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Wastewater Reuse and the Environment: Reaping the Benefits by Minimising the Impacts

ANDREW J. HAMILTON[1,2], VINCENT L. VERSACE[1], FRANK STAGNITTI[1], PEIJUN LI[3], WEI YIN[3], PETA MAHER[1], KAREN HERMON[1], ROBERT R. PREMIER[2] & DANIEL IERODIACONOU[1]
[1]School of Life and Environmental Sciences
Deakin University
PO Box 423, Warrnambool, Victoria 3280
AUSTRALIA
[2]Department of Primary Industries
Private Bag 15, Ferntree Gully Delivery Centre, Victoria 3156
AUSTRALIA
[3]Institute of Applied Ecology
Chinese Academy of Sciences
Shenyang 110016, Liaoning Province
PEOPLE'S REPUBLIC OF CHINA

Abstract: - The reuse of wastewater is becoming increasingly common as pressure on the world's water resources intensifies. The environmental benefits of wastewater reuse can be substantial, and are a major driver for the practice. Nonetheless, if not carefully planned, the reuse of wastewater can pose significant threats to natural and human environments. The challenge facing natural resource managers is to identify potential benefits and risks and to achieve an appropriate balance. This paper describes, largely through examples from our research in Australia and China, environmental benefits and threats concomitant with reuse, and recent progress on risk assessment and mitigation.

Key-Words: - irrigation, reclaimed water, recycled water, risk analysis, salinity, sodicity, wetlands

1 Introduction

Pollution and over-extraction have placed the world's freshwater resources in a state of crisis, and the discharge of polluted and nutrient-laden freshwater to the sea is putting marine systems, particularly coastal waters, under significant stress. Many approaches are being adopted in an attempt to redress these problems. One of these is the reuse of wastewater: it reduces the volume of wastewater discharged to receiving waters, and its substitution for freshwater leaves more water for the environment. Wastewater can be reused for a variety of purposes, including agricultural irrigation, heavy industry, urban and landscape irrigation, groundwater recharge, and wetland creation [1]. The environmental gains to be realised from reusing wastewater are major drivers for its reuse, although economic and social forces also play important roles [2, 3]. Nevertheless, care must be taken, as wastewater reuse itself also has the potential to be environmentally detrimental. The challenge is to achieve an environmental net profit.

In this paper we consider the environmental drivers for wastewater reuse, and then progress discussion on the environmental impacts and risks attendant with the practice. The term environment is interpreted in its broadest sense, and is taken to include natural systems, agriculture, and people themselves. We frequently illustrate issues with examples from Australia and China. These two countries face significant water resource challenges. Of the Earth's inhabited continents, Australia is the driest, has the lowest percentage of rainfall resulting in runoff, the lowest proportion of water in rivers, and the smallest area of permanent wetland [4]. China is encumbered with supporting 22% of the World's population (1.3 billion) with only 7% of its arable land and 8% of its available freshwater resources [5].

2 Environmental drivers for wastewater reuse

2.1 Over-extraction from freshwater systems

Human impacts on freshwater systems are substantial in most populated parts of the world. Over-extraction, mainly for agriculture, has lead to significant degradation of rivers, lakes, aquifers, and dependent systems, such as wetlands. Liberation of water for the environment through substitution with wastewater has been widely promoted as a means of reducing anthropogenic impacts [2, 6].

In Australia 26% of the surface-water management units are either fully- or over-used, 31% of the groundwater management units are over-allocated [7], and about half of its wetlands have been lost since European settlement [8]. China paints a similar picture. About two thirds of all extracted water comes from aquifers, which are in consequence so depleted that land-subsidence is a serious issue in some cities [9]. Complete cessation of river flows is common. In the 1970s the Yellow River experienced a no-flow duration of 21 days, and this steadily increased up to around 226 days in 1997 [10]. The demand for freshwater is so high that over 100 cities suffer from shortages, which in some instances are severe enough to interrupt industrial production [9], and over half of China's 667 cities are categorised as facing water shortages [11]. Wetland loss is also prolific. China is currently home to about 10% of the world's wetlands. The Sanjian Plain comprises some of the most significant wetland habitat in China, but if current rates of attrition occur it will be completely devoid of wetlands by 2020 [9].

