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Review

Groundwater recharge with reclaimed municipal wastewater: health and regulatory considerations

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Abstract

Groundwater recharge with reclaimed municipal wastewater presents a wide spectrum of technical and health challenges that must be carefully evaluated prior to undertaking a project. This review will provide a discussion of groundwater recharge and its management with special reference to health and regulatory aspects of groundwater recharge with reclaimed municipal wastewater. At present, some uncertainties with respect to health risk considerations have limited expanding use of reclaimed municipal wastewater for groundwater recharge, especially when a large portion of the groundwater contains reclaimed wastewater that may affect the domestic water supply.

The proposed State of California criteria for groundwater recharge are discussed as an illustration of a cautious approach. In addition, a summary is provided of the methodology used in developing the World Health Organization's *Guidelines for Drinking Water Quality* to illustrate how numerical guideline values are generated for contaminants that may be applicable to groundwater recharge.

Keywords: Advanced wastewater treatment; Drinking water guidelines; Groundwater recharge; Non-potable reuse; Pathogens; Organics; Potable reuse; Public health; Recharge; Soil-aquifer treatment; State of California; Wastewater reclamation and reuse; World Health Organization (WHO)

1. Introduction

Inadequate water supply and water quality deterioration represent serious contemporary concerns for municipalities, industries, agriculture, and the environment in many parts of the world. Factors contributing to these problems include continued population growth in urban areas, contamination of surface water and groundwater, uneven distribution of water resources, and frequent droughts caused by extreme global weather patterns. For more than a quarter century, a recurring thesis in environmental and water resources engineering has been that improved wastewater treatment provides a treated effluent of such quality that it should be put to beneficial use. This conviction in responsible engineering, coupled with increasing water shortages and environmental pollution, provides a realistic framework for considering reclaimed wastewater as a water resource rather than a liability.

Natural replenishment of underground water occurs very slowly; excessive exploitation and mining of groundwater at greater than the rate of replenishment causes declining groundwater levels in the long term and leads to eventual exhaustion of the groundwater resource. Artificial recharge of groundwater basins is becoming increasingly important in groundwater

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management and particularly where conjunctive use of surface water and groundwater resources is considered in the context of integrated water resources management.

Groundwater's major beneficial uses include municipal water supply, agricultural and landscape irrigation, and industrial water supply. The main purposes of artificial recharge of groundwater have been [1–3]: (a) to reduce, stop, or even reverse declines of groundwater levels, (b) to protect underground freshwater in coastal aquifers against saltwater intrusion and (c) to store surface water, including flood or other surplus water, and reclaimed municipal wastewater for future use. Groundwater recharge is also incidentally achieved in irrigation and land treatment and disposal of municipal and industrial wastewater via percolation and infiltration.

There are several advantages in storing water underground via groundwater recharge including:

(a) The cost of artificial recharge may be less than the cost of equivalent surface water reservoirs.
(b) The aquifer serves as an eventual natural distribution system and may reduce the need for transmission pipelines or canals for surface water.
(c) Water stored in surface reservoirs is subject to evaporation, taste and odor problems due to algae and other aquatic productivity, and to pollution, which may be avoided by soil-aquifer treatment (SAT) and underground storage.
(d) Suitable sites for surface water reservoirs may not be available or may not be environmentally acceptable.
(e) The inclusion of groundwater recharge in a wastewater reuse project may provide psychological and esthetic benefits as a result of the transition between reclaimed municipal wastewater and groundwater. This aspect is particularly significant when a possibility exists in the wastewater reclamation and reuse plans to augment substantial portions of domestic or drinking water supplies.

A wide spectrum of technical and health challenges must be carefully evaluated before undertaking a planned groundwater recharge project. Potential or hypothetical health risk considerations have limited expanding use of reclaimed municipal wastewater for groundwater recharge, when a large portion of groundwater contains reclaimed wastewater that may affect the domestic water supply.

Most of the research issues that address groundwater recharge and direct or indirect potable reuse are equally relevant to *unplanned* or *incidental* direct potable reuse such as municipal drinking water intakes located downstream from wastewater discharges or from polluted rivers and surface water reservoirs. Tapping of polluted water sources for unplanned or incidental potable reuse of polluted drinking water supply sources in the absence of adequate treatment may expose people to health risks not associated with protected water sources. Unresolved health concerns associated with drinking water drawn from polluted water sources certainly exist for wastewater reuse for potable purposes; however, a properly planned and managed water reuse project can produce higher quality finished water than unplanned reuse as is current common practice.

2. Techniques of groundwater recharge

Two types of groundwater recharge are commonly used with reclaimed municipal wastewater: surface spreading or percolation, and direct aquifer injection.

2.1. Groundwater recharge by surface spreading

Surface spreading is the simplest, oldest, and most widely applied method of artificial recharge [2]. In surface spreading, recharge waters such as treated municipal wastewater percolate from spreading basins through the unsaturated soil and ground (vadose) zone. Infiltration basins are the most favored methods of recharge because they allow efficient use of space and require only simple maintenance. In general, infiltration rates are highest where soil and vegetation are undisturbed.

