Degraded Water Reuse: An Overview

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Communities around the world face increasingly severe fresh water supply shortages, largely due to expanding populations and associated food supply, economic development, and health issues. Intentional reuse of degraded waters (e.g., wastewater effluents, irrigation return flows, concentrated animal feeding operations [CAFO] effluents, stormwater, and graywater) as substitutes for fresh waters could be one solution to the challenge. We describe the various degraded water types and reuse options and limitations and restrictions to their use. Emphasis is given to reuse scenarios involving degraded water applications to soil. The potential for degraded water reuse is enormous, but significant barriers exist to widespread adoption. Barriers include research questions (some addressable by traditional soil science approaches, but others requiring novel techniques and advanced instrumentation), the lack of unifying national regulations, and public acceptance. Educational programs, based on hard science developed from long-term field studies, are imperative to convince the public and elected officials of the wisdom and safety of reusing degraded waters.

Viewed from outer space, Earth is a blue planet dominated by extensive water coverage. All of us, however, recognize that we depend on a very small fraction of the total Earth water supply. Accessible fresh water supplies, suitable for humans, are estimated to constitute <0.02% of the Earth's water supply (Speidel and Agnew, 1988). Furthermore, fresh water supplies and water demands tend not to be equitably distributed, resulting in areas of water scarcity. Water scarcities associated with natural deficiencies in rainfall are exacerbated by population growth, expanding urbanization, and increased irrigation demand, directly related to increased food demands for the expanding population.

Insidious implications of water scarcities include hindered economic development and public welfare, inadequate food supplies, regional conflicts, and environmental degradation. Areas with the greatest water scarcities often have the greatest need for economic development, public welfare, and more food to supply growing populations. The same areas also tend to be subject to regional unrest and environmental degradation. Regions are defined as "water stressed" or "water scarce" if supplies are <1700 and <1000 m^3 per capita per year, respectively (World Resources Institute, 2000). By 2025, at least 3.5 billion people (48% of the world population) are projected to live in water-stressed river basins and at least 2.4 billion people will live under high water stress conditions (World Resources Institute, 2000). Water scarcity issues might be expected to be greater for "developing" countries than industrialized ("developed") countries, but the projections show serious and growing water shortages in the developed world as well, including the USA. Water scarcity problems are well known in the normally dry and increasingly populated southwestern USA, but even water-plentiful areas (the southeastern USA, Florida in particular) are facing severe competition for existing water resources, and water shortages are predicted in the near future as the population continues to grow (Metcalf & Eddy, 2007).

Water conservation practices have historically been viewed as standby or temporary measures, used in times of drought or other emergency water shortages. Today, various conservation measures are viewed as long-term supply augmentation options. Taking shorter showers or using low-flow toilets are familiar conservation practices

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Abbreviations: BOD, biochemical oxygen demand; CAFO, concentrated animal feeding operations; EC, electrical conductivity; ECOC, emerging chemicals of concern; FC, fecal coliforms; LR, leaching requirement; SAR, sodium adsorption ratio; TSS, total suspended solids.

today, and can reduce indoor domestic water use by ~30%. Reducing lawn irrigation using reduced watering frequency, converting to drought-resistant vegetation, and improving water delivery are commonly recommended to homeowners today. On average, American households consume at least 50% of their domestic water through lawn irrigation. In Florida, about 50 to 70% of potable water consumption is used outside, principally for irrigation (USEPA, 2004). Conservation and attitude adjustment (about "desirable" landscape vegetation) could conceivably reduce irrigation use of potable water by ~33 to 50%. Thus, substantial savings (~50%) in domestic potable water use are possible through conservation measures. Miller (2006) cites estimates by Gleick (unpublished, 2004) that up to one-third of California's current urban water use can be saved using existing technologies, such as installing low flush toilets and dual-piping systems (for urinals and high volume air conditioning systems) in new government buildings.