Similar stories can be told across the globe. According to the water stress index—the ratio of a country's total water withdrawal to its total renewable freshwater resources—about half of the countries of Europe are under water stress (an index above 10%) [12]. As with Australia and China, ecosystems in all these countries are suffering from heavy human extraction. Therefore, the key challenge facing many countries is to develop strategies to meet the increasing water demands of society but which do not further degrade the integrity of the environment. Reuse of wastewater is possibly a means, in concert with others, to this end.

2.2 Pollution of receiving waters and associated habitats

The other major environmental benefit to be garnered from reusing wastewater is diminution in pollution of waters receiving discharge of sewage. An audit in 1997–98 found that across Australia's major cities 1,350 GL of wastewater was released to water bodies, mostly marine, over the course of a year [13]. Most of Australia's large sewage treatment plants employ primary and secondary treatment (Appendix I in [1]). While clearly preferable to the release of raw sewage, the discharge of secondary-treated effluents can nonetheless have substantial adverse bearing on the ecology of aquatic ecosystems. Of particular concern is the potential for eutrophication of receiving waters. Nitrogen and phosphorus are the prime causative agents of eutrophication, the former tending to be more problematic in the marine environment, and the latter in freshwater systems.

Adverse environmental impacts upon receiving waters, fresh and marine, are numerous. One of the most dramatic examples is at the Gulf of St Vincent in South Australia, where outfall from the Bolivar sewage treatment plant is believed to be largely responsible for the loss of about 5,000 ha of seagrass since 1935 [14, 15]. Seagrass beds are important breeding sites for many marine animals [16], and the environmental effects of such devastation are considerable. Coastal impacts also extend to intertidal communities, with adverse effects on mangroves [14], macroinvertebrates [17], and maroalgae [18] having been documented. Effluent outfalls in Australia have even been reported to affect terrestrial plants, with the higher mortality rates of coastal banksias (*Banksia integrifolia*) nearer outfalls being attributed to sewage-derived surfactants present in sea-spray [19]. Effluent outfalls have also been in part attributed to the destruction of the natural *Suaeda heteroptera* community in the red beach landscape of the National Reserve of the Shuangtaizi River Estuary in Northeast China [20]. *S. heteroptera* is a plant that grows exclusively in intertidal areas. The National Reserve of the Shuangtaizi River Estuary is the largest breeding habitat for Saunders' Gull (*Larus saundersi*) in the world; however, recently the massive shrinkage of *S. heteroptera* vegetation has led to a decrease in the Saunders' Gull population.

In Australia in recent years the issue of eutrophication of receiving waters has been the impetus for adding tertiary treatment to existing sewage treatment plants. For example, until recently the Western Treatment Plant, which treats 54% (500 ML per day) of Melbourne's sewage, treated all its effluent to secondary standard before releasing it to Port Phillip Bay, and this accounted for about half of the nitrogen entering the bay. An extensive four-year study found that most of the nitrogen entering the Bay stayed there and is assimilated there [21]. Consequently, the report recommended a precautionary reduction of a 1,000 tonne/year in nitrogen load, with 50% of this assigned to the treatment plant. To meet this agendum several changes to the sewage treatment process were made, the most significant being the commissioning of two activated sludge plants [22, 23]. Also, the volume of water being discharged was reduced through diversion of treated effluent to the adjacent Werribee horticultural irrigation district—a prime example of an environmental driver occasioning wastewater reuse.

About 80% of China's domestic wastewater is discharged to the environment virtually untreated [10]. There are 867 main outfalls in China, and in 2003 20 of these accounted for 880 million tonnes of sewage being discharged to the sea [9]. Moreover, this discharge was believed to contain about 1.3 tonnes of polluting chemicals, including various heavy metals. Sediment concentrations of several heavy metals in the Yangtze Estuary have been found to be positively correlated with proximity to sewage outfalls and local industry [24]. China's freshwater systems are also subject to heavy pollution, with around 27% of the surface-water failing to meet the nation's minimum standard for agricultural irrigation [25].

In short, huge amounts of pollutant-laden wastewater are being discharged to water-bodies in most inhabited parts of the world. Reducing the volume of this discharge is a powerful driver for wastewater reuse.