Where hydrogeological conditions are favorable, wastewater reclamation can be implemented relatively simply by the SAT process. The necessary treatment can often be obtained by filtration as the wastewater percolates through the vadose zone, and then some distance laterally through the aquifer. Recommended pretreatment for municipal wastewater for the SAT process includes primary treatment or a stabilization pond, and dissolved air flotation. Pretreatment processes that leave high algal concentrations in the recharge water should be avoided, because algae can severely clog the soil of infiltration basins. While renovated wastewater from the SAT process is of much better water quality than the influent wastewater, it could be lower quality than the native groundwater. Thus, the SAT process should be designed and managed to avoid encroachment into the native groundwater and to use only a portion of the aquifer. The distance and transit time between infiltration basins and wells or drains should be as great as possible, usually at least 50–100 m and perhaps 6 months to give adequate SAT [1,4].

Advantages of groundwater recharge by surface spreading include: (a) groundwater supplies may be replenished in the vicinity of metropolitan and agricultural areas where groundwater over-drafting is severe, and (b) surface spreading provides the added benefits of the treatment effect of soils and transporting facilities of aquifers.

2.2. Direct injection to groundwater aquifer

Direct subsurface recharge is achieved when water is placed directly into an aquifer. In direct injection, highly treated reclaimed water is pumped directly into the groundwater zone, usually into a well-confined aquifer. Groundwater recharge by direct injection is practiced: (a) where groundwater is deep or where the topography or existing land use makes surface spreading impractical or too expensive, and (b) when direct injection is particularly effective in creating freshwater barriers in coastal aquifers against intrusion of saltwater [1,2,4,5]. In arid climates where the practice of groundwater recharge is most imperative, recharge will occur through such means as dry riverbeds and spreading basins, and in most situations there will be an unsaturated zone between the surface and the aquifer.

Both in surface spreading and direct injection, locating the extraction wells as great a distance as possible from the spreading basins or the injection wells increases the flow path length and residence time of the recharged water. These separations in space and in time contribute to the mixing of the recharged water and the other aquifer contents, the opportunity for favorable biological and chemical transformations to occur, and to the loss of identity of the recharged water originating from municipal wastewater. The latter is an important consideration in successful reuse of treated wastewater in order to facilitate public acceptance.

3. Pretreatment for groundwater recharge

Four water quality factors are particularly significant in groundwater recharge with reclaimed wastewater: (a) microbiological quality, (b) total mineral content (total dissolved solids), (c) presence of heavy metal toxicants, and (d) the concentrations of stable and potentially harmful organic substances. Thus, groundwater recharge with reclaimed wastewater presents a wide spectrum of technical and health challenges that must be carefully evaluated. Some basic questions that affect pretreatment choices include [6–8]

- What treatment processes are available for producing water suitable for groundwater recharge?
- How do these processes perform in practice at specific sites?
- How does water quality change during infiltration–percolation and in the groundwater zone?
- What do infiltration–percolation and groundwater passage contribute to the overall treatment system performance and reliability?
- What are the important health issues to be resolved?
- How do these issues influence groundwater recharge regulations at the points of recharge and extraction?
- What benefits, problems, and successes have been experienced in practice?

Pretreatment requirements for groundwater recharge vary considerably depending upon the purpose of groundwater recharge, sources of reclaimed wastewater, recharge methods, location, and, more importantly, public acceptance. Although the surface spreading method of groundwater recharge is in itself an effective form of wastewater treatment, some level of pretreatment must be provided to municipal wastewater before it can be used for groundwater recharge. For direct injection of reclaimed municipal wastewater to groundwater aquifer where domestic water supply may be affected, an extensive treatment consisting of microfiltration and reverse osmosis and ultraviolet disinfection has been installed in several California groundwater recharge projects [5,9].

4. Health and regulatory aspects of groundwater recharge with reclaimed wastewater

It is essential that water extracted from a groundwater basin for domestic use be of acceptable physical, chemical, microbiological, and radiological quality. The main concerns are that adverse health risks could result from the introduction of pathogens or trace amounts of toxic chemicals into groundwater that is eventually to be consumed by the public. Every effort should be made to reduce the number of chemical species and concentrations of specific organic constituents in the applied water [8,10,11]. A source control program to limit potentially harmful constituents entering the wastewater collection system must also be an integral part of any groundwater recharge project. Extreme caution is warranted because of the difficulty in restoring a groundwater basin once it has been contaminated. In the USA, national/federal requirements for wastewater reclamation and reuse have not been established. As a consequence, water reclamation and reuse requirements for groundwater recharge are established by state agencies, e.g., the State of California Department of Health Services (DHS) and the Regional Water Quality Control Boards (RWQCBs) with a case-by-case determination for each project [11,12].

4.1. Health considerations in groundwater recharge with reclaimed wastewater

Groundwater recharge with reclaimed municipal wastewater share many of the public health concerns encountered in drinking water withdrawn from polluted rivers and surface water reservoirs. The ramifications of long-term exposure to many of the chemical constituents in trace quantities are not well understood although the risks, if any, should be very low in well-treated recharged groundwater, and probably no greater than for typical surface water. Nevertheless, regulatory agencies are proceeding with extreme caution in permitting water reuse applications that affect potable water supplies [11,13].

Because of health and aesthetic concerns, drinking water is the highest level end use with the most stringent water quality requirements. The World Health Organization's (WHO) *Guidelines for Drinking Water Quality* (GDWQ) and the methodologies described therein provide a good initial basis for evaluating the quality and safety for consumption of drinking water, but they alone were not intended to be applied to drinking water derived from significantly contaminated sources. The GDWQ and the US National Drinking Water Regulations typically address source water derived from lakes, wells and rivers, which, although frequently contaminated, are almost always of much better quality and more diluted than municipal wastewater. Thus, guidelines and standards assume source water that would not contain significant quantities of known or unknown hazardous contaminants, and waters that have had a long history of apparently safe use albeit after suitable water treatment has been applied.