Improving agricultural irrigation efficiency has been the goal of research for decades, and improvements can dramatically reduce fresh water use in the USA and worldwide. Vast quantities of surface and ground waters are used in irrigated agriculture worldwide. The FAO (2003) estimates that ~70% of the water withdrawn from the Earth's rivers, lakes, and aquifers (~820 × 10^7 m^3 d^{-1}) is used for irrigation. For the USA alone, irrigation use is ~53 × $10^7 m^3$ d^{-1} (USGS, 2004). Few would argue with the social and economic value of the food produced in irrigated agriculture, but the investment of water in such operations is enormous and competition with other water demands intense. In New Mexico, ~80 to 90% of fresh water use is associated with irrigated agriculture, much of it applied via low efficiency flood irrigation (USEPA, 2004). Thus, calculations suggest that improving irrigation efficiency by ~10% could allow nearly a doubling of all other fresh water uses (including domestic and industrial).

The national pattern of water use in the USA has been tracked by the USGS for many years (USGS, 2004). In 2000, total water use was ~155 × 10^7 m^3 d^{-1} (~400 billion gal d^{-1}), with about 85% as fresh water. The largest freshwater demands were about equally associated with agricultural irrigation/livestock and thermoelectric power (total ~80%), while public and domestic water needs represent ~12%. The data are useful in targeting water conservation measures, identifying potential sources of non-consumptively used water, and addressing opportunities for water reuse.

Humans have long been reusing water as it moves through the hydrologic cycle. Irrigation return flow contributes significantly to stream flow in many basins. Humans have disposed of various water-dominated wastes (human, animal, industrial) to the land since the dawn of mankind. Water draining from irrigated or waste-amended fields, and effluents from wastewater treatment plants routinely find their way to surface and ground water bodies and are subsequently withdrawn as a part of "fresh water" supplies by down-gradient users.

Society no longer has the luxury of using water only once before in re-enters the hydrologic cycle (Metcalf & Eddy, 2007). Increased, intentional reuse of these "degraded" waters offers many opportunities to address current and future water shortages. Opportunities include (i) substituting for applications that do not require high quality potable water, (ii) augmenting water supplies and providing alternate sources of supply to assist in meeting present and future water needs, (iii) protecting ecosystems, (iv) reducing the need for additional water control structures, and (v) complying with environmental responsibilities (Metcalf & Eddy, 2007).

Definitions/Focus

We define degraded water as water that has suffered chemical, physical, or microbiological degeneration in quality. The degraded water may be treated (sometimes to better-than-original quality) before reuse, but remains identified as degraded for our purposes. Examples of degraded waters include municipal wastewater effluents, effluents from animal operations, irrigation return flow/drainage, industrial (including food processing) wastewaters, stormwater, graywater, and a host of other miscellaneous waters, typically of small quantity and unique quality. This paper identifies the concerns, and research approaches needed to address the concerns, for sustainable degraded water reuse in general, with a focus on conditions in the USA.

Our focus is on systems involving water applications to soil systems; thus, reuse scenarios such as boiler make-up water, direct ground water injection, fire protection, and toilet flushing are not directly addressed. Attention is also given to the sustainability of reuse options that include impacts on soils and on water supplies (inexorably tied to soils) and soil, plant, human, and animal health concerns. We adopt Mullin's (2004) definition of sustainability as the "triple bottom line" of economic prosperity, environmental stewardship, and corporate social responsibility, which emphasizes that academic, industrial, and political plans will fail without public trust in the safety of the plan and products used. Thus, schemes to reuse degraded waters must have earned populace "buy-in." Of the many issues pertinent to public support, environmental health and safety are paramount and are the focus of this overview.

Purpose

The purpose of this paper is to provide an overview of degraded water resources and how they can be used sustainably. We describe various examples of degraded water reuse and the associated limitations and restrictions (including regulatory issues) and suggest the general direction of research necessary to address issues of environmental and human health.

