.1	6.7	385	70	15.0
Qld.	339^{C}	38^{C}	11.2	310	45	12.7
SA	101	15.2	15.1	84	20	19.2
WA	126	12.7	10.0	124	15	10.8
Tas.	65	6.2	9.5	58	5	7.9
NT.	21	1.1	5.2	13	2	13.3
ACT	30	1.7	5.6	27	2	6.9
Total	1824	166.5	9.1	1634	212	11.5

Source: Radcliffe (2004); Australian Bureau of Statistics (ABS), 2006

Reclaimed water: its origins and use

'Treated' sewage water (commonly known as wastewater, recycled water, or reclaimed water) has been under-utilized in Australia, although increase in its reuse has been seen since mid-nineties (ABS, 2004; Anderson and Davis, 2006). The Australian Bureau of Statistics collects information about the patterns of recycled water in Australia and uses the term 're-use water' to describe water that has been recycled from sewerage, stormwater or other effluents. There has been a steady increase in the volume of water reuse in agriculture and, currently, around 11.5% of total wastewater generated is reused (ABS, 2000; ABS, 2004; ABS, 2010a) (Table 3).

Extent of treatment which the reclaimed water undergoes before it is supplied is dependent on the proposed end-use; the most stringent requirements apply when people are likely to come in direct contact with water. Reclaimed wastewater is currently not recycled to provide a potable resource; there are a number of residential developments that have adopted a dual reticulated-system, whereby, high-quality recycled water is provided in a second pipeline for toilet flushing and garden irrigation. A majority of the recycled water is used as a non-potable resource for agriculture, dual reticulated systems, for irrigation of community sports-grounds, parks and gardens, and to supply to the industry (ABS, 2010a). Figure 2 shows distribution of reuse water-consumption across the Australian economy in 2008-09; agriculture used the largest amount at 103 GL, just under one third of the total supplied (ABS, 2010a). However, this represents only 1% of the total volume of water used by the agricultural sector (ABS, 2010a).

Figure 3 shows both distribution of reuse water-consumption in the agricultural sector and reuse water-consumption as percentage of total water-use for each enterprise-type. While beef, sheep and grain production use the largest volume of reuse water, this amounts to just 1% of the industries' total water-use (ABS, 2010a). Fruits production and floriculture use the greatest amount as a proportion of their total water-use (10%), followed by vegetable and mushroom production (4%). This may be a reflection of the relative proximity of these industries to major waste-water treatment plants which supply a majority of the reuse-water and are located close to densely populated urban areas; in 2008-09, nearly two-thirds of reuse water was supplied by major urban water providers that had at least 50,000 connections (ABS, 2010a).

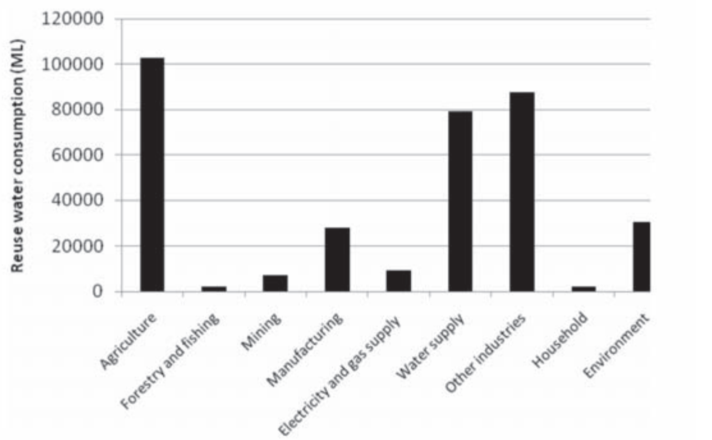

Fig 2. Reuse water consumption by major sectors in Australia (Source: Australian Bureau of Statistics, 2010a)

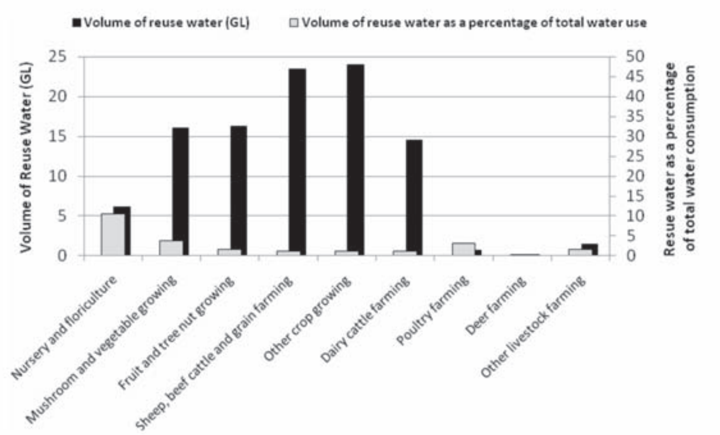

Fig 3. Reuse water consumption within the Australian agricultural sector and as percentage of total water consumption (Source: Australian Bureau of Statistics, 2010a)

WASTEWATER TREATMENT AND PUBLIC HEALTH

Hazards in reclaimed water

Untreated wastewater, or sewage, originates from domestic households, commercial premises and industrial activities. It does not include stormwater which is the rainfall run-off from sealed surfaces, including roofs and roads. It typically consists of 99.9% water and 0.1% impurities which include: dissolved and suspended organics, pathogens, nutrients, trace elements, salts, refractory organics, priority pollutants and heavy metals (Dinesh *et al*, 2006). As an irrigation source for edible crops, some of these contaminants either present a risk to human health or a hazard to soil, plants and water resources. Table 4 provides an outline of chemical and biological content of untreated wastewater and summarises hazards associated with each contaminant.

Varying degrees of treatment can be applied to remove or reduce these contaminants in wastewater. The aim of wastewater treatment is to produce water fit for the purpose, i.e., when used as intended, will not threaten human health or degrade the receiving environment. The extent of treatment required is usually regulated by Public Health or Environmental Protection Authorities.

Governance of reclaimed water-use

Regulations governing use of reclaimed water are not uniform throughout Australia; each state and territory has the responsibility of managing natural resources and public health in its jurisdiction. Legislation for wastewater reuse is covered by acts relating to food safety, public health and/or environment protection. As such, with the state Public Health Authority and /or Environmental Protection Agency rests the responsibility of policing reclaimed-water reuse.

Many states require enterprises which practice irrigation with reclaimed wastewater, or supply reclaimed wastewater for the purpose of irrigation, to produce and adhere to environmental (irrigation) management plans and/ or user agreements. The plans should include a study of irrigation-site characteristics and specify how the wastewater will be applied, so that its use will not threaten human health or adversely impact the receiving environment. The need for user-agreements, to ensure utilization of the wastewater in an approved manner, varies across jurisdictions as do requirements for ongoing monitoring, audits and reviews. Extent of the relevant authorities' ongoing involvement in a scheme depends on size, the risk associated with reuse and sensitivity of the receiving area.

Quality requirements for reclaimed-water irrigation of edible crops

Currently, each state authority holds the responsibility for defining quality of the water that can be used to irrigate fruits/vegetables; guidelines for reclaimed-water use exist in each state and territory (Power, 2010). Recycled-water guidelines set targets for removal of pathogens, nutrients, toxicants and salts. Health-based targets receive the greatest emphasis, and microbial contaminants present the greatest risk to human health; studies have shown that in achieving targets for pathogen removal, chemical hazards that threaten human health are also reduced to acceptable levels. Analyses of treated-reclaimed water in two major schemes in Australia indicated that chemical quality of the reclaimed water was generally consistent with requirements of Australian Drinking Water Guidelines (NRMMCEP and HCAHMC, 2006). Values above the levels in these Guidelines were deemed acceptable because of the lower exposure inherent in consuming irrigated-produce compared to drinking-water (NRMMCEP and HCAHMC, 2006).

Both the National and State guidelines for recycled water use were, until recent times, centered around matching defined classes of water (based largely on their pathogen burden, biochemical oxygen demand and turbidity), with pre-approved uses. The highest quality A+ recycled water could be used in residential dual reticulation systems and the lowest classes, C or D, could only be used for irrigation of non-food crops, e.g. instant turf, woodlots, flowers. Table 5 provides examples of the water-classes.

Risk-assessment based framework for reclaimed water quality – a new approach

In 2006, in the face of increasing pressure on freshwater resources, National Water Quality Management Strategy-*Australian Guidelines for Water Recycling: Managing Health and Environmental Risks* (AGWR) was released (NRMMCEP and HCAHMC, 2006). The AGWR was produced in an effort to establish consistent standards for reclaimed water schemes across the country and, to introduce the risk management framework promoted by the *World Health Organization's Guidelines for Drinking-water Quality* (WHO, 2008).

The AGWR does away with the class-based system and advocates a risk-assessment based approach. Each scheme is individually assessed; water quality targets, treatment processes and additional preventative measures are tailored to produce a safety level consistent with proposed end-use of the reclaimed water. The emphasis is no longer on end-of-line testing, but on developing a multi-barrier approach, to reduce the risk to an acceptable level known as "tolerable risk".