The irony is that water derived from the 'natural' but obviously imperfect sources, often receives only basic treatment (filtration and disinfection). The final product might not be as high quality as the reclaimed wastewater that has been subjected to much more rigorous treatment, water quality control, and management. The strengths of planned wastewater reclamation and groundwater recharge are that those projects are designed specifically to address the challenges associated with contaminated sources. They are designed, monitored and managed to assure that potential risks are consciously controlled. There is an extra burden to demonstrate that the source water, as proposed to be treated, managed and stored, will be appropriate for the intended use, and will not bear an unacceptable risk for the users.

Each proposed groundwater recharge project should be assessed with respect to the types and quantities of contamination in the source water (e.g., containing industrial and/or domestic wastewater, and unique contaminants). Other factors include the degree of pretreatment and the quality prior to surface spreading or injection into groundwater aquifers, the length of storage time and passage distance which can attenuate contaminants in the ground, the degree of dilution with groundwater, and the type, capability and reliability of treatment that the water will receive when extracted, and finally the extent and type of human exposure to result from the end use; e.g., ingestion, inhalation of aerosols, and dermal exposure, even when potable reuse is not intended.

Pathogenic microorganisms are by far the predominant concern, but trace chemicals must also be considered. Measurement techniques are available for virtually all inorganic substances and radionuclides. Well-established risk assessment methods exist for determining acceptable concentrations below which there is no significant risk to humans. However, some organic constituents are more difficult to assess [14,15].

To form a protective policy, the following questions should be considered: (a) is a water reuse option necessary as a water resource alternative; (b) what level of risk control is attained by a standard relative to the intended use; (c) how valid is the judgment of that level of risk, and, what is the acceptability of a given degree of risk? Risk analysis as applied to natural or reclaimed water entails the same difficulties as that for other health hazards in the environment. Basically, the problem lies in attempting to estimate the hypothetical risks involved and agreeing upon what level of risk to accept [16].

4.2. Concerns for pathogens, trace organics, and public health

Control of viruses and protozoa in reclaimed wastewater is of paramount concern even though such product water may meet microbiological standards set for drinking water, e.g., less than or equal to one total coliform bacterium/100 ml, or no detectable *E. coli* per 100 ml. The principal reason is that reclaimed wastewater is derived directly from municipal wastewater in which pathogen concentrations are higher than even heavily polluted natural waters, and the typical microbiological indicators alone are inadequate for that application. Thus, more extensive regimens for controlling and monitoring of microbial agents must be applied, and additional standards are required. Because routine monitoring for pathogens is not feasible, expensive and not real time; it is more important to design multiple-barrier systems to assure continuous production of safe water.

Removal of specific trace organic compounds through full-scale advanced wastewater treatment (AWT) processes including chemical clarification, filtration, air stripping, activated carbon adsorption, microfiltration (MF), nanofiltration (NF), reverse osmosis (RO), and advanced oxidation using hydrogen peroxide and UV irradiation has been demonstrated. These studies show that there is the capability to control virtually all synthetic organic compounds (SOC) to below current limits of acceptability. However, the majority of higher molecular weight "natural" organic compounds in AWT effluents were unidentified and of generally unknown health significance. Recently, however, methodologies have been developed to identify or classify most of the NOM. The presence of natural organic matter (NOM) also contributes to the formation of disinfection byproducts (DBPs) including trihalomethanes (THM) and other organic halogens (TOX) of potential health significance. The often observed mutagenic activity of AWT effluents is of unknown health significance and a matter of continuing research interest.

Emerging contaminants relevant to groundwater recharge will include: (a) trace organics such as: potential endocrine disrupting compounds (EDCs), pharmaceutically active compounds (PhACs), and *N*-nitrosdimethylamine (NDMA), (b) some trace inorganics and (c) microbes, e.g., nanobacteria ($\approx 0.1\,\mu m$). Wastewater indicators, EDCs, and PhACs selected for study usually are not detected in either NF or RO permeates at pilot- and full-scale. These findings indicate that advanced membrane treatment using NF or RO not only efficiently removes high molecular weight organic carbon compounds, but also selected organic wastewater indicators, such as EDCs and PhACs [17].

4.3. Rationale for establishing groundwater recharge guidelines and regulations

Risk avoidance or risk minimization certainly should be principal elements in the determination of recharge water standards and guidelines in relation to their end uses. However, technological and economic factors also enter into the ultimate quality parameters. Aesthetic factors of taste, odor, and appearance must be important considerations for drinking water even if they do not directly relate to the safety of the water, because consumer acceptance and confidence in the quality and safety are essential.

4.4. Risk assessment for water intended for human consumption

Risk assessment is fundamentally an attempt to quantify the possible health consequences of human exposure in particular circumstances. In the case of drinking water the conclusion would be expressed in terms of the probability (within specified levels of uncertainty) of cases of adverse effects (e.g., fatalities) in the reference population group; for example, an incremental upper bound risk of bladder cancer of one/million (E-6) in a population typically consuming 2 L of drinking water per day for 70 years. The lower bound risk might well be zero, especially if one or more assumptions is invalid. All of these computations and *conclusions* are limited in their reliability and credibility by the quality of the exposure and toxicological data, the mathematical expressions used, and the lack of scientific understanding of the mechanisms of carcinogenesis operative at low environmental doses in genetically diverse humans, as opposed to the high doses to which test animals are exposed. In addition, the significance of low-dose interactions between chemicals is a virtual unknown [18].