Degraded Water Sources

Fresh waters may suffer degradation in chemical (e.g., increased salinity, nutrient, trace element, organics concentrations), physical (e.g., increased suspended solids, temperature), and/or microbiological (e.g., pathogens) characteristics as a result of use. Some of these degraded waters are reused as is, while others receive considerable treatment. Reusing degraded waters in soil systems can further degrade water quality by increasing salinity or improve water quality through soil-facilitated processes such as microbial degradation of degraded water organics, denitrification, and retention of suspended solids, nutrients (NH_4^+, P), and trace constituents. Most of the water quality effects are well known from extensive research with fresh water supplies, but a few effects are new and/or confounded when degraded waters are reused.

Degraded water sources are many and include industrial process waters, irrigation return flow, concentrated animal feeding operations (CAFOs) effluents, stormwater runoff, domestic graywater, and food-processing effluents (WHO, 2006). Volumes of degraded waters also vary widely, especially on a local basis. In the USA, volumes of degraded water are dominated by thermoelectric power generation and irrigation/livestock operations, which account for ~80% of recurring fresh water demands and dispositions (USGS, 2004).

Thermoelectric

Water use associated with thermoelectric power generation is primarily for cooling purposes, and much of the water is "one-time pass-through." The major water quality impact is increased temperature, although the salinity increases as water is evaporated to effect the cooling process, and biocides may be added to control scaling problems in the cooling towers. Most thermoelectric degraded water is cooled and then discharged to streams under various discharge permits (or to the oceans, as about one-third of the water used for cooling is initially saline). Because the water is not directly applied to soil systems, its reuse is not considered further, but notes are made below of the potential for reuse of other degraded waters (e.g., wastewater effluents) to substitute for the large fresh water demands associated with thermoelectric power generation.

Irrigation

Irrigation/livestock operations require large quantities of fresh water and generate large volumes of degraded waters. Irrigation return flow results from drainage water intentionally generated to support sustainable irrigated agriculture (water used to meet leaching requirements, LR), canal seepage, and bypass (tail) water that exits the end of irrigated fields. Irrigation efficiency and crop salt tolerance largely determine the intentional volumes of return flow. The total volume of irrigation water in the USA is about 52×10^7 m^3 d^{-1} (USGS, 2004), and Solley et al. (1998) estimates that ~29% (~15×10^7 m^3 d^{-1}) appears as irrigation return flow. Major water quality concerns include salinity, sodicity, and specific ion toxicities, but nutrient (N and P) and trace inorganic (Se, B, and Mo, especially) and organic concerns can also be important (discussed below).

CAFOs

Livestock operations, especially CAFOs, use large volumes of water for various animal husbandry activities, but the major concerns associated with the degraded water generated is from animal wastes that are accumulated in lagoons and subsequently applied to the land. Most of the same quality issues identified for irrigation return flows also apply to CAFO wastes, but the latter also include pathogens, veterinary chemicals, and natural and synthetic hormones, collectively known as emerging pollutants of concern (EPOCs). Animal manures are also sources of plant essential nutrients and can be of great value to farming operations, but careful nutrient planning is necessary to avoid excessive nutrient loads to soils and water bodies (Bradford et al., 2008).

Municipal Wastewater Effluents

Public and domestic uses represent about 12% of the total fresh water demands (~19×10^7 m^3 d^{-1}) in the USA, and result in about 16×10^7 m^3 d^{-1} of treated wastewater. Solley et al. (1998) estimated that in 1995 only about 2% of the treated wastewater was reused for beneficial use (primarily, irrigation of golf course and public parks), but more recent estimates (Miller, 2006) were that about 9.8×10^6 m^3 d^{-1} (7.4% of the total) were reused, and that water reuse was growing at about 15% per year.

