Downstream of downtown: urban wastewater as groundwater recharge

S. S. D. Foster · P. J. Chilton

Abstract Wastewater infiltration is often a major component of overall recharge to aquifers around urban areas, especially in more arid climates. Despite this, such recharge still represents only an incidental (or even accidental) byproduct of various current practices of sewage effluent handling and wastewater reuse. This topic is reviewed through reference to certain areas of detailed field research, with pragmatic approaches being identified to reduce the groundwater pollution hazard of these practices whilst attempting to retain their groundwater resource benefit. Since urban sewage effluent is probably the only 'natural resource' whose global availability is steadily increasing, the socioeconomic importance of this topic for rapidly developing urban centres in the more arid parts of Asia, Africa, Latin America and the Middle East will be apparent.

Résumé L'infiltration des eaux usées est souvent la composante essentielle de toute la recharge des aquifères des zones urbaines, particulièrement sous les climats les plus arides. Malgré cela, une telle recharge ne constitue encore qu'un sous-produit incident, ou même accidentel, de pratiques courantes variées du traitement de rejets d'égouts et de réutilisation d'eaux usées. Ce sujet est passé en revue en se référant à certaines régions étudiées en détail, par des approches pragmatiques reconnues pour permettre de réduire les risques de pollution des nappes dues à ces pratiques tout en permettant d'en tirer profit pour leur ressource en eau souterraine. Puisque les effluents d'égouts urbains sont probablement la seule «ressource naturelle» dont la disponibilité globale va croissant constamment, l'importance socio-économique de ce sujet est évidente pour les centres urbains à développement rapide de l'Asie, de l'Afrique, de l'Amérique latine et du Moyen-Orient.

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Resumen La infiltración de aguas residuales es a menudo un componente principal de la recarga total en acuíferos ubicados en torno a zonas urbanas, especialmente en los climas más áridos. A pesar de ello, dicho componente todavía es una consecuencia secundaria (o incluso accidental) de diversas prácticas asociadas con la manipulación de las aguas residuales y con la reutilización de aguas depuradas. Este tema se revisa mediante referencias a ciertas áreas en las que existen investigación detallada de campo, identificando enfoques pragmáticos con el fin de reducir el riesgo de contaminación de las aguas subterráneas por tales prácticas, a la vez tratando de conservar los beneficios para los recursos del acuífero. Dado que los efluentes de aguas residuales urbanas son probablemente la única 'fuente natural' cuya disponibilidad global se halla en del aumento, la importancia socioeconómica de este tema será evidente para los centros urbanos de rápido desarrollo en Asia, Latinoamérica y Oriente Medio.

Keywords Urban groundwater · Wastewater reuse · Wastewater recharge

Wastewater and Groundwater— an Intimate but Unrecognised Relationship

Rapid growth in urban population and water demand in the last few decades have resulted in greatly increased water-supply provision and, thus, wastewater generation. It has also become apparent that common wastewater handling and reuse practices incidentally result in high rates of infiltration to underlying aquifers. Volumetrically, this is often the most significant local 'reuse' of urban wastewater, but one that is rarely planned and may not even be recognised. The infiltration of wastewater has important resource benefits, both improving its quality and storing it as groundwater for future use, but also represents a potential health hazard because it can pollute aquifers used for potable water-supply.

Groundwater recharge with wastewater occurs (Foster et al. 1997) regardless of whether the urban area is served, primarily by:

- on-site sanitation facilities, with discharge direct to the soil on a diffuse basis via septic tanks and latrines.

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Table 1 Summary of field conditions in research areas on wastewater recharge of groundwater systems

Location	Hydrogeology		Wastewater System		Aquifer Recharge	
	Aquifer Type(s)	Annual Rainfall	Years in Operation	Treatment Level	Treatment/ Distribution	Irrigation Reuse
Lima suburb, Peru	aeolian sand of local extension	20	30–35	Primary or secondary*	A	B
Wadi Dhuleil, Jordan	wadi alluvium on extensive limestone	150	10–15		B	B
Mezquital Valley, Mexico	intermontane valley-fill (local alluvial fans with lacustrine deposits)	450	20–40	None engineered, but equivalent to primary within canals and reservoirs	B	A
Leon (Gto), Mexico		600	10–30		A	B
Hat Yai, Thailand	coastal alluvial strip	1,600	About 20		B	

A Treatment in lagoons with varying conditions and retention periods; *B* relative importance of recharge from unlined lagoons/canals and excess field application

- main sewerage systems, with discharge of effluent downstream of the urban centre and subsequent reuse for irrigation.