3 The significance of agricultural reuse

Wastewater can be reused for many purposes, including, *inter alia*, agricultural irrigation, industrial processes (particularly cooling), fire fighting, aquaculture, domestic use, wetland creation, and aquifer recharge [1].

In countries that are heavily reliant upon agriculture, irrigation of crops has the capacity to use substantially greater volumes of water than the other sectors. For example, 67% (16,660 GL per annum) of the freshwater sequestered in Australia is used for agriculture, yet Australia's 22 largest cities (including capitals) collectively use 1,800 GL per annum [26]. Irrigated agriculture accounts for nearly 30% of Australia's gross value of agricultural production [26]. In China almost 50 million ha of land was irrigated in 1995; this accounts for 52% of the total cultivated area [10]. In South China and on the Huang-Huai-Hai plain, irrigation respectively accounted for around 80–90% and 60–70% of the cultivated land. Thus, in many regions agricultural reuse is likely to liberate sizeable volumes of water for the environment. This being said, some large cities, particularly the mega-cities of Asia, also have the potential to use vast amounts of treated wastewater [27, 28].

The current extent of wastewater-irrigation across the globe is a matter of conjecture, owing to a paucity of data and complications of definition: where to draw the line between wastewater and sewage-polluted river water is unclear. In 2001 it was estimated that globally 20 million ha of land is irrigated with raw sewage, neat or partially diluted [29]. Regardless of the true figure, most would agree that agricultural irrigation with wastewater is pervasive and is only likely to increase. In addition to the environmental drivers outlined above, economic and social forces are encouraging or necessitating the practice. Such drivers include water availability and consistency of supply, livelihood dependence, market proximity, and the fertilising properties of wastewater [3, 30].

Reuse for agricultural irrigation tends to pose a greater direct threat to the environment than other reuse scenarios. If one considers the agricultural landscape to be part of the environment, as is done here, then applying wastewater to land plainly has the potential to affect the environment through altering soil properties. Moreover, wastewater cannot usually be collected after it has been used for irrigation, and consequently enters the broader environment where it has potential to cause further damage. In contrast, the discharge from many other reuse scenarios can readily be collected and managed accordingly. For example, wastewater that has been reused for industrial cooling, aquaculture or for flushing toilets in domestic estates (i.e. waste-wastewater!) can be discharged to the sewer (again!). In effect, such scenarios can be seen as components of a larger sewerage system. There are of course exceptions: domestic wastewater irrigation and wetland creation are clearly open systems.

Therefore, agricultural reuse can be simultaneously beneficial and detrimental to the environment. This can be seen as a cruel irony, but it should be interpreted as a challenge that, if met, promises environmental gains.

4 Environmental risks

4.1 Groundwater and surface-water contamination

Leaching of nitrates poses one of the greatest threats to groundwater health arising from wastewater irrigation [31]. The risk of groundwater contamination with nitrate can be markedly reduced through appropriately matching plant production systems to effluent characteristics [32, 33]. For example, high-yielding crops with large amounts of nitrogen in their biomass would be more effective than tree plantations at reducing nitrate leaching. Other threats to groundwater and surface-water include contamination with pharmaceutically-active compounds and endocrine disrupting chemicals [34], nutrients (see 2.2 above), pathogens [35], and salts (see 4.2 below).

Clearly, the impacts of wastewater irrigation on aquatic systems are largely similar to the impacts of direct disposal of effluent to receiving waters. Water-bodies located near densely built-up areas have a high recreation value. However, storm-water and sewer overflows contribute significantly to water quality deterioration and reduce recreational and ecological amenity. Detention basins are often used in urban areas for both flood control and removal of pollutants. But constructed wetlands may offer the additional benefit of improving water quality by assimilating and transforming organic, inorganic and toxic constituents through the processes such as adsorption, settling, sedimentation and biodegradation [36, 37]. Constructed wetlands are ideal, low-cost, wastewater treatment systems; they provide an efficient and an easily-operated alternative to conventional treatment systems. In addition to treating pollutants and waste, they may also provide important wildlife and recreational benefits commonly associated with natural wetlands [50, 81].