To carry out risk-assessment, all the hazards involved in generating and using reclaimed water through a proposed scheme are identified. An assessment of the likelihood of each hazard occurring is made and its potential impact

Table 4. Summary of hazardous contaminants in untreated wastewater

Contaminant	Potential hazard	Routine measurement	Range of values in untreated wastewater
Solids – suspended, colloidal and particulate organic solids	● Shield microbes from disinfection ● Organic contaminants and heavy metals adsorb onto particulates ● Clog irrigation systems	Suspended solids (SS) mg/L	
Biodegradable dissolved organics	● Proteins, fats, carbohydrates represent a biologica oxygen demand (BOD) which can deplete oxygen and lead to putrefaction ● Interferes with disinfection processes and can facilitate formation of disinfection by-products	Biological oxygen demand (BOD) mg/L	230-450
Stable organics	● Organics which are not susceptible to standard wastewater treatment processes can impact environmental health, be carcinogenic or cause endocrine disruption in endpoints further along the food chain. Examples are: pesticides, chlorinated hydrocarbons, refractory organics & pharmaceutical products.		
Priority pollutants	● Known or suspected carcinogens, mutagens, teratogens or acutely toxic pollutants		
Salinity – dissolved inorganic elements	● Include salts such as sodium, calcium, magnesium, potassium, boron, bicarbonate, chloride & sulfate ● Chloride, sodium & boron are phytotoxic ● Reduces in yield, induces foliar injury ● Increases hardness and likelihood of scale or corrosive damage to distribution systems and irrigation equipment	Total dissolved solids (TDS) mg/L	500-1500
Nutrients - Nitrogen and phosphorus	● Excessive nutrient loading can leach into groundwater or reach surface waters ● Can cause plant damage if applied inappropriately	Total nitrogen (TN) mg/L	35-75
		Total phosphorus (TP) mg/L	10-30
Heavy metals/ micronutrients - Nickel, copper, iron, chromium, manganese, lead, mercury & zinc	● Excessive quantities can be toxic to plants, soil flora and animals. These can accumulate in soil, ground water, plants and be present in produce destined for human consumption	Find example trigger values	
Pathogens	● Disease can be transmitted through exposure to pathogens, particularly by ingestion ● Bacteria (*E. coli*, *Salmonella*, *Shigella*, *Vibrio cholera*) Protozoa (*Cryptosporidium parvum*, *E. hystolytica*, *Giardia lamblia*) ● Helminths (*Ascaris lumbricoides*, *Taenia spp.*) ● Viruses (*Hepatitis A*, Enteroviruses) ● Helminths in reclaimed water can be transmitted by meat to humans	*Escherichia coli (E. coli)* No./100mL	10^4-10^9
		Cryptosporidium No./L	0.85 x 10^3 to 1.4 x 10^3
		Giardia No./L	0.8 x 10^3 to 3.2 x 10^3
		Viruses No./L	5-10^5

Source: Stevens D (2006); Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (2000)

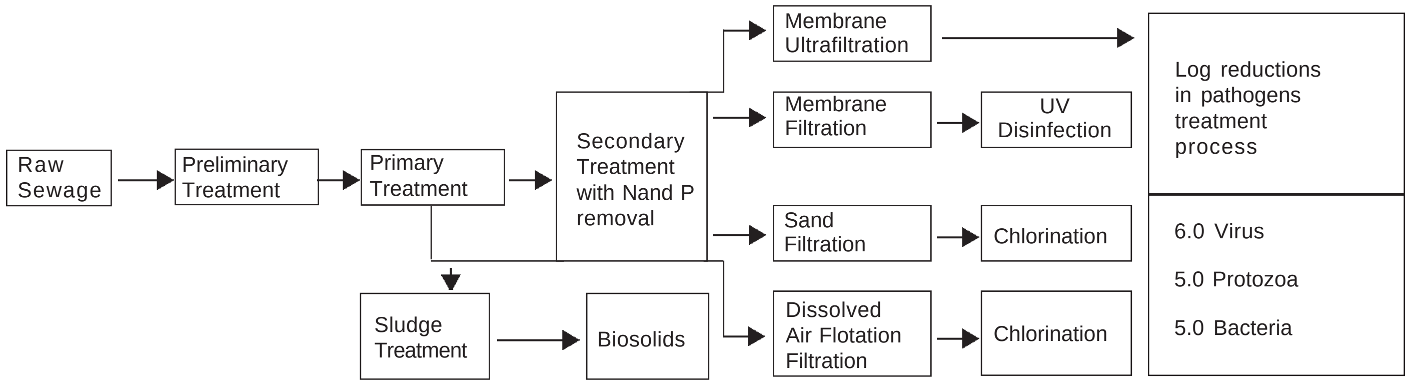

Fig 4.Typical process-train for treatment of wastewater to acceptable quality for irrigation of produce consumed raw (Source: Dinesh *et al,* 2006)

Table 5. Water quality standards and applications for water Classes A-D in South Australia

Class	Application	Microbiological criteria	Chemical/Physical criteria
A	Primary Contact recreation Residential non-potable Unrestricted crop irrigation Dust suppression with unrestricted access Municipal use with public access	<10 *E. coli*/100mL Specific removal of viruses, protozoa and helminths may be required	Turbidity ≤2 NTUBOD <20mg/L Chemical content to match use
B	Secondary Contact recreation Restricted crop irrigation Irrigation of pasture and fodder for grazing animals Dust suppression with restricted access Municipal use with restricted access	<100 *E. coli*/100mL Specific removal of viruses, protozoa and helminths may be required	BOD <20mg/LSS <30mg/L Chemical content to match use
C	Passive recreation Municipal use with restricted access Restricted crop irrigation Irrigation of pasture and fodder for grazing animals	<1000 *E. coli*/100mL Specific removal of viruses, protozoa and helminths may be required	BOD <20mg/LSS <30mg/L Chemical content to match use
D	Restricted crop irrigation Irrigation for turf production Silviculture	<10 000 *E. coli*/100mL helminths may need to be considered for pasture and fodder	Chemical content to match use

Source: DOH&EPS SA (1999)

determined; if the resultant product of likelihood and impact are above tolerable levels of risk, then measures must be taken to reduce the risk to a tolerable level.

Risk assessment is carried out largely in relation to hazards to human health and, in this regard, microbial pathogens are the greatest threat (NRMMCEP & HCAHMC, 2006). The AGWR national guidelines are not mandatory, and several states have elected not to adopt the new approach at this point in time (Power, 2010). Table 6 summarizes water-quality targets in each state for reclaimed-water use on produce that may be consumed raw and, an intermediate quality of reclaimed water which requires some additional precautions. The general requirements are very similar throughout various jurisdictions.

From sewerage to sustainable irrigation source: the treatment process

Wastewater reclamation processes are traditionally broken down into preliminary, primary, secondary and tertiary treatment processes, though, it is possible to find a significant overlap at wastewater treatment plants (Figure 4).

- At the ***preliminary stage***, large debris and finer abrasive material are removed to prevent damage to downstream equipment.
- ***Primary processes*** are predominantly physical. Sedimentation is used to remove approximately 65% of the solid content of raw sewage, and approximately 35% of the Biochemical Oxygen Demand (BOD). Sedimentation also removes a proportion of the heavy metals which, being cations, bind to negatively charged organic matter and clay particles. Fifty to ninety percent of parasitic eggs and 25% of bacteria can also be removed at this stage.
- ***Secondary processes*** are biological. Bacteria remove soluble and colloidal wastes by assimilating organic matter, to form new microbial biomass, and by producing gas through the use of organic matter for endogenous respiration. Microbial mass (including the assimilated organic matter) is removed by

sedimentation. This biological removal takes place in lagoons & wetlands, trickling filters and activated sludge. Biological Nutrient Removal (BNR) can be incorporated into the activated sludge process; cycles of anaerobic and aerobic conditions maximize removal of phosphate by poly-P accumulating organisms and enhance nitrogen removal by nitrification-denitrification.