This paper deals with how the installation and extension of main sewerage systems affect groundwater. It concentrates on common current practices of sewage effluent handling and reuse, and makes only passing reference to more novel schemes of direct recharge and aquifer treatment of wastewater (Idelovitch and Michail 1984; George et al. 1987; Foster et al. 1994). The topic has major implications in terms of future approaches to groundwater and wastewater management in rapidly developing urban centres, especially (but not exclusively) in the more arid regions.

The expansion of waterborne sewerage in developing cities has proceeded intermittently over many years, with the first small systems having been introduced in the hearts of the older capitals early in the 20th century, following public health concerns or copying European engineering fashion.

As a result of their piecemeal development, most systems generate effluent to a variety of convenient watercourses with minimal treatment, although some settlement will have usually occurred. There has been little concern about the pollutant assimilation capacity of receiving watercourses, and in the more arid regions the bulk of dry-season flow downstream of urban centres will be raw sewage. The 'wastewater' currently available for irrigation reuse is thus normally either untreated or partially treated, but often diluted, sewage effluent.

Nevertheless, such wastewater is very valuable in agricultural production for poorer farmers not only because of its continuous availability, but also because of its role as a soil conditioner as a result of its large organic load and high plant nutrient content (Jimenez and Garduño 2002). There are, however, numerous instances of indiscriminate practice, such as irrigation with raw wastewater directly from sewer lines and cultivation of vegetables or fruit, which are eaten uncooked. These practices involve a very high public health risk. There may also be longer-term hazards if certain types of industrial effluent are present in wastewater, such as build-up of toxic elements (notably lead, chromium, cadmium, boron, etc) in soils, reduction of soil fertility and possible up-take into the food-chain.

Wastewater as Aquifer Recharge—a Useful Resource

Although the provision of mains sewerage lags considerably behind population growth and water-supply provision, sewage effluent is now being generated in significant volumes by most developing cities. There are various ways in which groundwater recharge occurs incidentally during effluent handling and reuse: –the most common of which is by excess agricultural irrigation in downstream riparian areas following effluent discharge to surface watercourses.

At all the field research areas (Table 1) there is clear evidence of high rates of groundwater recharge, for example:

- at the Lima site, the vadose zone Cl balance suggests field infiltration rates of 1,400–1,600 mm/year with over 60% of the wastewater delivery, of some 10 Mm^3/year, infiltrating (Geake et al. 1987), despite the fact that this pilot scheme was primarily intended for agricultural demonstration
- similar unit rates have been estimated for the Mezquital Valley, the largest wastewater reuse area in the world (Fig. 1), which receives most (about 1,500 Mm^3/year) of Mexico City's wastewater and comprises over 50,000 ha of irrigated land, and here

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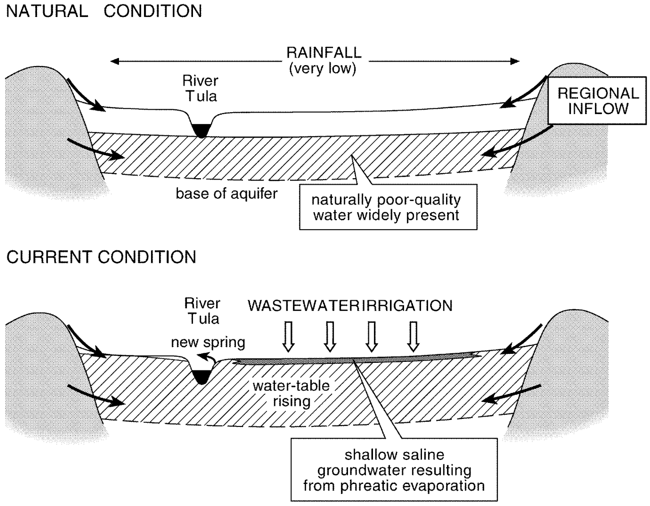

Fig. 1 Cross section of Mezquital Valley, Mexico, showing effects of wastewater irrigation and recharge on aquifer water levels

there is also a major recharge component from unlined wastewater canals and reservoirs (CNA et al. 1998).
– in the Leon area, aquifer groundwater levels have stabilised locally as a result of wastewater reuse and incidental recharge, despite heavy abstraction for municipal water-supply

It can thus be strongly argued that major incidental recharge of aquifers is so ubiquitous that it should always be contemplated as an integral part of the wastewater disposal or reuse process, and thus be planned for accordingly.