In its lowest terms a risk assessment (RA) could be represented as follows:

$$\begin{aligned} \text{RA} = &(\text{concentration distribution}) \\ &\times (\text{persons exposed at each dose}) \\ &\times (\text{risk per dose}) \times (\text{time}). \end{aligned} \qquad (1)$$

The basic information required to perform a qualitative and quantitative risk assessment includes quantitative information on: (a) the occurrence, (b) human exposure, and (c) toxicology of the substance. Although methodologies are available to attempt to quantify each of these factors, in practice, data limitations and analytic complexities usually lead to many simplifying assumptions.

Computing human exposure from occurrence data requires detailed information on water and food consumption patterns and other life-style factors that often are very difficult to model. These would be age-, size-, season-, and location-dependent. Water consumption has been studied in several countries and reasonable distributional data are available. For example, the average drinking water consumption estimated from eight studies was 1.63 L/d. A dietary study [19] concluded that the median daily water consumption in the USA was 1.2–1.4 L/d and that 80–85% consumed less than 2 L, and about 1% consumed more than 4 L per day. This included all tap water including coffee, tea, and reconstituted juices, soups, and food water (e.g., from rice). These estimates are probably low for very warm climates.

Dietary patterns are, however, much more complex and databases amenable to extrapolation to populations are not very extensive. Localized ambient air inhalation data are available for a few substances. Indoor air quality data are potentially of greatest interest but also limited. Water can also contribute to indoor air exposure to volatile substances such as trihalomethanes or radon, or even *Legionella* spp. organisms from growth in plumbing systems. This indirect exposure should also be considered when projecting total exposure and the drinking water contribution. For VOCs in drinking water, this inhalation dose can be equivalent to the amount from ingestion of water. Drinking water standards and guidelines usually have large safety margins that accommodate the inhalation contribution to total intake.

A conceptual framework for various assays and the relative significance to human health is shown in Fig. 1. Toxicological risks that are postulated for exposure

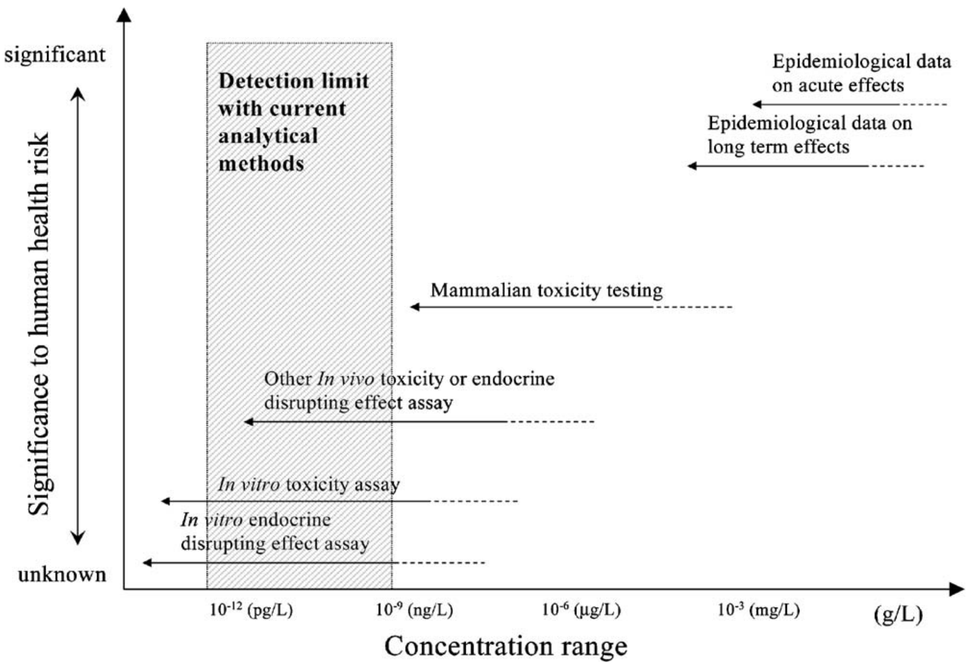

Fig. 1. Conceptual framework for various assays for trace organic compounds and their relative significance to human health risk (Adapted from Tsuchihashi et al. [20]).

levels typical to drinking water are usually well beyond the capability of epidemiological studies to measure. Since regulatory policy generally strives to limit risks nominally below about 1/100,000 for life threatening diseases like cancer, these lower risks are projected orders of magnitude beyond the experimental data by making inferences about the shape of the dose–response curve and extrapolations from effects to humans at higher doses or animal testing, and in vitro assays. At times these projections may encompass a million-fold range with commensurate uncertainty. Imperfect though this system is, it attempts to incorporate all of the available information and creating usable (albeit unverifiable) low dose risk hypotheses that can be helpful for decision making that is designed to err on the side of safety. Thus, *WHO Guidelines for Drinking Water Quality* [21,22] along with expanded detection and evaluation methodologies aimed at the source specific contaminants, and site and technology specific factors should be applied on a case-by-case basis and extended significantly to determine the design and operation of each specific project to assure the suitability of the product water for its end use. Expansion of these guidelines to include wastewater reclamation and recharge applications is recommended. Indeed, the recommendations and methodologies described in the *WHO Guidelines for Drinking Water Quality* provide for appropriate authorities to make suitable water quality and safety determinations based upon the societal, economic and feasibility factors that bear upon the cost/risk/benefit balance that must be struck to assure access to water of both adequate quantity and quality.