- ***Tertiary processes*** such as nutrient removal, filtration and disinfection are employed as an additional step

Table 6. Water quality objectives for irrigation with reclaimed wastewater

Jurisdiction	Water quality objectives for irrigation of produce that can be consumed raw	Parameters given for irrigation of produce requiring addition of on-site preventative measure
Australia *Australian Guidelines for Water Recycling* (NRMMCEP and HCAHMC, 2006)	● To be determined on a case by-case basis, depending on technology ● Could include turbidity and disinfection criteria ● *E. coli* <1 per 100ml	● BOD <20mg/l ● SS<30mg/l ● Disinfectant residual (eg. minimum chlorine residual) or UV dose ● *E. coli* less than 100cfu/100ml
South Australia, Victoria *South Australian Reclaimed Water Guidelines – Treated Effluent* (SA EPA 1999); *Guidelines for Environmental Management: Use of Reclaimed Water* (EPA Victoria, 2003)	● Have adopted AGWR risk assessment approach; These systems are assessed on a case by case basis	● ***South Australia*** ● <100 *E. coli* /100ml ● <20 mg/l BOD ● <30mg/l SS ● Chemical content to match use ● Specific removal of viruses, helminths and protozoa may be required ● ***Victoria*** ● < 100 *E. coli*/ 100ml ● pH: 6-9 ● <20/30 mg/l BOD/SS
New South Wales, Northern Territory, Western Australia Interim NSW Guidelines for Management of Private Recycled Water Schemes (Department of Water and Energy NSW, 2008); *Guidelines for Management of Recycled Water Systems* (DH & FNT, 2009); *Guidelines for the Use of Recycled Water in Western Australia* (WA DoH, 2009)	● *E. coli* : <1 cfu/100ml ● Turbidity <2 NTU (95% ile) ● <5 NTU (maximum ● pH: 6.5-8.5 ● Disinfection: Cl 0.2-2mg/l residual ● UV: to be announced ● Ozone: TBA	● *E. coli*: <10cfu/100ml ● Turbidity: <5 NTU (95% ile) ● pH: 6.5-8.5 ● Disinfection: Cl 0.2-2mg/l residual ● UV: to be announced ● Ozone: TBA
Tasmania *Environmental Guidelines for the Use of Recycled Water in Tasmania* (Tasmanian Department of Primary Industries, Water and Environment, 2002)	● Median value of <10 thermotolerant coliforms per 100ml ● pH: 5.5-8.0 ● BOD <10mg/l ● Nutrient, toxicant and salinity controls	● median value of < 1,000 thermotolerant coliforms per 100ml ● pH 5.5 – 8.0 ● BOD < 50mg/l ● Nutrient, toxicant and salinity controls
ACT Wastewater Environment Protection Policy *Wastewater Reuse for Irrigation - Environment Protection Policy* (Environment ACT, 1999)	● Thermotolerant coliforms – median value of < 10 cfu/100ml ● Disinfection: ≥ 1mg/l chlorine residual after 30 minutes or equivalent level of pathogen reduction ● pH 6.6 – 8.0 (90% compliance) ● Turbidity: ≤2NTU	● Thermotolerant coliforms – median value of <1000 cfu/ 100ml ● Biological Oxygen Demand/ Suspended Solids monitoring ● pH: 6.5- 8.0 (90% compliance)
WHO *Guidelines for Drinking-water Quality. Third edition incorporating the first and second addenda, Vol. 1, Recommendations* (World Health Organization, 2008)	Provide an overview on how to set up a regulatory framework; these are not regulations by themselves	

to achieve sufficient removal of coliforms, parasites, salts, trace organics and heavy metals to make the water suitable for unrestricted irrigation of food crops. These steps can be carried out concomitantly with the earlier processes, for example: BNR, or employed as additional stages.

- Nutrient removal through precipitation (as in the case of P) and gaseous emission (as in the case of N, though denitrification)
- Filtration facilitates finer scale solid-removal, further reducing turbidity and pathogen numbers. The capacity for removing undesirable components increases with finer filtration systems, but it also carries increasing cost.
- Disinfection by UV light, chlorine, lagoons or ozone reduces the number of pathogens present in the waste stream by inactivation.

KEY ENVIRONMENTAL HAZARDS

Contaminants in reclaimed water that present greatest risk to the receiving environment include. boron, cadmium, chlorine disinfection residuals, nitrogen, phosphorus, sodium and chloride. Each of these hazards, and the emerging area of organic contaminants, are discussed below.

Nutrients

Human and domestic wastes contribute large amounts of nitrogen and phosphorus to sewage. Only 50% of the nitrogen and 60% of the phosphorus are removed during treatment, so, concentration of these major nutrients is still high in treated sewage than in irrigation water from other sources (Kelly *et al*, 2006). Residual levels of nutrients in treated wastewater can be of great benefit to irrigators. Recycled wastewater has been shown to produce increased crop yields compared with traditional fertilizer application in vines, lettuce and celery (Sheikh *et al*, 1998). Kelly *et al* (2006) explain that plants grow best when nutrient concentration at the root surface is maintained close to the plant uptake rate. Reclaimed water may better meet crop nutrient requirements because rate of irrigation is directly related to evapo-transpiration which increases with crop leaf area.

While the use of treated wastewater can benefit crop nutrient management, applying it in excess can be detrimental to both the crop and local environment. Nutrient load supplied to a crop is determined by nutrient concentration of the reclaimed water and irrigation depth (which is usually in the range of 300mm to 1000mm in Australia) (Kelly *et al*, 2006). Table 7 outlines macronutrient uptake of a range of vegetables and nutrient load supplied by an irrigation depth of 1000mm from wastewater treated to the tertiary level; data demonstrate that at this level of irrigation, some nutrients would be supplied in excess of requirement, thereby likely resulting in loss of nutrients through leaching and surface runoff.

Nitrate is the most mobile form of nitrogen in soil and can be subject to leaching if nitrate and water are applied in excess of the plant's needs. This is a particular risk in colder, wetter seasons where plant growth is slow (Kelly *et al*, 2006) Nitrate can reach surface waters through run-off, contaminate ground water and impact public health if the water is used as a potable resource; it can potentially cause eutrophication of groundwater dependent ecosystems.

Australia has some of the oldest and least fertile soils in the world; therefore, P in the waste water is generally of great benefit to crops here. Reclaimed wastewater typically contains less than 3mg/L of soluble P, which is rapidly adsorbed onto soil particles after irrigation (Kelly *et al*, 2006). When plant demand is low, P accumulation and immobilization in the soil is more likely than leaching or over-fertilization; an exception is sandy soils, where there is some risk of leaching off (Kelly *et al*, 2006). The main concerns associated with phosphorus are its potential toxicity to Australian natives who have evolved on our low P soils, and the run-off or accidental discharges to water bodies leading to eutrophication (NRMMCEP and HCAHMC, 2006).

To prevent excess nutrients from negatively impacting the land and associated ecosystems, several states mandate that nutrient budgets, particularly for nitrogen and phosphorus, be constructed as part of irrigation management

Table 7. Crop macronutrient uptake and supply in reclaimed water (kg/ha)

Crop	Typical yield (t/ha)	Nutrient content (kg/ha) N	P	K	Ca	Mg
Cabbage	50	147	24	147	36	13
Capsicum	20	41	4	69	52	7
Carrot	44	210	19	270	175	10
Cauliflower	50	181	28	225	127	18
Celery	190	308	97	700	290	38
Cucumber	18	66	12	120	34	8
Lettuce	50	100	18	180	10	3
Potato	40	264	23	310	66	21
Tomato	194	572	133	856	348	87
Reclaimed water[A]	1000mm	82	11.5	468	399	308

A - Nutrients applied in 1000mm from Virginia Pipeline Scheme, South Australia

Source: Kelly *et al* (2006)

plans ((DoH and EPA SA, 1999). The nutrient input should be equal to crop requirement; this mass-balance approach must also take into account the effect of water-use efficiency, leaching rate and nutrient losses from soil and water (Kelly *et al*, 2006). These calculations are further complicated by the fact that crop water requirements may not always match crop nutrient requirements, and the depth of irrigation may vary with season. If mass-balance of nutrients cannot be demonstrated, a monitoring programme must account for the fate of nutrients (DoH and EPA SA, 1999).

Heavy metals and Metalloids

Most heavy metals and metalloids are very effectively removed from wastewater in the treatment process such that their levels are very low in the reclaimed water. Boron and cadmium are the only two heavy metals included in the list of key environmental hazards in the current Australian Guidelines for Water Recycling - they are not as readily separated from reclaimed water during standard treatment (NRMMCEP and HCAHMC, 2006).

Metals get partitioned to the biosolids formed during sedimentation processes, because their cationic nature causes them to sorb strongly to negatively-charged organic matter and clays (Bolan *et al*, 2003; Stevens and McLaughlin, 2006). Arsenic, which exists as an oxyanion, partition to biosolids through binding to iron or aluminium oxide in sludges; Molybdenum and Selenium exhibit this behaviour to a lesser extent and should be treated with some caution (Stevens and McLaughlin, 2006).

At low levels, some heavy metals are considered as micronutrients; but, above the plant requirement, foliar application can produce phytotoxicity (Bolan *et al*, 2011a). By virtue of their persistent nature they can also accumulate in the soil, thereby resulting in soil biota toxicity, phytotoxicity through root uptake and entry into the food chain, leading to negative impact on food quality and human health. The trigger values and cumulative contaminant loading in soil in the Australian and New Zealand Guidelines for Fresh and Marine Water, shown in Table 8, were determined with an aim of preventing these detrimental impacts (ANZECC and ARMCANZ, 2000).