Wastewater as a Groundwater Pollution Hazard—Risk Assessment

The range of potential groundwater pollutants from wastewater infiltration includes pathogenic microorganisms, excess nutrients and dissolved organic carbon (Ronen et al. 1987) and, particularly where a significant component of industrial effluent is present, toxic heavy metals and xenobiotic organic compounds. However, the actual effect on groundwater quality (as illustrated from the research areas in Table 2) can vary widely (Foster et al. 1997, 2002) with:

– the pollution vulnerability of the aquifer concerned
– the quality of native groundwater and thus its potential use
– the origin of the sewage effluent, which determines the likelihood of persistent contaminants being present
– the quality of wastewater, and its level of treatment and dilution
– most importantly, the scale of wastewater infiltration compared with that of aquifer through flow
– the mode of wastewater handling and land application

Although the lattermost factor varies little in practice since common wastewater reuse practices still mostly employ unlined treatment lagoons and distribution reservoirs with flood irrigation at field level.

In some hydrogeological conditions, notably those with shallow water-table or near-surface fractured aquifers, there is likely to be significant penetration of pathogenic bacteria and viruses to aquifers (Fig. 2A; CNA et al. 1998), but in most other conditions vadose zone attenuation (over percolation depths of 2–5 m) will be very effective in eliminating most pathogens (Fig. 2B; Geake et al. 1987) and (in this sense) achieving tertiary level wastewater treatment.

However, even under favourable conditions in terms of aquifer vulnerability and wastewater quality, the wastewater infiltration process alone cannot achieve strict potable water-quality standards in phreatic aquifers (Bouwer 1991). This is mainly a consequence of the following:

– the N content of wastewater considerably exceeds plant requirements, leading to the excess being leached from irrigated soils and resulting in NO_3 concentrations of over 45 mg/l in groundwater recharge (Table 2)
– where wastewater infiltrates directly, NH_4 is generally the stable N species and is likely to reach troublesome levels (Table 2)
– elevated DOC concentrations are typically 3–5 mg/l and peak at 6–9 mg/l (Fig. 3) compared with normal background levels of less than 1–2 mg/l

These elevated DOC concentrations give rise to two associated concerns:

Table 2 Typical composition of shallowest groundwater affected by wastewater infiltration in research areas at time of study (BGS et al. 1998)

Location	Selected Dissolved Constituents (mg/l)							Trace elements[a]
	Na	Cl	NO_3	NH_4	B	DO_2	DOC	
Lima suburb, Peru[b]	90/85	182/168	40/85	3.2/0.8	n.d.	n.d.	5/4	n.d.
Wadi Dhuleil, Jordan[c]	570[c]	1,190[c]	130	1.3	1.2	2	3	Mn, Zn
Mezquital Valley, Mexico	240	220	60	<0.1	0.8	3	4	As
Leon (Gto), Mexico[d]	210	340	40	<0.1	0.3	2	4	Mn, Ni, Cr, Zn
Hat Yai, Thailand	40	50	<1	6.2	<0.1	0	3	Mn, Fe, As

[a] indicates those detected in low concentrations
[b] separate values given for aquifer beneath treatment lagoons/irrigated fields
[c] aquifer also subject to some saline intrusion
[d] wastewater has major industrial component