A recent innovative study conducted in the Taohuadao area in Hanyang, a district of Wuhan city in Hubei province in China, illustrated the efficiency of using constructed wetlands for treating wastewater generated in intensive urbanised areas. Whilst the use of constructed wetlands for treating wastewater is not new, this study was unique in a number of ways. The wastewater treatment efficiency was remarkable, even in the freezing winter months [37]. A dual wetland system was adopted. The first system, comprising ponds and horizontal subsurface wetlands, treats municipal wastewater from the combined sewer and stormwater, and the removal efficiencies of different pollutants are COD_{Cr} 79.1%, TP 84.3%, TN 69.8%, SS 94.7%. A second system of constructed ponds and hybrid subsurface wetlands is used to clean the lake water and supply the fish-pond. The removal efficiencies of different pollutants in second system are COD_{Cr} 85.4%, TP 91.8%, TN 94.4% and SS 97.1%. Also, in this system the concentrations of TP and TN are reduced below 0.3 mg L^{-1} and 1.5 mg L^{-1} respectively. The water in the second system is also re-used to maintain consistent flow through the first system in periods of low wastewater input or to avoid chemical overloading. In winter months, the wetland functions are maintained by passing water through saturated soils heated by decomposing harvested plants.

4.2 Agricultural sustainability

Wastewater irrigation poses several threats to agricultural sustainability. Heavy metals derived from sewage can retard plant growth [39]. Nitrogen in high concentrations, while usually beneficial to crops through its fertilising properties [40], can also limit plant growth and crop yield [41, 42]. Salinity and sodicity, however, are by far the most important sustainability constraints [31, 43] and will be the focus of the following discussion.

The properties of wastewater clearly depend on its origin, but most wastewaters are higher in salts than traditional irrigation waters, with electrical conductivity roughly ranging from 600 to 1,700 μScm^{-1} [44]. Salts can affect plants either through causing osmotic stress or via direct toxicity. High concentrations of salt in the root-zone lead to a decrease in the osmotic potential of the soil-water solution, thus retarding the water uptake rate of the plant. The plant expends considerable energy trying to osmotically adjust, by accumulating ions, and this is typically at the expense of yield [45, 46]. Toxicity occurs when salt ions enter the plant and interfere with cellular processes. Most horticultural crops uptake salts more readily through the leaves than through the roots [47]. Therefore, through substituting over-head irrigation with drip, furrow or sub-subsurface methods, the toxic effects of salinity can be easily remedied, but not the osmotic effect.

Salinity is a pragmatic constraint for many horticultural reuse schemes. For example, at Australia's Werribee horticultural irrigation scheme, which commenced in 2005, salinity concerns lead to a precautionary approach where the salty wastewater (annual average ~1,700 $\mu S\ cm^{-1}$) is mixed with river water before being distributed to growers [50]. Indeed, the ratio of the mix is determined so as to satisfy a target salinity in the mix: the long-term target is 1,000 μS cm^{-1} and the more immediate targets range from 1,400–1,800 μS cm^{-1} (see [48] for details of targets and shandy rules). The shandying process is complicated by the fact that salinity of the river water, while typically less than the wastewater, varies substantially (annual average from ~697–1,680 μS cm^{-1}). It is anticipated that by 2009 the salinity of the treated wastewater could be reduced to 1,000 μS cm^{-1}, i.e. the long-term target value, through reducing salt inputs into the sewer and commissioning desalination technology at the sewage treatment plant [48]. This would obviate the need for dilution with river water.

Sodic soils develop when sodium is present in appreciably greater concentrations than other ions, particularly calcium and magnesium. Sodicity induces changes in the soil's physical properties, the most notable effect being the dispersion of soil aggregates. Dispersion, in combination with other processes, such as swelling and slacking, can ultimately affect plants through decreasing the permeability of water and air through the soil, water-logging, and impeding root penetration. The effects of such processes on cropping systems were reviewed by Maher *et al.* [49] and are summarised in the schema below (Figure 1).