Table 8. Contaminant guidelines for metals and metalloids in irrigation water

Element	ANZECC and ARMCANZ (2000)			Australian Drinking Water Guidelines Health (mg/L)
	Cumulative loading limit (kg/ha)	Long-term trigger value (mg/L)	Short-term trigger value (mg/L)	
Aluminium	-	5	20	0.2
Arsenic	20	0.1	2.0	0.007
Boron	-	0.5	0.5-0.15	0.3
Cadmium	2	0.01	0.05	0.002
Chromium-(VI)	-	0.1	1	0.05
Cobalt	-	0.05	0.1	-
Copper	140	0.2	5	2.0
Fluoride	-	1	2	1.5
Iron	-	0.2	10	-
Lead	260	2	5	0.01
Lithium		2.5	2.5	-
Manganese	-	0.2	10	0.5
Mercury	2	0.002	0.002	0.001
Molybdenum	-	0.01	0.05	0.05
Nickel	85	0.2	2	0.02
Selenium	10	0.02	0.05	0.01
Uranium	-	0.01	0.1	-
Vanadium	-	0.1	0.5	-
Zinc	300	2	5	-

Source: NRMMCEP AND HCAHMC (2006)

Boron

Boron (B) in wastewater originates principally from household water softeners and cleaners as sodium perborate; its presence in waste water can be reduced to negligible level if B use in detergents is phased out (NRMMCEP and HCAHMC, 2006). Boron is not retained in biosolids because it exists as an uncharged species within the normal pH range of wastewater and, thus, remains in the reclaimed water (Page and Chang, 1985). Boron is a micronutrient at very low levels; it has a narrow safety margin and if leaching fractions are insufficient, it can accumulate in the soil profile and cause reduction in yield and also phytotoxicity in sensitive species (Unkovich *et al*, 2006). Toxicity initially presents in older leaves as yellow and brown speckling pattern between leaf veins and leaf edges (Bolan *et al*, 2011a; Bennett, 1994).

Boron can theoretically be managed by leaching it out from the soil; however, it is often absorbed onto soil particles. Dudley (1994) found that three times more water was required to leach out B than Na^+ or Cl^-. Any deterioration in soil structure would impede this process. An alternative to leaching is to grow crop species more tolerant to boron.

Cadmium

Cadmium (Cd) presents the highest health-risk of all heavy metals in reclaimed water; it is loosely bound to soil and causes phytotoxicity at relatively low levels; it is a particular threat to humans and animals because toxicity occurs at a threshold lower than for plants. Consequently, there are national and international schemes to monitor Cd concentration in foods (Naidu *et al*, 1997; Stevens and McLaughlin, 2006).

Improvement in the quality of trade wastes has lowered Cd level in sewage (Oliver *et al*, 2005) such that the current Australian Guidelines for Recycled Water considers that low risk is associated with level of Cd in reclaimed water (NRMMCEP and HCAHMC, 2006). Rather, greater risk is associated with Cd already present in soils (commonly from historical use of superphosphate containing Cd) displaying increased mobility in the presence of chloride in reclaimed water (Weggler *et al*, 2004; NRMMCEP and HCAHMC, 2006).

Maximum permissible level (MPC) of Cd in vegetables in Australia is 0.1mg Cd/kg fresh weight for root, tuber and leafy vegetables (Warne *et al*, 2007). Potatoes are of particular concern because they have been shown to contribute more than half the dietary intake of Cd (Stenhouse, 1992; McLaughlin *et al*, 1994). Probability of potatoes having Cd levels above MPC increases when the irrigation source has salinity levels greater than 2.0 dS/m. Growers are advised to use irrigation water with lower salinity level (Warne *et al*, 2007; McLauglin *et al*, 1994).

Organic contaminants

Three main groups of organic contaminants are found in reclaimed wastewater (Ying, 2006; Mueller *et al*, 2007)

- Natural organic matter (NOM) consisting of refractory molecules like fulvic and humic acids
- Disinfection by-products formed during chlorination
- Synthetic organic compounds including pesticides, organohalothanes, pthalates, aromatic hydrocarbons, surfactants, endocrine disruptors, pharmaceuticals and personal care products

The fraction of NOM present in reclaimed water that can be readily degraded is a function of treatment technology (Ying, 2006); more stringent the technology, smaller the fraction of NOM that remains after treatment. Fulvic and humic acids are believed to be formed from breakdown of organic matter and are somewhat resistant to microbial breakdown (Bolan *et al*, 2011b). Although NOM can induce putrefaction in stored reclaimed water (by depleting oxygen), there is little concern regarding discharge of NOM onto agricultural land because it should eventually get broken down by natural microbial populations (Ying 2006). Where chlorine disinfection is used NOM, contributes to formation of chlorine disinfection by-products (Singer, 1999) and increases the amount of chlorine required for disinfection - this warrants maximising its removal by filtration.

Disinfection by-products (DBP) can be formed by reaction of chlorine with NOM (Singer 1999). Trihalomethanes are the most well known of the DBPs. They have been shown to be carcinogenic in animals at high doses and are implicated in a form of bladder neoplasia in humans (Singer, 1999; Villanueva *et al*, 2007). Chloramination is another chemical disinfection process; it can trigger formation of N-Nitrosodimethylamine which has been demonstrated to be carcinogenic, mutagenic and clastogenic (Kim and Clevenger, 2007).

Synthetic organic compounds represent a wide range of chemicals. Some are susceptible to wastewater treatment processes, while others fall into the group of stable organics that may remain in very small amounts in reclaimed water. Many have been implicated to be endocrine disrupting chemicals (EDCs) which interfere with normal hormone communication systems; they impact adversely growth, reproduction and development (EPA SA, 2008). There is limited data on their presence in wastewater, and due to their potential to cause adverse environmental and human health impacts, further monitoring and research is warranted (Holmes *et al*, 2010).

Chlorine residuals

When disinfecting water, if sufficient dose of chlorine is administered, a small amount of this chemical may remain after the disinfection process is over. This residual chlorine provides ongoing disinfection whilst the treated water is in storage or in transit in the distribution system. While this prevents pathogens from multiplying to dangerous levels and from biofilms developing within the infrastructure, chlorine-residues can harm terrestrial or aquatic ecosystems (NRMMCEP and HCAHMC, 2006).

Chlorine is phytotoxic and has been shown to produce chlorosis and reduce weight in geranium and begonias at 2mg/L, and in peppers and tomatoes at 8mg/L (NRMMCEP and HCAHMC, 2006). Current Australian Guidelines for Water Recycling suggest that levels below 1mg/L chlorine can be considered as low risk for irrigation, while levels between 1-5mg/L should pose little risk for most crops. As the target level of free chlorine post- disinfection is 1.5mg/L-with a critical limit of 2mg/L (NRMMCEP and HCAHMC, 2006) well managed disinfection processes are not likely to generate chlorine levels that present unacceptable hazard for irrigation. Aquatic organisms are far more sensitive to chlorine and, although discharge to water bodies produces a diluting effect, chronic effects of chlorine residuals must be considered and this practice should be avoided by irrigators.

Salinity and Sodicity

Soil salinity and sodicity result from excess of salts and imbalance of type of salt in the soil profile, respectively.

Irrigating with reclaimed water carries the risk of inducing soil salinity and/or sodicity, because, reclaimed water often contains high levels of salts, in particular sodium (Rengasamy, 2006). The salts enter wastewater streams from drinking water, detergents, water softeners, residential kitchens and industrial wastes (NRMMCEP and HCAHMC, 2006). Soil salinity is encountered when elevated concentration of soluble salts in the soil-water solution induces osmotic stress in the vegetation. Sodicity is an increase in the proportion of sodium relative to divalent cations and adversely affects soil structure.

Salinity

Managing soil salinity has been identified as one of the most important area for developing a sustainable recycled-water scheme (Naidu and Sumner, 1998; Stevens *et al*, 2003). Salts that contribute to salinity include: Na^+, K^+, Ca^{2+}, Cl^-, Mg^{2+}, SO_4^{2-} and HCO_3^-; but sodium and chloride ions exert the greatest environmental impact because their solubility in water renders them more available for interactions in soil (NRMMCEP and HCAHMC, 2006).

Salinity is measured by either electrical conductance (EC) in deciSiemen per metre (dS/m) or total dissolved salts (TDS) in mg/L. Reclaimed wastewater can have TDS values ranging from 200mg/L to 3000mg/L (Table 9) (Feigin *et al*, 1991). Reclaimed water can induce soil salinity when salts become concentrated in the soil through evaporation, the principle signs of which relate to osmotic stress. At high enough level, individual ions can directly induce toxicity.

Salinity reduces plant growth because increased osmolarity makes it difficult for plants to absorb water and nutrients. In response to reduced water uptake, plants produce the hormone abscisic acid which signals stomata to close, reducing transpiration water losses. Consequently, carbon dioxide absorption is reduced and photosynthesis slows down leading to diminished plant growth (Hartung and Davies, 1994).

Table 9. Irrigation water salinity ratings based on electrical conductivity

EC (dS/m)	Approximate TDS (mg/L)[a]	Water Salinity Rating	Plant suitability
<0.65	<390	Very low	Sensitive crops
0.65 - 1.3	390-780	Low	Moderately sensitive crops
1.3 - 2.9	780-1740	Medium	Moderately tolerant crops
2.9 - 5.2	1740-3120	High	Tolerant crops
5.2 - 8.1	3120-4860	Very High	Very tolerant crops
>8.1	>4860	Extreme	Generally too saline

Source: Reid and Sarkis (2006)

By virtue of their free-draining nature, sandy soils are less prone to developing soil salinity than soils with high clay content; in sandy soils, the saline solution leaches through the soil profile, and is less susceptible to evaporative concentration. Table 10 provides root-zone salinity tolerance of a range of vegetables.