The minimum level of processing provided by most municipal wastewater treatment facilities is "secondary treatment," defined by the USEPA as meeting <30 mg L^{-1} 5-d biochemical oxygen demand (BOD_5) and total suspended solids (TSS) monthly average, and 85% removal of these parameters under most circumstances. However, many of the treatment plants meet much more stringent water requirements for discharge to specific receiving waters. In some cases, the requirements are more restrictive than drinking water standards. The National Research Council (NRC, 1996) reported that the quality of secondary treated effluent from municipal wastewater treatment facilities for most parameters is generally well below the levels found in the Colorado River and the recommended minimum irrigation water quality criteria.

Stormwater Runoff

Stormwater runoff is defined as excess precipitation that is not retained by vegetation, surface depressions, or infiltration, and thereby collects on the surface and drains into a surface water body (NRCS, 1986). Stormwater runoff volumes from urban and rural areas vary considerably across the USA, primarily as a result of different precipitation patterns and landscape conditions. A computer model (HydroCAD) is available from NRCS to facilitate runoff calculation predictions. Sediment (suspended solids) contained in stormwater is a major water quality issue (Fletcher et al., 2008), as well as solvents, greases, oil, and ECOCs.

Most reuse interest today deals with urban runoff. Expansion of cities, especially "mega-centers" with populations of ≥10 million inhabitants, is already rapid and is expected to increase in the future (Metcalf & Eddy, 2007). The expansion results in loss of green space and porous surfaces to accept rainfall, as well as increased extent of impervious surfaces that increase runoff (Fletcher et al., 2008). Interest in urban runoff is growing (Fletcher et al., 2008), but remains a relatively small component of the overall degraded water resource.

Industrial Wastewaters

High water use industries, such as food processors, coal gasification facilities, and pulp and paper mills produce substantial quantities of wastewater with particular significance on a local basis (USEPA, 2004). On a national level, industrial degraded waters represent only ~5% of the total (USGS, 2004). Industrial degraded waters often have unique qualities (e.g., high BOD, TSS, pesticide residues, high nutrient loads, and even toxic organics– dioxins) that challenge normal reuse applications, and require specialized treatment schemes and site-specific guidelines.

Graywater

Graywater is all residential wastewater originating from clothes washers, bathtubs, showers, and bathroom sinks and is distinguished from "black water" (wastewater from toilets, kitchen sinks, and dishwashers). Wastewater from kitchen sinks and dishwashers are not included because their high organic content leads to oxygen depletion and increased microbial activity. Of the total residential usage, the sources contributing to graywater are baths and showers (about 18% of total usage), clothes washers (22%), and some portion of faucets (16%) (WERF, 2006). Thus, graywater sources comprise about half of the total per capita residential water usage and typically represent about 113 L d^{-1} (~30 gal d^{-1}).

Graywater reuse is gaining in popularity for landscape irrigation and toilet flushing in multi-unit dwellings like hotels and dormitories. In the USA, the most common application is residential landscape irrigation using washing machine water. The majority of graywater is reused without any treatment. Besides lowering the demand on fresh water supplies, graywater reuse reduces the load on septic tanks, leach fields, and wastewater treatment plants. Household graywater reuse is gaining in popularity in communities addressing water resource sustainability. Some states (e.g., Arizona, California, New Mexico, Texas, and Utah) have comprehensive graywater reuse regulations and guidelines (WERF, 2006). Guidelines address setback distances, filtration requirements, restrictions on vegetable watering, and prohibition of runoff generation.

Despite the generally low level of degradation of graywater, there are lingering concerns about the long-term impacts of the practice. Because of the potential multitude of chemicals used in households (e.g., cleansers, bleach, personal care products), uncertainties remain about how combinations of chemicals might impact irrigated areas in terms of residential plant health and soil quality. Because graywater typically contains fecal coliform levels above regulatory levels for natural waters subject to body contact, the risk to homeowners from graywater pathogen exposure remains a question unless some type of disinfection (e.g., UV) is employed. Other contaminants of concern that are common in graywater include soap (and its components, e.g., chelating agents), B, P, etc. Potential impacts on ground water quality have yet to be fully defined.