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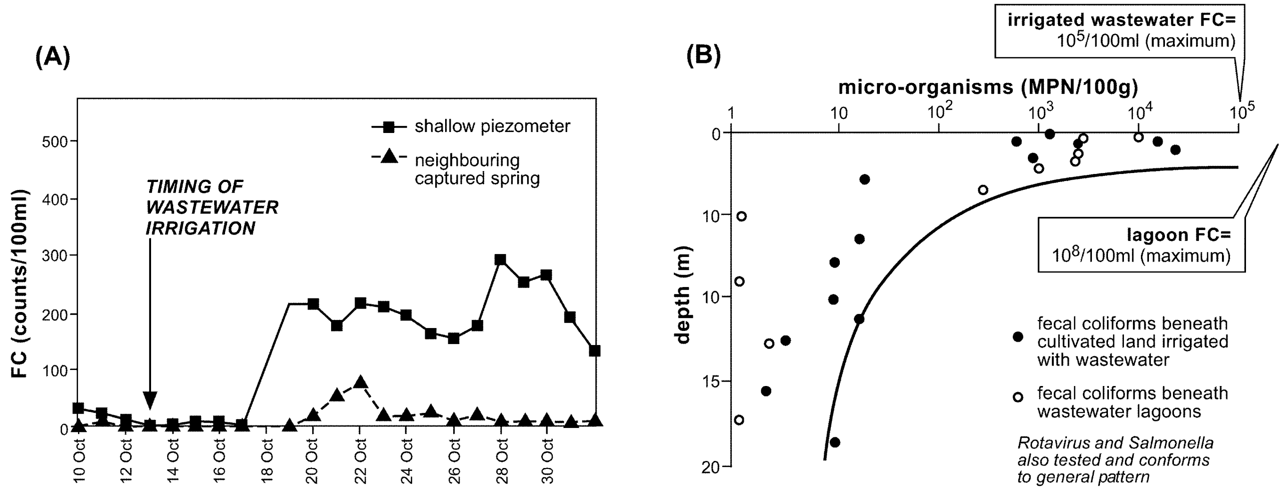

Fig. 2 Transport of faecal pathogens from wastewater with groundwater flow: **A** saturated zone penetration in intermontane deposits with shallow water-table in Mezquital Valley, Mexico, area and **B** vadose zone attenuation in aeolian sand at Lima, Peru, site

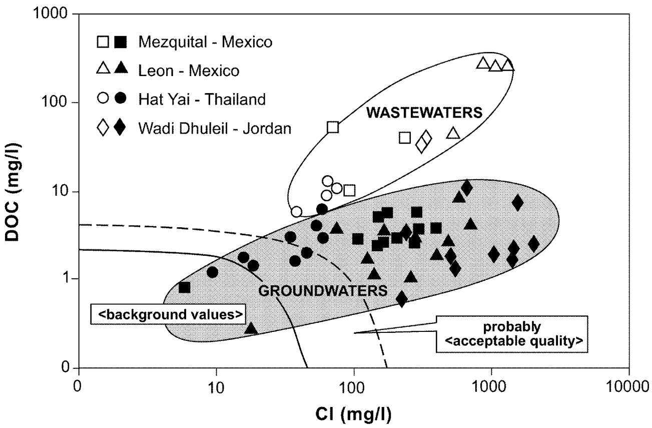

Fig. 3 Range of increased Cl and DOC concentrations in groundwater from wastewater infiltration research areas (BGS et al. 1998)

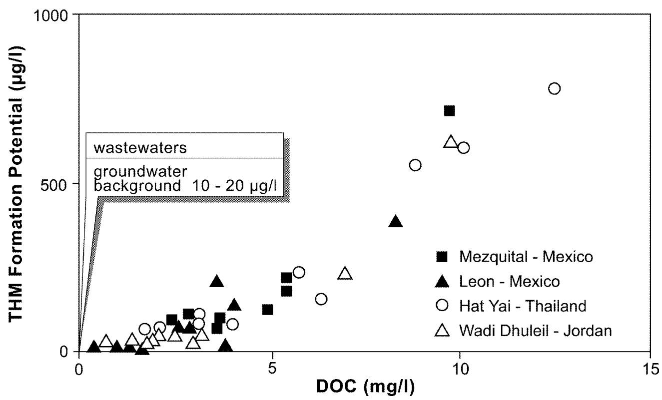

Fig. 4 Correlation of DOC with THM formation potential of groundwater from wastewater infiltration research areas (Stuart et al. 2001)

– potential for the formation of harmful trihalomethanes if the groundwater is disinfected for potable-supply.
– ‘affected groundwaters’ from the research areas had a ‘DOC reactivity’ of 20–45 µg/mg and some samples recorded relatively high trihalomethane (THM) formation potential values of over 100 µg/l (Fig. 4)
– the possibility that the DOC (which is mainly humic-like acids but includes sterols, phthalates, phenols, non-ionic detergents and a wide variety of ‘not positively identified compounds’) could also include trace levels of manmade organic chemicals potentially harmful to human health (Bouwer 1991) — although broadscan GC-MS screening for the more common of these did not reveal any serious problems in the areas concerned (BGS et al. 1998), and the presence of carcinogenic compounds, endocrine disrupters or other hazardous chemicals has rarely been confirmed in groundwater

Some sewage effluent has elevated salinity levels as a consequence of the following:

– exfiltration to sewers of brackish soil water in arid regions
– a substantial flow contribution from saline industrial discharge