In relation to plants' comparative sensitivity to salinity, Unkovich *et al* (2006) put forward the following generalities:

- Vegetable crops are most sensitive to salinity
- Woody crops are generally very sensitive to salinity; however, saline-tolerant rootstocks are available and can be used to improve salinity tolerance
- Sensitivity to salinity increases with clay content
- For some species, sensitivity to salinity increases on foliar contact with irrigation water

To prevent salt accumulation, a leaching fraction must be incorporated into the crop's irrigation requirements to drive salts below the root zone. However, the given climatic variations in rainfall and evaporation throughout the year, supplying correct leaching volumes can be difficult. Maintaining the soil structure such that the leaching fraction can permeate various soil layers is also critical, and this is further complicated by sodicity (see below).

While it is possible to 'store' salts in the space between root zone and the water table, this is not a long-term solution and it is likely that the leached salt will ultimately reach groundwater. In cases where the ground water is already saline, there is little impact. Salinisation of a potable groundwater source can impact drinking water supplies or reduce suitability of that water-source for irrigation. These threats can be minimized by choosing a site where the underlying groundwater will not be affected by addition of salt. Monitoring of the groundwater may be required if the resource is sensitive (DoH and EPA SA, 1999).

There is some danger in incorporating a leaching fraction into irrigation requirements because Australia has large areas of land susceptible to anthropogenic induced (secondary) salinity through rising water tables. Salt has accumulated in our landscape largely though thousands of years of rainfall-evaporation cycles (Dimmock *et al*, 1974). Historically, in the presence of deep-rooted native plants, salt accumulated either below the root zone or made its way into groundwater (which gradually became saline). The comparatively shallow roots of horticultural crops have a lower capacity to intercept and use water percolating through the soil profile, thereby allowing greater volume of water to recharge the water table. This movement of water

Table 10. Root-zone salinity tolerance in some vegetables and in grape

Common name	Scientific name	Mean root salinity tolerance (EC_e dS/m)	Maximum irrigation water salinity before yield loss (dS/m)			% Yield loss (dS EC_e)
			Sandy soil	Loamy soil	Clayey soil	
Asparagus	*Asparagus officinalis*	4.1	5.2	3.0	1.7	2.0
Bean	*Phaseolus vulgaris*	1.0	1.9	1.1	0.6	19.0
Broccoli	*Brassica oleracea*	2.8	3.3	2.8	1.6	9.2
Carrot	*Daucus carota*	1.0	3.3	1.2	0.7	14.0
Cucumber	*Cucumis sativus*	2.5	3.3	2.4	1.4	13.0
Grape	*Vitis spp.*	1.5	3.3	1.9	1.1	9.6
Lettuce	*Lactuca sativa*	1.3	3.3	1.5	0.9	13.0
Onion	*Allium cepa*	1.2	3.3	1.3	0.8	16.0
Bell Pepper	*Capsicum annuum*	1.5	3.3	1.6	0.9	14.0
Potato	*Solanum tuberosum*	1.7	3.2	1.8	1.1	12.0
Spinach	*Spinacia oleracea*	2.0	4.2	2.4	1.4	7.6
Tomato	*Lycopersicon esculentum*	2.3	3.5	2.0	1.2	9.9

Source: Unkovich *et al* (2006)

can mobilize salts accumulated below the root zone and induce rising water tables. Once the water table reaches within 2 meters of the surface, salts can move upwards through the soil profile by capillary forces (Ayers and Westcot, 1976). So, while saline reclaimed water can directly induce salinity or worsen pre-existing salinity, excess irrigation can also induce salinity through a rising water table.

Sodicity

Reclaimed waters frequently have higher levels of sodium ions compared to other cations and can induce sodicity or saline-sodicity (Bond, 1998). Sodium ions enter the soil as free sodium salts [sodium chloride (NaCl), sodium carbonate (Na_2CO_3), sodium bicarbonate ($NaHCO_3$) and sodium sulfate (Na_2SO_4); sodicity develops when free sodium ions bind to cation exchange sites on clays and, by this mechanism, remain in the soil while other free salts are leached downwards (Naidu and Sumner, 1998; Rengasamy, 2006). In situations where the other free salts remain, the soil is known as saline-sodic and the soil structure remains intact.

The extent to which sodium ions bind to cation exchange sites on a clay particle is determined by the ratio of sodium ions to calcium and magnesium ions in the soil solution. This can be expressed either as percentage of sodium which occupies the cation exchange capacity of clay- the Exchangable Sodium Percentage (ESP), or the ratio of sodium ions to calcium and magnesium ions in the soil solution the Sodium Adsorption Ratio (SAR). SAR is commonly used because it is easier to calculate for a soil solution (Naidu and Sumner, 1998). It is also used to assess sodicity of irrigation waters.

In Australia, water with SAR greater than 6 is considered to have a potential to cause sodicity; the SAR of recycled water is in the range of 2.6-20, with an average of 6 while the average salinity is 1.2 dS/m (NRMMCEP and HCAHMC, 2006).

Sodic soils have poor physical characteristics because the high levels of sodium interfere with structural integrity of clay particles when the soil is wetted (Laurenson *et al*, 2010). Normally, clay particles contribute to stabilization of soil aggregates which creates spaces within the soil matrix; spaces that can be occupied by water, air and roots - dispersion of clay particles destroys these aggregates and closes the soil matrix. As a consequence, sodic soils display the following characteristics and problems (Rengasamy, 2006):

- reduced porosity and permeability
- reduced infiltration and hydraulic connectivity
- surface-crust formation which impedes infiltration and promotes run-off and erosion
- difficult to cultivate
- an impediment to development of a root network and
- expose plant roots to anoxic or waterlogged conditions and slow the plant growth

Reduced drainage can also lead to further accumulation of salts through poor downward movement of irrigation water and evaporative concentration. Clays with low hydraulic connectivity are more prone to developing sodicity because these have a low leaching fraction (Rengasamy, 2006); these soils retain water in their profile which, if subjected to evaporation, leaves salts behind.

MANAGEMENT

Irrigation methods and management

When reclaimed water is used as an irrigation source, the crop irrigation requirement must be carefully calculated to avoid the effects of hydraulic loading, which include: waterlogging, poor crop-growth and health, mobilization of salts and contaminants, rising water tables and run-off (NRMMCEP and HCAHMC, 2006). Irrigation requirement is essentially the difference between crop water requirement and rainfall, but also must take into account seasonal changes in rainfall, homogeneity of water infiltration and leaching requirement (Christen *et al,* 2006). While leaching is often necessary to drive salts below the root-zone, it is important that it is not at the expense of a rising water table. A balance must be reached between the total water requirement of the crop and preserving normal hydrologic function. Regional and local groundwater levels should be monitored so that changes, if any, can be detected and managed appropriately.

Pathogen content of reclaimed water is often a limiting factor with regards to the irrigation method; for example, class A water can be applied to crops that are eaten raw by any irrigation method; water consistent with class B can only be used to irrigate such crops by furrow or dripper irrigation, and class C must be applied by sub-surface drippers. Furrow or flood irrigation has the advantage of being relatively inexpensive and low in manpower requirement but, unless it is well-designed and managed, infiltration can vary greatly throughout the irrigation space. Because sprinklers commonly apply water directly on foliage, their use on produce consumed raw is limited to class A water. Even with Class A water, direct ion toxicities (with saline-reclaimed water) and an increased propensity to develop fungal disease can be a concern with foliar application of water (Christen *et al,* 2006):

The most efficient system with the least environmental and human risk is generally considered to be drip irrigation (Christen *et al.* 2006). Although installation carries quite high overhead costs and dripper systems require the most maintenance, they provide the following benefits (Christen *et al.* 2006);

- limited contact of reclaimed water with workers and plants
- even distribution of water and the best control over application rate
- reduced risk of environmental impact – less likelihood of causing run-off besides less water-penetration past root-zone, if well managed

Downsides to the dripper systems are: a persistently wet area can develop around the dripper, leading to deep percolation; they are prone to clogging, and they require a filtration system (Christen *et al,* 2006). Table 11 outlines relative suitability of each system in relation to a range of parameters.

Best Practice Management

Best practice irrigation with reclaimed water cannot be achieved by a one-solution-fits-all approach because there are a multitude of variables that must be considered, and each enterprise is unique. Irrigation schemes using reclaimed water should be tailored to optimize the economic returns to the grower whilst also minimizing impact on the receiving environment. This can be best achieved by undertaking comprehensive risk assessment of the whole scheme and designing an Irrigation Management Plan to minimize the risk of adverse outcome.