Reuse Applications

Types of degraded water reuse applications are identified in three major references (USEPA, 2004; WHO, 2006; Metcalf & Eddy, 2007), which should be consulted for detailed descriptions. The USEPA and Metcalf & Eddy references focus on wastewater effluent reuse, but the guidance is generally applicable to other degraded waters. Below are the major types of reuse applications, discussed in order of current reuse prominence. Major emphasis is given to those applications that include soil systems.

Industrial

Major industrial users of degraded waters (especially wastewater effluents) are power plants, oil refineries, and manufacturing facilities. Degraded water is used principally for cooling purposes, either in "once-through" or in "recirculating" systems (USEPA, 2004). Thermoelectric power generation typically requires large quantities of cooling water, and represents a major reuse opportunity for degraded waters assuming corrosion, biological, and scaling concerns are addressed. There are also major opportunities, especially on a local basis, for reuse of degraded water in various production steps of some industries, including the pulp and paper, chemical, textile, and the petroleum and coal industries. Specific requirements for the degraded waters and examples of reuse are discussed elsewhere (USEPA, 2004; Metcalf & Eddy, 2007).

Environmental and Recreational

Environmental uses of degraded waters include wetland enhancement and restoration, creation of wetlands for wildlife habitat and refuge, and stream augmentation (USEPA, 2004). Recreational uses range from landscape impoundments (e.g., water hazards on golf courses) to full-scale development of water-based recreational impoundments that allow either restricted (incidental) contact with the water (e.g., fishing and boating) or unrestricted (full body) contact (e.g., swimming and wading). Only seven states have regulations that specifically address recreational and environmental uses of degraded waters (i.e., wastewater effluents). Examples of the regulations and of the federal guidelines for wastewater effluents are detailed elsewhere (USEPA, 2004). These regulations and guidelines largely focus on minimum treatment standards (BOD, TSS, turbidity) or microbial quality criteria (fecal or total coliforms).

Ground Water Recharge

Ground water recharge with degraded waters can: (i) reduce, or even reverse, declines of ground water levels, (ii) protect underground freshwater in coastal aquifers against saltwater intrusion, and (iii) store surface water, including flood, stormwater, or other surplus water and degraded water for future use (Metcalf & Eddy, 2007). Methods of recharge include surface spreading, vadose zone injection wells, or direct aquifer injection. The first two methods directly involve soil and soil processes (e.g., microbial degradation of water contaminants, retention of nutrients [NH_4^+, P, trace elements], and physical filtration of suspended solids). Alternating aerobic and anaerobic conditions in the vadose and saturated zones are critical to maintain infiltration rates and for successful contaminant removal (including toxic organics; AWWARF, 2006). Direct injection involves pumping water directly into the ground water zone, usually a well-confined aquifer. It is used when ground water is deep or where hydrogeologic (soil) conditions are not conducive to surface spreading. Direct injection is effective to construct barriers against saltwater intrusion and to create a fresh water plume in a saline aquifer for later reuse. Most states in the USA allow use of relatively low quality water (i.e., secondary treatment with basic disinfection of wastewater effluents) based on the proven ability of the surface recharge systems to provide additional treatment

Table 1. Water quality and treatment requirements for unrestricted urban reuse (USEPA, 2004).

State	AZ	CA	FL	TX	WA
Treatment	Secondary treatment, filtered, and disinfection	Oxidized, coagulated, filtered, and disinfected	Secondary treatment, filtration, and high-level disinfection	NS†	Oxidized, coagulated, filtered, and disinfected
BOD_5‡	NS	NS	20 mg L^{-1} $CBOD_5$	5 mg L^{-1}	30 mg L^{-1}
TSS	NS	NS	5 mg L^{-1}	NS	30 mg L^{-1}
Turbidity	2 NTU (Avg); 5 NTU (Max)	2 NTU (Avg); 5 NTU (Max)	NS	3 NTU	2 NTU (Avg); 5 NTU (Max)
Coliform	Fecal None detectable (Avg) 23 100 mL^{-1} (Max)	Total 2.2 100 mL^{-1} (Avg) 23 100 mL^{-1} (Max in 30 d)	Fecal 75% of samples below detection 25 100 mL^{-1} (Max)	Fecal 20 100 mL^{-1} (Avg) 75 100 mL^{-1} (Max)	Total 2.2 100 mL^{-1} 23 100 mL^{-1} (Max)

† Not specified by state regulations.