The sodicity of irrigation waters is typically expressed in terms of the sodium adsorption ratio (SAR), which defines the relation between soluble sodium ions and soluble divalent cations (Ca^{2+} and Mg^{2+}) [49]. The potential for sodicity-related problems generally warrants attention for irrigation waters with an SAR in excess of 3, particularly on heavy soils. The SAR of wastewater tends to be greater than 3 (e.g. 4.5–8.0, [50]). There are, however, a suite of management options that can be used to combat sodicity. Deep-tillage can be used to bring calcium-rich sub-soils (e.g. gypsum) to the surface [51], or amendments can be added directly to the soil or to the irrigation water [31, 49, 52]. Another approach, known as conjunctive reuse, is to flush sodium from the soil with conventional low-sodium water and collect the leachate [53]. At a landscape planning level, sodicity can be addressed through appropriate matching of soil types: irrigation of heavy soils with high SAR water should be avoided where possible. For individual enterprises, the management of sodicity can be a costly exercise.

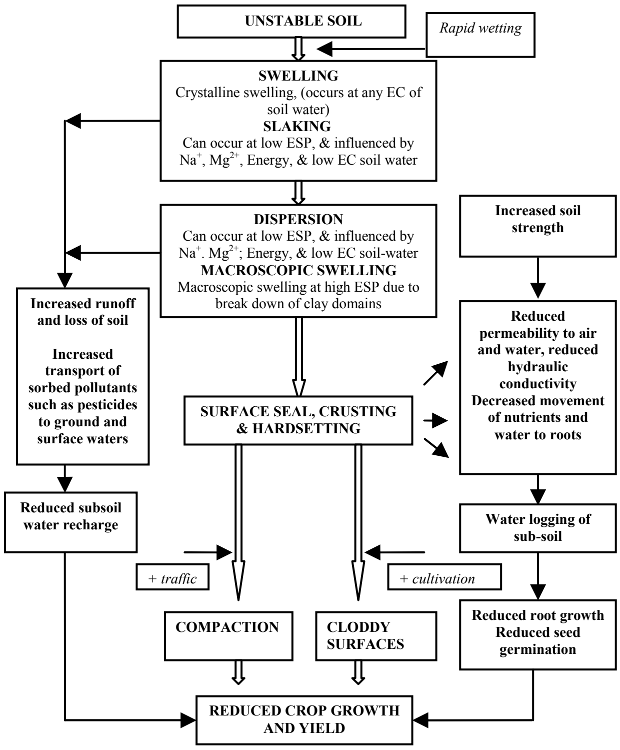

Fig. 1. Schema of sodicity-related processes and their influence cropping systems. After [49].

We are currently investigating sodicity management for the Australian viticultural industry, which is keen to exploit the benefits of wastewater irrigation. The research programme comprises two main parts: studies on the likely impact of waste-water irrigation on soil structural properties in vineyards [54], and an assessment of the performance of a range of soil amendments and row management practices [55].

4.3 Human health

Wastewater irrigation poses a number of risks to human health, including pathogenic microorganisms [56]; organic chemicals, particularly endocrine disrupting compounds and pharmaceutically-active compounds [57, 58]; and heavy metals [59, 60]. Of these, pathogenic microorganisms are generally considered to pose the greatest threat to human health [56, 61], and the discussion from here will solely focus on them. This is done with trepidation though, as we do not want to underplay the potential importance of other risks.

A wide variety of pathogenic microorganisms is found in wastewater, including bacteria, viruses, protozoans, and parasitic worms [56, 62]. The concentrations of pathogens in wastewaters are dependent upon the health of the source population [63]. Also, for pathogens that induce an immune response, the susceptibility to infection varies from one population to the next. For example, people in under-developed and developing countries tend to exhibit higher immunity to enteric viruses than those in developed countries, owing to frequent exposure early in life [64].

In recent years, the risks to human health arising from wastewater irrigation of horticultural crops have been determined using Quantitative Microbial Risk Assessment (QMRA) [65]. QMRA modelling for wastewater reuse has been approached from two perspectives: deterministic [66, 67, 68] and stochastic [69, 70, 71, 72, 73]. Simply stated, each parameter in a deterministic model is represented by one value only, a point-estimate, whereas probability distributions are used to define parameters in stochastic models. Thus, generally speaking, the stochastic approach accounts for uncertainty but the deterministic does not. Moreover, the output of a stochastic model is itself a probability distribution. Whilst it may be considered that stochastic models are theoretically superior for QMRA, they are more complex to construct, typically requiring simulation methods such as Monte Carlo. The simpler deterministic approach may often be more pragmatic from the perspective of water resource managers [74]. Furthermore, a recent study where deterministic and stochastic QMRA models for various wastewater reuse scenarios were run revealed negligible difference between the two approaches for most scenarios [75].