South Australia has been a leader in reclaimed-water use; the guidelines *Wastewater irrigation management plan (WIMP) - a drafting guide for wastewater irrigators,* developed by South Australian Environmental Protection Agency (EPA SA, 2009) provide a framework for achieving the best practice. In summary, the guidelines recommend that an initial risk assessment should be carried out to identify potential hazards. The results provide an indication of the level of planning and management required and form the rationale behind the plan. Risk assessment should be based on potential health impacts, soil, site and wastewater characteristics, as follows:

- Soil properties examined should include: soil texture, top-soil depth, depth to drainage or root-impeding layers, infiltration rates, soil water-holding capacity and soil chemistry
- Site characterization must make assessment of topography, slope, soil homogeneity (to determine sampling intensity), history of waste storage or disposal on site, depth to ground water and seasonal or permanent water tables, areas of drainage hazard and separation distances from sensitive areas
- Wastewater analysis should describe reclaimed water with reference to: total solids, suspended and volatile solids, total P, inorganic P, total Kjeldahl N, NH_4^+-N, K, SO_4^{2-}, BOD, pH, electrical conductivity, SAR, Ca, Mg, organic C, Na and Zn
- Potential health impacts must be addressed with relevant state health authorities

Table 11. Advantages and disadvantages of three commonly used methods of irrigation

	Parameter	Irrigation method suitability		
		Drip	Sprinkler	Furrow
Irrigation system suitability based on salinity	*Salinity level TDS: mg/L*	*Suitability*		
	Low TDS <900	High	High	Medium
	Moderate TDS 900-2000	High	Medium	Medium
	High TDS 2000-3000	High	Low	Low
Risk associated with occupational exposure	*Exposure type*	*Risk Level*		
	Ingestion risk	Low	Medium	Medium
	Contact risk	Low	High	High
	Aerosol risk	Low	High	Low
Effect on irrigation equipment: risk of clogging precipitation & corrosion	*Water quality issue*	*Risk level*		
	High SS 100mg/L	Low	High	High
	High potential precipitates >100 mg/L $HCO3^-$	Low	Medium	High
	High biological activity > 10000 bacteria/L	Low	Medium	High
	pH<6 , >8	Low	Low	Medium
Risk of surface run-off	*Soil texture*	*Risk level run-off*		
	Sand	Low	Low	Low
	Loam	Low	Medium	Medium
	Clay	Low	High	High
Risk of deep percolation	*Soil texture*	*Risk Level deep percolation*		
	Sand	Medium	High	Extreme
	Loam	Low	Low	High
	Clay	Low	Low	Medium
Suitability of irrigation system based on soil type	*Soil texture*	*System Suitability*		
	Sand	Low	High	Not suitable
	Loam	High	Medium	High
	Clay	Medium	Low	Medium
Suitability of system for crop establishment	*Type of crop*	*Suitability for establishment*		
	Small-seeded crop	Low	High	Medium
	Large-seeded crop	Low	High	High
	Transplants or cuttings	High	Medium	Medium
Disease risk associated with irrigation method	*Crop type*	*Disease risk*		
	Large surface-area crops	Low	High	Medium
	Root crops	Low	Medium	Medium
	Cucurbits and tomatoes	Low	High	Medium
	Vines	Low	Medium	Medium

Source: Christen *et al* (2006)

Hazards identified through the risk assessment process and the corresponding risk minimization strategies form the backbone of a management plan. The EPA guidelines state that the plan should include (EPA SA, 2009):

- *Soil suitability or limits for wastewater irrigation, and any treatment necessary to improve the soil*
- *Constituents of the wastewater which would limit disposal to land and any strategy that will be employed to counteract the limiting effect, e.g. pretreatment*
- *Mass balance equations for hydraulic load, organics, nutrients and salts*
- *Suitable crops, including requirements to prevent accumulation of pollutants in the soil or crop*
- *Sustainable wastewater application rate to maximize plant nutrient assimilation and water efficiency*
- *A soil moisture monitoring system to schedule irrigation to crop moisture requirements*
- *An irrigation layout that allows different application rates to be delivered to soils with varying drainage capacities*
- *The human resources and training that will be required to operate and maintain the scheduling and monitoring equipment*
- *The capacity of the wastewater storage to cope with severe weather, particularly a 1:10 wet year or severe storm*

- *Potential long-term impact of the planned wastewater irrigation on soil structure or nutrient accumulation*

Additionally, a review-schedule for the management plan should be detailed, and an outline of the long-term management plan including expected timescale for accumulation of contaminants in soil or groundwater and a planned response to accidental discharge. Lastly, monitoring and maintenance programs should be outlined and adhered to.

CASE STUDY: NORTHERN ADELAIDE PLAINS IRRIGATION SCHEME

The Northern Adelaide Plains Reclaimed Water Scheme (or Virginia Pipeline Scheme), South Australia, provides irrigation for over 20 different types of crops in an area of approximately 200 km^2 (Keremane and McKay, 2007; Laurenson *et al*, 2010). It was the first and largest scheme of its type in Australia and remains one of the largest reclaimed water schemes in the southern hemisphere (Keremane and McKay, 2007; Water, 2004a). It supplies approximately 180 GL of tertiary treated, Class A wastewater from the Bolivar Waste Water Treatment Plant (WWTP) to horticultural growers on the Northern Adelaide Plains, through over 100 km of pipelines (Water, 2004 a; Laurenson *et al*, 2010). In 2008, the scheme encompassed 400 connections with capability to supply upto 105 ML/day during peak seasons (WIG, 2009); it delivers nearly half the water required by growers at Virginia (WIG, 2009). The water is used to irrigate a wide range of fruit and vegetables, which supply local and interstate markets, including: beans, broccoli, cabbage, capsicum, carrots, cucumber, eggplants, lettuce, melons, onions, parsnips, pears, potatoes, pumpkins, tomatoes, zucchini, nuts, olives and wine grapes (Marks and Boon, 2005).

The scheme is a joint venture between Virginia Irrigators Association (representing the growers), Water SA (the state water authority responsible for wastewater treatment) and a private company, Water Infrastructure Group, Tyco (Keremane and McKay, 2007; WIG, 2009). Establishment of this scheme in 1999 was largely driven by local growers facing shortage of irrigation water.

Groundwater had been the traditional irrigation-source in the region (Kelly *et al*, 2003). In face of deterioration of this resource, both due to reduction in supply and salt water intrusion, it was recognized that ground water had been over-allocated and was being extracted at an unsustainable rate (Marks and Boon, 2005; Thomas, 2006). Growers were seeking alternative sources of water and some had gained licenses to irrigate with Class C water from the Bolivar WWTP (Laurenson *et al*, 2010).

Meanwhile, 40GL per annum of sewage effluent that was being released from Bolivar WWTP into the Spencer Gulf, had been linked to dramatic losses of sea grass and occasional algal blooms and, was affecting the fishing industry (Marks and Boon, 2005). Under a mandate to reduce WWTP's impact on marine environment and need for an additional water source for growers in the Northern Adelaide Plains, the Bolivar plant was upgraded to produce A class water for unrestricted irrigation.

Bolivar WWTP is the largest of four metropolitan wastewater treatment plants in Adelaide, processing approximately 70% of Adelaide's wastewater, @ approximately 160ML per day (Water, 2004a). Water is now treated to a tertiary level, including Biological Nutrient Removal, lagoon detention, Dissolved Air Flotation Filtration (DAFF) and chlorination. Lagoon detention achieves pathogen-removal through sedimentation, sunlight and microbial predation; however, the lagoons do facilitate some build-up of algae and DAFF treatment removes this suspended load (Marks and Boon, 2005).

Health constraints

The specifications for Class A water in South Australia are: <10 *E.coli*/100ml, Turbidity ≤ 2NTU, Biological Oxygen Demand ≤ 20mg/l (refer Table 5). In terms of human health, the water is considered as fit for 'unrestricted use' – meaning, direct wetting of produce eaten raw is acceptable. However, both health and environmental safety precautions apply:

- Growers are educated in personal hygiene practices relating to contact with water
- It cannot be used to wash food nor in the production process and
- Spray-drift control must be implemented to ensure the spray does not reach another property

The distribution company which sells most of the produce in the area employs quality assurance assessors to carry out audits on both the growers' management practices and the quality of produce sold in terms of food safety – the reported compliance with safety practices is very high around 98-99% (Marks and Boon, 2005).

Effect on produce

The growers are guaranteed water of <1500mg/L total dissolved salts (approximately equivalent to 2.34dS/m

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EC); EC is continually monitored at the WTTP and the water is sometimes diluted (i.e. shandying) with mains water in summer to achieve this level (Marks and Boon, 2005). By comparison, salinity in the aquifers that supply bore water ranges between 500 to over 2000mg/L (NABCWMB, 2007). Respondents to social appraisal of the scheme undertaken in 2004, including wholesale purchasers, commented that the salt made the produce taste better than the interstate produce, although it was slightly less attractive in appearance (Marks and Boon, 2005). Interestingly, Cuartero and Fernandez-Munoz (1999) have shown that tomatoes grown in saline conditions can show both positive and negative effects; fruit size and weight are reduced, while taste is enhanced. Some growers had experienced difficulty in growing particular vegetables like cucumbers and tomatoes; they felt that salinity level in the reclaimed water was to blame. However, these difficulties were not universal and factors that differ from farm to farm (such as pre-existing salinity or fertilizer regime use) may be important in determining crop response to reclaimed water (Marks and Boon, 2005).