A brief description of the type of process used by WHO and US regulatory agencies to determine acceptable concentrations of contaminants in drinking water is provided in Appendix A [23]. The methodology is evolving and variations are commonly applied, but this does describe the basic thought processes that are involved. The methodologies may also be applicable to groundwater recharge with reclaimed municipal wastewater.

5. Proposed State of California groundwater recharge criteria

The proposed California criteria for groundwater recharge with reclaimed municipal wastewater rightly reflect a cautious attitude as discussed above toward short-term and long-term health concerns. The criteria rely on a combination of controls intended to maintain a microbiologically and chemically safe groundwater recharge operation. No single method of control would be effective in controlling the transmission and transport of contaminants of concern into and through the environment. Therefore, source control, wastewater treatment processes, water quality, recharge methods, recharge area, dilution, extraction well proximity, and monitoring wells are all specified. An illustration of this cautious and conservative approach for regulating planned groundwater recharge projects is given in Appendix B, excerpted from draft DHS regulations dated April 23, 2001 [24,26].

California's groundwater recharge criteria are not necessarily applicable to circumstances with different water quantity/quality, economic and risk/benefit environments, but they are instructive of the potential for a comprehensive and protective regulatory program being implemented. These proposed groundwater recharge criteria have undergone several iterations since the early 1990s, and, while several refinements have been made to improve the criteria, many of the requirements specified in earlier drafts remain unchanged. More recent revisions emphasized dilution and unregulated organics and groundwater mound monitoring.

6. Summary and conclusions

To increase the supply of groundwater, artificial recharge of groundwater basins is becoming increasingly important in groundwater management and particularly where the conjunctive use of surface water and groundwater resources is planned. Use of reclaimed wastewater including groundwater recharge for a variety of applications has been implemented and it is safely undertaken provided appropriate planning, treatment, water quality control, assessment, and precautions are followed.

The lack of specific criteria and guidelines governing artificial recharge of groundwater is currently hampering the implementation of additional large-scale groundwater recharge operations. Thus, the establishment of policies and guidance for planning and implementing new groundwater recharge projects is encouraged. The rational basis and other background information for producing groundwater recharge guidelines were briefly presented in this paper and in key references and are further elaborated in Appendices A and B.

Drinking water will be the highest level use with the most stringent quality requirements. The WHO's *Guidelines for Drinking Water Quality* and the methodologies described therein provide a good initial basis for evaluating the quality and safety for consumption of drinking water from common sources, but they alone were not intended to be applied to drinking water derived from significantly contaminated sources such as municipal wastewater. The State of California's draft groundwater recharge criteria is also presented emphasizing a multiple barrier approach.

Much of the concerns and research that address groundwater recharge and potable water reuse are of equal relevance to unplanned or incidental direct potable reuse such as the common practice of municipal drinking water supply intakes located downstream from wastewater discharges or from increasingly polluted rivers and surface water impoundments. The strengths of planned water reuse and recharge are that those projects are designed specifically to address the challenges associated with contaminated sources. They are designed, monitored and managed to assure that the potential risks are consciously controlled.

Chemical and microbial contamination, hazards and risks as well as aesthetic characteristics are the key decision factors for a proposed use of a water of a particular quality. Measurement techniques are available for virtually all inorganic substances and natural and synthetic radionuclides. Well-established risk assessment methods exist for determining acceptable concentrations below which there is no significant risk to humans.

Microbial contaminants can be bacterial, viral, or protozoan or larger organisms and they are by far the most important common risk factors when producing drinking water or reclaimed water for direct or indirect human contact. Their control should never be compromised because of other treatment considerations, e.g. disinfectant byproducts.

The most controversial group of chemical contaminants in wastewaters is the organic substances, which are always present and most difficult to measure and assess. These are mostly natural products, most of which are not likely to be harmful as well as industrial chemicals, and disinfection byproducts. Most discreet industrial chemicals and many disinfection byproducts are measurable by sophisticated instrumental methods, and procedures are available to assess exposure risks in many cases; however, often insufficient experimental toxicology data are available to perform detailed risk assessments. Most of the primarily natural organic chemicals and their derivatives have been historically not readily identifiable; however, great progress is now being made in their characterization. In general, operational standards for water reuse projects have tended to rely on use of treatment trains designed to give significant reduction of difficult to define organic chemicals using a non-specific chemical indicator such as TOC along with measurements and criteria for specific chemicals, (e.g., benzene or nitrosamines). This approach can show that a large portion of the organic chemicals of most types has been removed by the treatment technology, and in addition that specific measurable hazardous chemicals do not exceed limits. If the final TOC is low enough then it is logical that insignificant amounts, if any, of the difficult to define substances of unknown concern remain.

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Appendix A. WHO Guidelines For Chemical Drinking Water Quality

A.1. Introduction

The primary aim of the Guidelines for Drinking Water quality is the protection of public health [21,22]. The latest iteration of the WHO Guidelines is being prepared for release in late 2004. These health-based guidelines are intended to be used as a basis for the development of national standards that, if properly implemented, will ensure the safety of drinking water supplies through the elimination, or reduction to a minimum concentration, of constituents of water that are known to be hazardous to health. Guideline values are not mandatory limits. Thus, the guideline values must be considered in the context of local or national environmental, social, economic, and cultural conditions. The main reason for not providing international standards for drinking water quality is the advantage provided by the use of a risk-benefit approach (qualitative or quantitative) to the establishment of national standards and regulations. The guideline values have sufficient flexibility (i.e. acceptable ranges) to enable national authorities to make judgments regarding the specific values to be required for drinking water of acceptable quality and safety.