‡ BOD_5 = 5-d biochemical oxygen demand; $CBOD_5$ = carbonaceous 5-d biochemical oxygen demand; TSS = total suspended solids; NTU = Nephelometer turbidity units.

(USEPA, 2004). Potable water supplies are assumed protected by requiring a minimum separation between the point of application and potable water wells (USEPA, 2004).

Augmentation of Potable Supplies

Indirect (but planned) augmentation of potable water supplies with degraded water is a careful and deliberate process, with an over-riding focus on health and environmental safeguards (Metcalf & Eddy, 2007). Degraded water augmentation of raw water supplies (reservoirs, ground water) relies on mixing, dilution, and assimilation that provide multiple barriers (environmental buffers) to protect potable water supplies. Furthermore, effective drinking water treatment and extensive treated water monitoring to ensure high quality drinking water is the final protective barrier. Many communities currently use surface water sources subject to various upstream discharges of degraded waters, including wastewater effluents, agricultural runoff and return flows, and stormwater runoff and overflows. The use of these surface water sources containing degraded water discharges is referred to as *de facto* potable reuse (Metcalf & Eddy, 2007).

Urban Reuse

Urban degraded water reuses can be divided into "restricted" and "unrestricted" applications. Restricted reuse includes irrigation of areas where public access can be controlled, such as golf courses, cemeteries, and highway medians. Unrestricted urban reuse includes irrigation of areas where public access is not controlled/restricted (e.g., parks, playgrounds, school yards, and residences), use for toilet and urinal flushing in commercial and industrial buildings, air conditioning, fire protection, construction, ornamental fountains, and aesthetic impoundments (USEPA, 2004).

Florida is a major degraded water reuser, and currently leads the nation in the reuse of wastewater effluent (~2.6×10^6 m^3 d^{-1} [~700 million gal d^{-1}), representing ~50% of the state wastewater capacity). Reuse is dominated by urban applications, especially public access irrigation of golf courses and new housing developments. Florida's wastewater effluent reuse guidelines for restricted (golf course) and unrestricted (residences) use are the same and some of the strictest in the nation (Table 1). Reuse programs in Florida enjoy wide public support and are routine parts of irrigation plans for the constantly growing number of golf courses and housing developments in the state. Acceptance is influenced by reduced costs of reclaimed water versus fresh water supplies, increased scarcity of fresh water supplies, and the perceived safety of the reuse application (strict guidelines). Florida relies almost exclusively on wastewater effluents for urban (and other) reuse applications, and has detailed guidelines for each reuse option (USEPA, 2004).

California has the most comprehensive water reuse regulations. The regulations call for tertiary treatment and disinfection for unrestricted use (Table 1), but secondary treatment and disinfection of 2.2 to 23 median counts of total coliform bacteria per 100 mL for restricted reuse. Much of the current urban reuse in California is on turf grasses in golf course and lawns. Opportunities exist to increase urban reuse (e.g., replace potable water currently used to irrigate golf course, increased reuse in urban landscapes, including trees, shrubs, ornamentals, and flowers of other landscapes). A recent comprehensive review of literature and research (Tanji et al., 2008) was intended to overcome the reluctance of some professional landscapers to use recycled water due to concerns about salinity damage to landscape plants. Salinity management for irrigated landscapes is similar to well established management principles for irrigated agriculture, but the latter aims at maximizing yields and the former focuses on maintaining aesthetic quality of landscapes (Tanji et al., 2008). Guidance offered in Tanji et al. (2008) should allay fears of recycled water use, and increase urban reuse in California.