While theoretically, the levels of phosphorus and nitrogen generally remain higher in reclaimed water, farmers participating in social appraisal had conflicting beliefs in the fertilizing capacity of water from Bolivar (Marks and Boon, 2005). In an ideal situation, nutrient inputs from both reclaimed water and fertilizer application should match the crop's requirement. In practice, achieving this-particularly, as the nutrient loading is inextricably coupled with the plants' water requirements is difficult (Laurenson *et al*, 2010). Some farmers had continued to apply fertilizer at the same rates; however, a local businessman reported he no longer sold as much fertilizer in the area because of the nutrients in the reclaimed water (Marks and Boon, 2005).

Environmental effects

Water Irrigation Management Plan (WIMP) is part of the licensing requirements of the scheme; it must justify how irrigation with reclaimed water will be managed in order to prevent any negative impact on environmental endpoints (DoH and EPA SA, 1999; Keremane and McKay, 2007). The WIMP includes a monitoring program, administered through the EPA, to determine effect of the reclaimed water on groundwater and soil; the results are independently assessed on annual basis. Growers are provided with advice on how to manage irrigation with reclaimed water so as to avoid negative impact on soil and groundwater.

Although salt load in the Bolivar reclaimed water is high (1097 mg/L TDS) (Kelly *et al*, 2001) compared to typical surface waters in South Australia, (329 mg/l TDS) (Unkovich *et al*, 2004), salinity in the local aquifers which supply bore water ranges between 500 and >2000mg/L (NABCWMB, 2007). Irrigation with either groundwater or the reclaimed water warrants particular care with respect to maintaining a leaching fraction that will drive the salt below the root zone, yet, avoid salinization of the underlying groundwater.

A social appraisal found that many stakeholders believed that overwatering was occurring, either in an effort to leach salts out or to make full use of water allocation (Marks and Boon, 2005). Groundwater levels in the local aquifers were in decline prior to 2000. Since then, these have generally risen, so that by 2003 they had recovered to 1980's levels (NABCWMB, 2007). While it may be difficult to differentiate between effects of reduced groundwater extraction and increased inputs, in 2003, rising water tables beneath irrigation areas in Virginia region were suspected to be due to excessive leaching. Hence, a need to improve water use efficiency was identified (Marks and Boon, 2005). In response, the "Obs[ervation] Wells Network" used for monitoring ground water levels and salinity in the region was expanded, and a shallow water-table monitoring network was also instigated (Marks & Boon, 2005).

Reclaimed waters frequently have higher levels of sodium ions compared to other cations and threaten to degrade soil structure through sodicity (Bond, 1998). It might be expected that continued irrigation with reclaimed water could induce structural changes in soil. However, despite annual evaluations through the EPA as a requirement of the Water Irrigation Management Plan, there have been no reported deleterious effects of Class A water on soil properties in the region.

Benefits of the scheme

Virginia Pipeline Scheme has provided a secure water resource during a period known to be one of the driest on record (WIG, 2009). In some cases, the reclaimed water replaced groundwater resources and in others, provided a water source where framers were unable to receive groundwater allocation: as one grower commented during the social appraisal *"If I didn't have 'Bolivar water', I wouldn't be growing anything. It is hard to get a bore water quota"* (Marks and Boon, 2005).

The scheme has ensured long-term economic sustainability of Adelaide's food bowl. The recycled water is sold at a reduced rate compared to mains water. About $50 million worth of the produce grown in the area each year uses reclaimed water (WIG, 2009). Water

Infrastructure Group (2009) translates this to $1 billion benefit to the district over the first 10 years of the project.

Environmentally, the scheme results in 35% of water being recycled at Bolivar WWTP (Water, 2004b), reduces discharge of harmful nutrients into the marine environment; reduces demand for groundwater extractions and contributes to reducing South Australia's dependence on the pressured surface-water systems (Water, 2004a). As one proponent eloquently summed it up: "The scheme has operated for 10 years with no human-health issues and no detrimental environmental impact, proving that recycled water can provide a safe and sustainable water resource" (WIG, 2009).

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REFERENCES

Anderson, J. and Davis, C. 2006. Reclaimed water use in Australia: An overview of Australia and reclaimed water. In: Growing Crops with Reclaimed Wastewater (Ed: D. Stevens), CSIRO Publishing, Victoria, Australia, p 5

Australian Bureau of Statistics. 2000. Water Account Australia 1993-4 to 1996-7, ABS Catalogue No: 4610.0. Commonwealth of Australia, Canberra, Australia

Australian Bureau of Statistics. 2004. Water Account Australia 2000-01 (Corrigendum), ABS Catalogue No: 4610.0. Commonwealth of Australia, Canberra, Australia

Australian Bureau of Statistics. 2006. Water Account Australia 2004-05, ABS Catalogue No: 4610.0. Commonwealth of Australia, Canberra, Australia

Australian Bureau of Statistics. 2010a. Water Account Australia 2008-09, ABS Catalogue No: 4610.0. Commonwealth of Australia, Canberra, Australia

Australian Bureau of Statistics. 2010b. Measure of Australia's Progress 2010, ABS Catalogue No: 1370.0. Commonwealth of Australia, Canberra, Australia

Australian Bureau of Statistics. 2010c. Year Book Australia 2009-10, Number 91, ABS Catalogue No: 1301.1. Commonwealth of Australia, Canberra, Australia

Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand. 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. ANZECC and ARMCANZ, Canberra, Australia

Ayers, R.S. and Westcot, D.W. 1976. Water quality for irrigation. Irrigation and Drainage Paper 29: Food and Agriculture Organisation of the UN, Rome

Bennett, W.F. 1994. Nutrient deficiencies and toxicities in crop plants. The American Phytopathological Society, St. Paul, Minnesota

Bolan, N.S., Ravi Naidu and Dedik Budianta. 2011a. Bioavailability of minor elements in soils. In: Handbook of Soil Science (Ed. Sumner, M.) (in Press)

Bolan, N.S., Adriano, D., Senesi, N., Kunhikrishnan, A., James, T. and McDowell, R. 2011b. Dissolved organic carbon: biogeochemistry, dynamics and agro-environmental significance in soils. *Ad. Agron*., **110**:1-75

Bolan, N.S., Adriano, D.C., Duraisamy, A. and Mani, P. 2003. Immobilization and phytoavailability of cadmium in variable charge soils: III. Effect of biosolid addition. *Pl. Soil*, **256**: 231-241

Bond, W.J. 1998. Effluent irrigation and environmental challenge for soil science. *Austr. J. Soil Res.*, **36**: 543-55

Christen, E., Ayers, J., Hornbuckle, J. and Biswas, T. 2006. Design and management of reclaimed water irrigation systems. In: Growing Crops with Reclaimed Wastewater (Ed: D. Stevens), CSIRO Publishing, Victoria, Australia, pp 107-123

Cuartero, J. and Fernandez-Munoz. 1999. Tomato and salinity. *Sci. Hort.*, **78**:83-125

Department of Health and Community Services. 2009. Northern Territory Guidelines for Management of Recycled Water Schemes. Northern Territory Government, Darwin, Australia

Department of Health and Environment Protection Agency. 1999. South Australian Reclaimed Water Guidelines (Treated Effluent). Government of South Australia, Adelaide, Australia

Department of Health and Families Northern Territory. 2009. Guidelines for Management of Recycled Water Systems, Northern Territory Government, Casuarina, Northern Territory, Australia

Department of Sustainability, Environment, Water, Population and Communities (DSEWPC). 2008. 5. Thematic Review - Integrated land and Water Management. In: WSSD - Australian National Assessment Report. DSEWPC, Commonwealth of Australia, Canberra, Australia

Dimmock, G.M., Bettenay, E. and Mulcahy, M.J. 1974. Salt content of lateritic profiles in the Darling Ranges, Western Australia. *Austr. J. Soil Res.*, **12:**63-69

Dinesh, N., Sickerdick, L. and Liston, C. 2006. Wastewater reclamation processes. In: Growing Crops with Reclaimed Wastewater (Ed: D. Stevens), CSIRO Publishing, Victoria, Australia, pp 63-80

Dudley, L. 1994. Salinity in the soil environment. In: Handbook of plant and crop stress (Ed: M Pessarakli), Marcel Decker, New York, pp.13-30

Environment Protection Authority South Australia. 2008. Risks from endocrine disrupting substances in the South Australian aquatic environment. Environment Protection Authority, Adelaide, South Australia, Australia

Environmental Protection Authority South Australia. 2009. EPA Guidelines: Wastewater irrigation management plan (WIMP) - a drafting guide for wastewater irrigators. Environment Protection Authority, Adelaide, South Australia, Australia

Environmental Protection Authority Victoria. 2003. Guidelines for Environmental Management: Use of Reclaimed Water, EPA Victoria, Victoria, Australia