Most problems associated with chemical constituents of drinking water arise primarily from their hypothetical potential to cause adverse health effects after prolonged periods of low dose exposure. Of particular concern are contaminants that have cumulative toxic properties, such as heavy metals, and carcinogenic substances. Few common chemical constituents of water can lead to acute health problems except through massive accidental or deliberate contamination.

Guideline values have been set for numerous potentially hazardous water constituents and provide a basis for assessing drinking water quality. They represent the concentration of a constituent that would not, with a margin of safety, result in any significant risk to the health of the consumer over a lifetime of consumption. Guideline values are not set at concentrations lower than the detection limits achievable under routine laboratory operating conditions. Moreover, guideline values are recommended only when control techniques are available to remove or reduce the concentration of the contaminant to the desired level.

In some instances, provisional guideline values have been set for constituents for which (a) there is some evidence of a potential hazard but where the available information on health effects is limited, or (b) the calculated guideline value would be below the practical quantification level, or below the level that can be achieved through practical treatment methods.

A.2. Assumptions

(a) *Drinking water consumption and body weight*. In developing the guideline values for potentially hazardous chemicals, a daily per capita consumption of 2 L by a person weighing 60 kg was generally assumed. The guideline values set for drinking water using this assumption do, on average, err on the side of caution. However, such an assumption may underestimate the consumption of water per unit weight, and thus exposure, for those living in hot climates as well as for infants and children who consume more fluid per unit weight than adults.

(b) *Inhalation and dermal absorption*. The contribution of drinking water to daily exposure includes direct ingestion as well as some indirect routes, such as inhalation of volatile substances and dermal contact during bathing and showering. That portion of the total tolerable daily intake (TDI) allocated to drinking water is generally sufficient to allow for these additional routes of intake.

(c) *Mixtures*. Chemical contaminants of drinking water supplies are present together with numerous other organic and inorganic constituents. The guideline values were calculated separately for individual substances; the large margin of safety incorporated in the majority of guideline values is considered to be sufficient to account for potential interactions of each substance with other compounds present.

(d) *Health risk assessment*. The principal sources of information on health effects resulting from exposure to chemicals used in deriving guideline values are human epidemiology and animal toxicology. Epidemiology is usually limited due to lack of quantitative information on the concentrations to which people are exposed or on simultaneous exposure to other agents, and because the epidemiological tools are relatively insensitive to low risk situations due to confounders. Animal studies are generally limited because of the small number of animals used and the high doses administered, as well as the need to extrapolate the results to the lower doses to which human populations are exposed.

(e) *Derivation of guideline values using a TDI approach*. For most kinds of non-cancer toxicity, it is generally believed that there is a dose to individuals below which no adverse effects will occur. For chemicals that give rise to such toxic effects, a TDI can be derived as follows:

$$\mathrm{TDI} = \frac{\mathrm{NOAEL\ or\ LOAEL}}{\mathrm{UF}},$$

where NOAEL is the no-observed-adverse-effect level, LOAEL the lowest-observed-adverse-effect level, UF the uncertainty factor.

The guideline value (GV) is then derived from the TDI as follows:

$$\mathrm{GV} = \frac{\mathrm{TDI} \times \mathrm{bw} \times P}{C},$$

where, bw is the body weight (60 kg for adults, 10 kg for children and 5 kg for infants), P the fraction of the TDI allocated to drinking water, C the daily drinking water consumption (2 L for adults, 1 L for children, 0.75 L for infants).

(f) *Tolerable daily intake*. The TDI is an estimate of the total amount of substance in food or drinking water, expressed on a body weight basis (mg/kg or μg/kg of body weight), that can be ingested daily over a lifetime without appreciable health risk.

Short-term exposure to levels exceeding the TDI is not a cause for concern, provided the individual's intake averaged over longer periods of time does not appreciably exceed the level set. However, consideration should be given to any potential acute toxic effects that may occur if the TDI is substantially exceeded for short periods of time.

(g) *Uncertainty factors*. There were four sources of uncertainty, each assigned a factor of 1–10: interspecies variation (animals to humans), intraspecies variation (individiual variations), adequacy of studies or database, and nature and severity of effect. For most contaminants, there is great scientific uncertainty, and hence, there may be a large margin of safety above the guideline value before adverse health effects might result.

(h) *Allocation of intake*. In many cases, the intake of a substance from drinking water is small in comparison with that from other sources such as food and air. Guideline values derived using the TDI approach take into account exposure from all sources by apportioning a default percentage (commonly 10%) of the TDI to drinking water. This conservative approach ensures that the total daily intake from all sources does not exceed the TDI.

(i) *Derivation of guideline values for potential carcinogens*. Evaluation of the potential carcinogenicity of chemical substances is usually based on long-term animal studies. Sometimes data are available on carcinogenicity in humans, mostly from occupational exposure. On the basis of the available toxicological evidence, the International Agency for Research on Cancer (IARC) categorizes chemical substances with respect to their potential to be carcinogenic to humans.