The risks posed by wastewater irrigation are plainly dependent upon the reuse situation at hand. We constructed QMRA models for broccoli, cucumber, lettuce and three cultivars of cabbage. The models are complex and are not presented in detail here but can be found in [72, 73]. In brief, we calculated the risk to consumers of succumbing to enteric virus infection after eating vegetables that had been spray-irrigated with non-disinfected secondary-treated wastewater. When the model was run using enteric virus concentrations derived from data for the effluent of the Monterey Regional Water Pollution Control Agency activated sludge plant [69], we found that the annual risk of infection was markedly influenced by the duration of the period since the last wastewater-irrigation event (Table 1). Considering that the generally-accepted annual risk of infection is $\leq 10^{-4}$ [76], this exercise illustrates that, for the scenarios under consideration, a fourteen-day withholding period could be a practical means of mitigating risk.

Table 1. The annual probability of enteric virus infection associated with consuming vegetables that have been spray-irrigated with secondary effluent. Each value is the upper 95% confidence limit of the mean ($UCL_{0.95}$). 'Delay' is the time between harvest and the last wastewater irrigation event. S, GS, and WH are cultivars of cabbage: Savoy, Grand Slam, and Winter Head. After [72].

Delay	*1 day*	*7 days*	*14 days*
Broccoli	3×10^{-2}	8×10^{-4}	1×10^{-6}
Cucumber	2×10^{-2}	3×10^{-4}	3×10^{-7}
Cabbage (S/GS)	5×10^{-2}	2×10^{-3}	3×10^{-6}
Cabbage (WH)	7×10^{-2}	4×10^{-3}	7×10^{-6}
Lettuce	2×10^{-1}	8×10^{-3}	1×10^{-5}

The fact that not all horticultural crops carry the same risk can itself be exploited in risk management. Most horticultural crops are grown in a manner that the risk of direct contact with reclaimed water is minimal. Also the physical characteristics of horticultural crops mean that some have more inherent risks than others. The smooth skins of tomato and cucumber afford them comparatively more protection than leafy vegetables, for example. Moreover, leafy vegetables, by virtue of growing too close to the ground, support high microbial populations on their surfaces, which can lead to biofilms that protect pathogens. One way to reduce the risks of using reclaimed water is to exclude some of the higher risk produce from irrigation with reclaimed water. The removal of a small number of crops from a wastewater irrigation scheme can be an effective tool for risk minimisation.

4.4 Greenhouse gases: the hidden impact

Water possesses a property that can lead to significant environmental consequences: it is heavy. A large agricultural reuse proposal in Queensland, Australia, was recently shelved primarily because the environmental externalities associated with pumping water uphill, i.e. greenhouse gas emissions, were too great [77]. This issue is plainly not unique to wastewater, and some other promulgated solutions to water shortages, such as desalination, can be considerably more energy-hungry than wastewater reuse [78]. It does nonetheless highlight that in the haste to reap environmental benefits through reusing wastewater for irrigation, detrimental impacts could easily be overlooked.

Historically, vegetable market gardens tend to be situated on the outskirts of major cities, as are major sewage treatment plants, and this geographical convenience probably explains, at least partially, why vegetable irrigation has been one of the most prominent agricultural uses of wastewater. In Australia, effluents from two large sewage treatment plants on the eastern and western fringes of Melbourne are being used to irrigate adjacent market garden districts [79, 80]. In South Australia, the treated wastewater from the Bolivar sewage treatment plant is distributed to 250 vegetable growers in the Virginia Plains district, which accounts for 35% of the State's horticultural production [81, 82].

5 Conclusion

The world's freshwater resources are under strain. Reuse of wastewater, in concert with other water conservation strategies, can help lessen anthropogenic stresses arising from over-extraction and pollution of receiving waters. On the other hand, there are concomitant environmental risks with wastewater reuse. Ultimately, the challenge facing wastewater reuse is to minimise such risks so as to maximise the net environmental gain.

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