Feigin, A., Ravina, I., and Salhevet, J. 1991. Irrigation with treated sewage effluent: Management for Environmental Protection. Springer-Verlag, Berlin

Hartung, W. and Davis, W.1994. Abscisic acid under drought and salt stress. In: Handbook of plant and crop stress (Ed: M, Pessarakli), Marcel Dekker, New York, pp. 401-411

Holmes M, Kumar A, Shareef A, Doan H, Stuetz R and Kookana, R 2010. Fate of indicator endocrine disrupting chemicals in sewage during treatment and polishing for non-potable reuse. *Water Sci. and Tech.*, **62**:1416-1423

Kelly, J., van Der Weilen, M. and Stevens, D.P. 2001. Sustainable use of reclaimed water on the Northern Adelaide Plains: Growers' Manual. Department of Primary Industries and Resources South Australia (PIRSA) Rural Solutions, Adelaide, South Australia, Australia

Kelly, J., Stevens, D. and White, T. 2003. Achievements of the Virginia Pipeline Scheme: Horticultural production with reclaimed water. *Water recycling Australia: second national conference*. Brisbane, Queensland, Australia

Kelly, J., Unkovich, M. and Stevens, D. 2006. Crop nutrition considerations in reclaimed water irrigation systems. In: Growing Crops with Reclaimed Wastewater (Ed: D. Stevens), CSIRO Publishing, Victoria, Australia, pp 92–105

Keremane, G.B. and McKay, J. 2007. Successful wastewater reuse scheme and sustainable development: a case study in Adelaide. *Water and Envir. J.*, **21**:83-91

Kim, J. and Clevenger, T.E. 2007. Prediction of *N*-nitrosodimethylamine (NDMA) formation as a disinfection by-product . *J. Hazardous Materials*, **145:**270-276

Kirkham, M.B. 2006. Cadmium in plants on polluted soils: Effects of soil factors, hyperaccumulation and amendments. *Geoderma*, **137**:19-32

Laurenson, S., Kunhikrishnan, A., Bolan, N.S., Naidu, R., McKay, J. and Keremane, G. 2010. Management of recycled water for sustainable production and environmental protection: A case study with Northern Adelaide Plains recycling scheme. *Int'l J. Envirtl. Sci. Devt.*, **1**:176-180

Marks, J.S. and Boon, K.F. 2005. A social appraisal of the South Australian Virginia Pipeline Scheme: Five years' experience. Report to Land and Water Australia, Horticulture Australia Ltd., 20th May, Flinders University, Adelaide, South Australia, Australia

Mclaughlin, M.J., Palmer, L.T., Tiller, K.G., Beech, T.A. and Smart, M.K. 1994. Increased soil-salinity causes elevated cadmium concentrations in field-grown potato-tubers. *J. Envirtl. Qual.*, **23**:1013-1018

Müller, K.G.N. Magesan and N.S. Bolan. 2007. A critical review of the influence of wastewater irrigation on organic chemical transformation and transport in soil. *Agri. Ecosyst. Envir.*, **120**:93-116

Naidu, R, R.S. Kookana, M.E. Sumner, R.D. Harter and K.G. Tiller. 1997. Cadmium sorption and transport in variable charge soils: A Review. *J. Environ. Qual.* **26**:602-617

Naidu, R. and Sumner, M.E. 1998. Sodic Soils - Distribution, Properties, Management and Environmental Consequences. Oxford University Press, New York

Natural Resource Management Ministerial Council Environment Protection and Heritage Council Australian Health Ministers Conference (NRMMCEP & HCAHMC). 2006. Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1), National Water Quality Management Strategy. Natural Resource Management Ministerial Council Environment Protection and Heritage Council Australian Health Ministers Conference, Canberra, ACT, Australia

Northern Adelaide and Barossa Catchment Water Management Board. 2007. Fact Sheet: Groundwater Trends in the NAP. Adelaide and Mt. Lofty Ranges Natural Resource Management Board, Government of South Australia, Adelaide, South Australia, Australia

Oliver, I., McLaughlin, M.J. and Merrington, G. 2005. Temporal trends of total and potentially available element concentrations in sewage biosolids: a comparison of biosolids surveys conducted 18 years apart. *Sci. Total Envir.*, **337**:139-145

Page, A.L. and Chang, A.C. 1985. Fate of wastewater constituents in soil and groundwater: trace elements. In: Irrigation with reclaimed municipal wastewater – a guidance manual (Eds: G.S. Pettygrove and T. Asano), Lewis Publishers, Chelsea, MI, pp13.1-13.16

Power, K. 2010. Recycled water use in Australia: regulations, guidelines and validation requirements for a national approach, Waterlines Report Series No. 26. National Water Commission Australian Government, Canberra, ACT, Australia

Reid, H. and Sarkis, S. 2006. Australian and international reclaimed water guidelines: the fundamentals. In: Growing Crops with Reclaimed Wastewater (Ed: D. Stevens), CSIRO Publishing, Victoria, Australia, pp 39- 61

Radcliffe, J. 2004. Water recycling in Australia. Australian Academy of Technological Sciences and Engineering, Parkville, Victoria

Rengasamy, P. 2006. Soil salinity and Sodicity. In: Growing Crops with Reclaimed Wastewater (Ed: D. Stevens), CSIRO Publishing, Victoria, Australia, pp 125-146

Sheikh, B., Cort, R., Cooper, R.C., and Jaques, R.C. 1998. Tertiary-treated reclaimed water for irrigation of raw-eaten vegetables. In: Wastewater reclamation and reuse (Ed: T. Asano), Technomic Publishing, Lancaster, Pennsylvania, pp 779-826

Singer, P.C. 1999. Humic substances as precursors for potentially harmful disinfection by-products. *Water Sci. Tech.*, **40**:25-30

Stenhouse, F. 1992. The 1992 Australian market basket survey. National Food Authority, Australian Government Publishing Service, Canberra, ACT, Australia

Stevens, D. 2006. Growing crops with reclaimed wastewater, CSIRO Publishing, Victoria, Australia

Stevens, D. and McLaughlin, M. 2006. Managing risks to soil and plant health from key metals and metalloids in irrigation waters. In: Growing crops with reclaimed wastewater (Ed: D. Stevens), CSIRO Publishing, Victoria, Australia, pp 139 -146

Stevens, D.P., McLaughlin, M.J and Smart, M. 2003. Effects of longterm irrigation with reclaimed water on soils of the Northern Adelaide Plains, SA. *Austr. J. Soil Res.*, **41**:933-948

Thomas, R. 2006. Reuse in South Australia. In: Growing crops with reclaimed wastewater Ed: Stevens, D., CSIRO Publishing, Victoria, Australia. pp 6–14

Unkovich, M., Kelly, J. and Stevens, D. 2006. Managing risks to plant health from salinity, sodium, chloride and boron in reclaimed waters. In: Growing crops with reclaimed wastewater (Ed: D. Stevens), CSIRO Publishing, Victoria, Australia, pp 147-158

Unkovich, M., Stevens, D., Ying, G. and Kelly, J. 2004. Impacts on crop quality from irrigation with water reclaimed from sewage. Australian Water Conservation and Reuse Research Program, Australian Water Association, CSIRO and Arris Pty. Ltd., Adelaide, Australia

Villanueva, C.M., Cantor, K.P., Grimalt, J.O., Malats, N., Silverman, D., Tardon, A., Garcia-Closas, R., Serra, C., Carrato, A., Castaño-Vinyals, G., Marcos, R., Rothman, N., Real, F.X., Dosemeci, M. and Kogevinas, M. 2007. Bladder cancer and exposure to water disinfection by-products through ingestion, bathing, showering, and swimming in pools. *Amer. J. Epidemiol.*, **165:**148-156

Warne M., Rayment, G.E., Brent, P., Drew, N., Klim, E., McLaughlin, M.J., Milham, P., Shelly, B., Stevens, D. and Sparrow, L.A. 2007. Final report of National Cadmium Committee (NCMC)

Water Infrastructure Group. 2009. 10 years of recycled water use at water infrastructure groups' Virginia Pipeline Scheme: ten years of irrigating fresh vegetables with recycled water in Australia. Media Release – 7 October 2009. Water Infrastructure Group, Tyco International Ltd.

Water, S.A. 2004a. Bolivar EIP. SA Water, Government of South Australia, Adelaide, South Australia, Australia.

Water, S.A. 2004b. Virginia Angle Vale Reuse Extension. SA Water, Government of South Australia, Adelaide, South Australia, Australia

Weggler, K, McLaughlin, M.J., Graham, R.D. 2004. Effect of chloride in soil solution on the plant availability of biosolid-borne cadmium. *J. Envirtl. Quali.*, **33**:496-504

World Health Organisation (WHO). 2008. Guidelines for Drinking-water Quality, Third edition, incorporating the first and second addenda, Vol. 1, Recommendations. WHO

Ying, G. 2006 .Organic compounds in reclaimed water and their potential risks to the environment and human health. In: Growing Crops with Reclaimed Wastewater (Ed: D. Stevens), CSIRO Publishing, Victoria, Australia, pp 159-170