It is generally considered that the genotoxic mechanism of chemical carcinogenesis does not have a threshold; consequently, there is a probability of harm at any level of exposure albeit vanishingly small at extremely low levels. Therefore, the development of a TDI is considered inappropriate, and probabilistic low-dose risk extrapolation is applied. The linearized multistage model was generally adopted in the development of the guidelines, and the guideline values are presented as the concentration in drinking water associated with an estimated excess lifetime cancer risk of 10^{-5} ($\pm$a factor of 10) from consumption of 2 L of water per day. These models provide, at best, a rough projection of the cancer risk; they do not usually take into account a number of biologically important considerations, such as detoxification pathways, pharmacokinetics, DNA repair, or immunological protection mechanisms. The models used are conservative and probably err on the side of caution.

Some carcinogens are capable of producing tumors in animals or humans without exerting genotoxic activity, but acting through an indirect mechanism. It is generally believed that a threshold dose exists for these non-genotoxic carcinogens, and guideline values for these compounds were calculated using the TDI approach.

Appendix B. Summary of proposed State of California criteria for groundwater recharge

Summary of proposed groundwater recharge criteria with reclaimed municipal wastewater is shown in Table 1.

B.1. Source control

A well operated and strictly enforced source control program is a prerequisite to groundwater recharge project which must be approved by the State of California Regional Water Quality Control Boards.

B.2. Treatment processes

The definition of ''filtered disinfected wastewater'' in the proposed revisions to the existing regulations for nonpotable uses of reclaimed wastewater now includes the use of membranes to meet the filtration requirements. This includes and does not distinguish between microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Although the performance requirement for membranes is more stringent than that for granular medium filtration (average 0.2 NTU versus 2 NTU), the work done by the City of San Diego, California indicates that a filtered wastewater turbidity of greater than 0.1 NTU signals a breach in the integrity of the membranes.

Table 1
Proposed State of California criteria for groundwater recharge with reclaimed wastewater

Contaminant type	Type of recharge	
	Surface spreading	Subsurface injection
Pathogenic microorganisms		
Secondary treatment	SS $\leqslant 30$ mg/L	
Filtration–turbidity	$\leqslant 2$ NTU	
Disinfection	4-log virus inactivation, $\leqslant 2.2$ total coliform 100 mL	
Retention time underground	6 mos.	12 mos.
Horizontal separation	153 m	610 m
Regulated contaminants	Meet all drinking water maximum contaminant levels (MCLs)	
Unregulated contaminants		
Secondary treatment	BOD $\leqslant 30$ mg/L, TOC $\leqslant 16$ mg/L	
Reverse osmosis	Four options available depending on local conditions	100% treatment to $\text{TOC} \leqslant \frac{1\ \text{mgTOC/L}}{\text{RWC}}$
Spreading criteria for SAT 50% TOC Removal credit	Depth to groundwater at initial percolation rates of: <0.5 cm/min = 3 m. <0.8 cm/min = 6 m.	NA
Mound monitoring option	Demonstrate feasibility of the mound compliance point	NA
Recycled water contribution	$\leqslant 50$% of affected groundwater volume	

Note: RWC = the percent recycled water contribution in groundwater extracted by drinking well water. Adapted from State of California [25], Crook et al. [24], and Hultquist et al. [26].

Also included in the definition of filtered disinfected wastewater is the requirement that the wastewater be oxidized to a TOC concentration of 16 mg/L or less. The current State of California's *Wastewater Recycling Criteria* defines "oxidized wastewater" as wastewater in which the organic matter has been stabilized, is nonputrescible, and contains dissolved oxygen. The TOC requirement of 16 mg/L is a performance based water quality standard.

To address the issue of unregulated organics, the previous drafts of the proposed criteria allowed the use of granular activated carbon (GAC) or reverse osmosis (RO) for organics removal. While it was recognized that GAC and RO could be complementary with respect to the fractions of organics removed by the processes, GAC is generally regarded as not being as efficient as RO for organics removal. Consequently, the proposed groundwater recharge regulations reflect the conclusion that GAC alone is not deemed to be an effective process for controlling unregulated organics.

B.3. Disinfection

The disinfection requirement in the proposed California regulations for non-potable reuse where a high degree of public exposure is expected is also required for all groundwater recharge projects. This is because it assures a substantial log virus reduction, which is the only pathogenic microorganism not effectively removed by the aquifer. Many groundwater recharge projects also provide non-potable water for other urban uses, and the disinfection requirement is readily achievable with reclamation technologies commonly in use in California. The two options for compliance are: (a) filtration followed by chlorination with a modal chlorine contact time multiplied by the chlorine residual (CT value) of 450 mg-min/L; or (b) any combination of filtration and disinfection that has been demonstrated, and is operated, to achieve a 5-log virus reduction.

B.4. Water quality

While the application of an organics removal requirement would appear to solve a plethora of water quality issues, several water quality issues remain. For example, the nitrogen requirement remains under discussion. A proposed total nitrogen standard of 10 mg-N/L was developed in conservative manner to ensure that, should all ammonia forms of nitrogen be converted to nitrate, the effluent nitrate concentration would approach, but never exceed the nitrate maximum contaminant level (MCL). Dilution underground is not considered to be a reliable method for controlling the nitrogen content of the water for a chemical that poses such acute public health threat. Therefore, the total nitrogen standard must be met above ground.