It can be seen (Fig. 3) that this can lead to groundwater recharge from wastewater infiltration containing in excess of 250 mg Cl/l. Typical of this situation is Leon in Mexico, a major leather processing and shoe manufacturing centre, which is extensively sewered. It produced, at the time of investigation, some 90 Mm^3/year of wastewater used for agricultural irrigation. There is continuous infiltration, from streambeds, irrigation canals and irrigated fields, of wastewater with high salinity, chromium content and organic load. Wastewater in the main sewers from industrial areas contained 500–600 mg

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Cl/l, and 15–40 mg Cr/l, but almost all of the Cr (which is not deposited in streambed and reservoir sediments) accumulates in the soil. The impact on groundwater quality is less marked, except that deep municipal boreholes in the wastewater irrigation area are seriously threatened by increasing salinity from a downward-moving NaCl front (Chilton et al. 1998).

Groundwater and Wastewater Management—a Pragmatic but Integrated Approach

Improving Groundwater Source Protection

Because groundwater is often the preferred source of public water-supply, and is also widely exploited for private domestic and sensitive industrial use, aquifer pollution hazard is a serious consideration. However, little progress in reducing this hazard is likely to be made in the developing world by simply advocating rigorous quality standards. Indeed, the existence of such standards can be counterproductive, often leading environmental health agencies to 'turn a blind eye' to the situation because they do not have the personnel capacity and financial resources to respond.

There is a pressing need to confront the reality of current practices pragmatically, by identifying where cost-effective interventions and incremental investments can best be made to reduce the risks to groundwater users (George et al. 1987) rather than constructing conventional sewage treatment works that may be of questionable operational sustainability. These priority actions then need to be pursued consistently (as part of a package that includes those directed at other critical issues such as cropping controls, farm-worker health and soil fertility) with the participation of representatives of all rural and urban stakeholders involved.

A high priority should always be to improve wastewater characterisation as an aid to the assessment of a groundwater pollution hazard. Where potential problems associated with persistent contaminants (such as high salinity and certain toxic industrial organic and inorganic chemicals) become apparent, the best approach will be to evaluate their origin within the overall sewerage system and establish the feasibility of control at source or separate collection and disposal (Foster et al. 1997; Dillon 2002).

The impact of wastewater infiltration on specific groundwater supply sources will depend not only on the effect on the shallow aquifer system, but also on the siting of these sources relative to the wastewater infiltration area, their depth of water intake and the integrity of well construction. With careful control of such factors, and under favourable circumstances in terms of aquifer vulnerability and wastewater quality, compatibility between wastewater reuse and groundwater supply interests can be achieved through:

- increasing the depth and improving the sanitary sealing of potable waterwells
- establishment of appropriate source protection areas for such waterwells
- increasing monitoring of FCs, THM formation potential, Cl, N species and other indicators
- using shallow irrigation wells to recover most of the wastewater infiltration and provide a partial 'hydraulic barrier' for the protection of deeper potable water-supply wells
- improving irrigation water-use efficiency and thus reducing wastewater recharge to aquifers
- urging constraints on the use of shallow private domestic wells for potable use

Making Balanced Decisions in Wastewater Management

A related question is how can future urban wastewater engineering take adequate account of groundwater resource interests. Current decisions to extend mains sewerage coverage are normally taken in relation to the following technical and social factors:

- inadequate subsoil capacity to dispose of liquid effluent due to the presence of low-permeability surface strata and/or high water table, causing malfunction and overflow of in-situ sanitation units
- high-density residential development with inadequate access and/or space for removal of solid residues from in-situ sanitation units

Adequate consideration is rarely given to the new environmental problems that may be created by discharge of sewage effluent compared with those associated with existing in-situ sanitation and its potential up-grade to higher ecological standard. Nor is much emphasis placed on water resource issues (Dillon 2002) such as:

- providing additional water supplies for amenity or agricultural irrigation through wastewater reuse
- reduction of the ingress of saline groundwater into sewers in arid areas
- reducing the pollution hazard to municipal wellfields and/or private wells situated within the urban area
- the increase in water supply required for the water-borne sewerage system, some of which is likely to be met from groundwater sources

A more integrated approach is needed, but to achieve this there are significant institutional questions to be addressed (Jimenez and Garduno 2002), such as:

- Which agency should have final responsibility for wastewater management?
- How best can a broader base of stakeholder consultation be introduced?
- What are the legal rights and obligations of wastewater users with respect to those of wastewater generators and, in particular, how should wastewater discharge permits consider reuse factors?