At issue is the nitrite drinking water MCL of 1 mg-N/L. Since biological nitrification and denitrification processes produce nitrite as an intermediate product, it is not known how protective the 10 mg-N/L standard would be of the nitrite MCL.

B.5. Dilution and unregulated organics

The draft criteria use the percent of the drinking water supply that comes from recycled municipal wastewater as a factor in determining the required degree of unregulated organic removal. This fraction is the recycled water contribution (RWC). The previous drafts set separate organic chemical removal requirements for subsurface injection and surface spreading projects going to a 20% RWC and those going to a 50% RWC.

The proposed criteria now contain one set of requirements (in a continuum) for projects with a recycled water concentration up to 50%. Although there are provisions for allowing up to a 100% RWC, the criteria establish, in effect, a dilution requirement for most groundwater recharge reuse projects. The rationale for maintaining this dilution requirement has not changed. An alternative to the 50% maximum RWC criterion is proposed that will assure an equal level of public health protection [24,25].

References

[1] Bouwer H. Groundwater hydrology. New York, NY, USA: McGraw-Hill Book Co; 1978.
[2] Todd DK. Groundwater hydrology, 2nd ed. New York, NY, USA: Wiley; 1980.
[3] Asano T. Artificial recharge of groundwater. Boston, MA, USA: Butterworth Publishers; 1985.
[4] Bouwer H. Groundwater recharge as a treatment of sewage effluent for unrestricted irrigation. In: Pescod MB, Arar A, editor. Treatment and use of sewage effluent for irrigation. Boston, MA, USA: Butterworth Publishers; 1988.
[5] Crook J, Asano T, Nellor MH. Groundwater recharge with reclaimed water in California. Water Environ Technol 1990;42–9.
[6] Asano T, Wassermann KL. Groundwater recharge operations in California. J Am Water Works Assoc 1980; 72(7):380–5.
[7] Roberts PV. Water reuse for groundwater recharge: an overview. J Am Water Works Assoc 1980;72(7):375.
[8] National Research Council. Ground water recharge using waters of impaired quality. Washington, DC, USA: National Academy Press; 1994.
[9] Asano T, editor. Wastewater reclamation and reuse. Water quality management library, vol. 10. Boca Raton, FL: CRC Press, 1998.
[10] National Research Council. Quality criteria for water reuse, Panel on quality criteria for water reuse. Washington, DC, USA: National Academy Press; 1982.
[11] State of California. Report of the scientific advisory panel on groundwater recharge with recycled wastewater. Prepared for State Water Resources Control Board, Department of Water Resources, and Department of Health Services, Sacramento CA, USA, 1987.
[12] US Environmental Protection Agency, and US Agency for International Development. Manual—guidelines for water reuse, EPA/625/R-92/004, Washington, DC, 1992.
[13] National Research Council. Issues in potable reuse—the viability of augmenting drinking water supplies with reclaimed water. Washington, DC: National Academy Press; 1998.
[14] National Research Council. Setting priorities for drinking water contaminants. Washington, DC: National Academy Press; 1999.
[15] Haas CN, Rose JB, Gerba CP. Quantitative microbial risk assessment. New York, NY: Wiley; 1999.
[16] Ongerth HJ, Ongerth JE. Health consequences of wastewater reuse. Ann Rev Public Health 1982;3:419–44.
[17] Drewes J, Amy G, Reinhard M. Targeting bulk and trace organics during advanced membrane treatment leading to indirect potable reuse. AWWA Water Sources Conference Proceedings, Las Vegas, Nevada, January 27–30, 2002.
[18] Cotruvo JA. Drinking water standards and risk assessment. Regul Toxicol Pharmacol 1988;8:288–99.
[19] Ershow AG, Canter KP. Total water and tapwater intake in the United States: population—based estimates of quantities and sources. National Cancer Institute, Order No. 263-MD-810264. Bethesda MD, USA: Life Sciences Research Office, Federation of American Societies for Experimental Biology; 1989.
[20] Tsuchihashi R, Sakaji RH, Asano T. Health aspects of groundwater recharge with reclaimed water. In: Dillon PJ. editor. Management of Aquifer recharge for sustainability. Adelaide, Australia: A. A. Balkema Publishers; 2002.
[21] World Health Organization. WHO guide lines for drinking water quality, vol. 2. Geneva, Switzerland, 1993.
[22] World Health Organization. WHO guide lines for drinking water quality, vol. 1. Geneva, Switzerland, 1996.
[23] Cotruvo JA. WHO guidelines for drinking water quality: assessment methodologies. Unpublished report to WHO on a comparative analysis of risk assessment methodologies used for development of drinking water standards and guidelines, 1999.
[24] Crook J, Hultquist RH, Sakaji RH, Wehner MP. Evolution and status of California's proposed criteria for groundwater recharge with reclaimed water. Proceedings of the American Water Works Association Annual Conference and Exposition, New Orleans. Denver, CO, USA: American Water Works Association; 2002.
[25] State of California. Proposed guide lines for ground water recharge with recycled municipal waste water, and Background information on proposed guidelines for groundwater recharge with recycled municipal wastewater, Interagency water reclamation coordinating committee and the Groundwater recharge committee, Sacramento, CA, USA, 1992.
[26] Hultquist RH, Sakaji RH, Asano T. Proposed California regulations for groundwater recharge with recycled municipal wastewater. American Society of Civil Engineers, Environmental Engineering Proceedings, 759–764, Specialty Conference/EE Div/ASCE, New York, USA, 1991.