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– How can training on wastewater–groundwater relations best be implemented?

The groundwater dimension is often still one of the 'missing links'. It can be strongly argued that major incidental recharge of aquifers through wastewater handling and reuse is so widespread that it should always be contemplated as an integral part of wastewater management and, thus, planned for accordingly (Foster et al. 1997). Those responsible for wastewater need to be made aware of the benefits and hazards of wastewater recharge to aquifers, and how hydrogeological environments vary with regard to pollution vulnerability. Because the contaminant attenuation capacity of the soil–vadose zone–aquifer system varies widely, specific local studies will be necessary to determine safe loading rates and patterns, and appropriate separation distances and travel times to drinking water sources. Then, a stronger element of municipal planning will be needed for the worst (and least sustainable) of past practices to be avoided in future.

If viewed primarily from the perspectives of groundwater recharge and quality protection (justified in view of the destiny of much urban wastewater in the more arid areas), then decisions on wastewater management often take on a very different light. Much more attention needs to be put on:

– defining wastewater collection and treatment approaches in relation to the threats to groundwater posed by contaminants that are known to be mobile and persistent in the subsurface
– exchanging treated wastewater for waterwell abstraction rights in irrigation areas of lower aquifer pollution vulnerability, as a means of conserving high-quality groundwater for potable uses
– using infiltration through the vadose zone of aquifers for tertiary treatment of wastewater, with recovery for the irrigation of high-value crops, while protecting other parts of the groundwater system from quality deterioration
– recognising that aquifer storage of reclaimed wastewater will often be the best overall option where demand for irrigation water exhibits large seasonal variation

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References

BGS, CNA, SAPAL, WAJ, DMR, PSU (1998) Protecting groundwater beneath wastewater recharge sites. BGS Technical Report WC/98/39
Bouwer H (1991) Groundwater recharge with sewage effluent. Water Sci Technol 23:2099–2108
Chilton PJ, Stuart ME, Escolero O, Marks RJ, Gonzalez A, Milne CJ (1998) Groundwater recharge and pollutant transport beneath wastewater irrigation: the case of Leon, Mexico. Geol Soc Spec Publ 130:153–168
CNA, BGS, LSHTM, UB (1998) Impact of wastewater reuse on groundwater in the Mezquital Valley, Hidalgo State, Mexico. BGS Technical Report WD/98/42
Dillon PJ (2002) Management of aquifer recharge for sustainability. Proc 4th International Symposium on Artificial recharge of Groundwater, Adelaide, September 2002. Balkema, Rotterdam
Foster SSD, Gale IN, Hespanhol I (1994) Impacts of wastewater reuse and disposal on groundwater. BGS Technical Report WD/94/55
Foster SSD, Lawrence AR, Morris BL (1997) Groundwater in urban development : assessing management needs and formulating policy strategies. World Bank Technical Paper 390
Foster SSD, Hirata RA, Gomes D, D'Elia M, Paris M (2002) Groundwater quality protection: a guide for water utilities, municipal authorities and environment agencies. World Bank Book Publication, Washington, DC
Geake AK, Foster SSD, Wheeler D (1987) Unsaturated zone pollutant transport beneath a low-technology wastewater reuse facility. UNESCO-RIVM Symposium, Noordwijk, pp 1011–1025
George DB, Leftwhich DB, Klein NA, Claborn BJ (1987) Redesign of a land-treatment system to protect groundwater. J Water Pollut Control Fed 59:813–820
Idelovitch E, Michail M (1984) Soil-aquifer treatment: a new approach to an old method of wastewater reuse. J Water Pollut Control Fed 56:936–943
Jimenez B, Garduño H (2002) Social, political and scientific dilemmas for massive wastewater reuse in the world. In: Navigating rough waters: ethical issues in the water industry. AWWA Publication, USA, ISBN 1-58321-129-2
Ronen D, Magaritz M, Almon E, Amiel AJ (1987) Anthropogenic anoxification (eutrophication) of the water-table region of a deep phreatic aquifer. Water Resour Res 13:1554–1560
Stuart ME, Goody DC, Kinniburgh DG, Klinck BA (2001) Trihalomethane formation potential : a tool for detecting non-specific organic groundwater contamination. Urban Water 3:173–184

 DOI 10.1007/s10040-003-0296-y