Agricultural Reuse

Agricultural degraded water reuse can also be divided into restricted and unrestricted applications, based on the crops grown and the expected human exposure to water constituents (USEPA, 2004). The distinction is especially pertinent for reuse of wastewater effluents, but can be applied to any degraded water that is expected to represent a significant human exposure to pathogens (e.g., animal manure effluents, some stormwaters, graywaters). Use of degraded waters on food crops intended for direct human consumption typically require water of the highest quality (the highest level of treatment), and the requirements are similar to the quality demanded for unrestricted urban reuse (Table 1). Some states do not allow irrigation of food crops with wastewater effluents of any quality. Florida does not allow direct contact (spray) irrigation with effluent water of edible crops that will not be peeled, skinned, cooked, or thermally processed before consumption (USEPA, 2004). Indirect contact irrigation methods (ridge and furrow, drip, subsurface) are allowed. Irrigation of non-food crops (e.g., fodder, fiber, and seed crops) is generally al-

Table 2. Issues and constraints associated with major soil-based degraded water reuse options (adapted from Metcalf & Eddy, 2007).

Category	Application	Issues/Constraints
Agricultural irrigation	Food and fodder production Commercial nurseries Sod farms Silviculture Frost protection	Water quality impacts on soils, crops, and ground water Buffer zone requirements Marketing of crops Public health concerns Runoff and aerosol control
Landscape (urban) irrigation	Public parks Golf courses and athletic fields Highway medians & shoulders Landscaped areas surrounding residences and public buildings	Public health concerns Public acceptance Runoff and aerosol control Impacts on vegetation
Environmental uses	Wetlands creation and augmentation	Toxicity to aquatic life and wetlands vegetation
Aquifer recharge	Infiltration basins Percolation ponds Soil Aquifer Treatment (SAT)	Availability of suitable sites Ground water contamination Public health concerns

lowed with water of lower quality, similar to the requirements for restricted urban use. Many western states in the USA use wastewater effluents primarily for agricultural irrigation, as opposed to the dominant urban use in Florida.

Aside from pathogen concerns, issues associated with the reuse of degraded waters tend to focus on the same water quality parameters considered in irrigation with fresh waters. Thus, factors to consider include salinity, sodicity, specific ion toxicities, trace element concentrations, and nutrient concerns. Evaluation of degraded water quality for agriculture irrigation can take advantage of decades of salinity- and irrigation-related research and guidelines (e.g., Ayers and Westcot, 1985), with few exceptions. Consideration of organic contaminants (e.g., veterinary and human pharmaceuticals, endocrine disrupting chemicals from a host of sources, pesticide residues, asphalt/vehicular-generated PAHs) is a growing concern. Contaminant concentrations are largely unregulated and their effects on soil-plant-human-aquatic systems poorly understood (Metcalf & Eddy, 2007).

In some parts of the world, there is also considerable interest in using degraded water reuse in aquaculture (WHO, 2006).

Issues and Constraints for Degraded Water Reuse

Reuse of degraded water is growing in importance in many areas of the world, but its full potential remains largely untapped due to numerous barriers (Miller, 2006). Wide-scale reuse of degraded water faces a number of technical, environmental, and social challenges. Four major issues must be addressed for implementation of a soil-based degraded water reuse program: (i) meeting water quantity and quality requirements for the intended use, (ii) protection of health, (iii) maintaining soil productivity, and (iv) public acceptance. Superimposed on these issues are technological, regulatory, and water resource planning obstacles and challenges. Some of the challenges are the same faced when fresh water sources are applied to the soil via the major types of reuse. For example, ensuring that excessive salts do not impact plant growth or soil structure is a common challenge in arid regions. Some constituents in degraded waters, however, present unique challenges in soil-based reuse systems.

Table 2 lists the largest and most important types of soil-based degraded water reuses and the associated issues and constraints. For any specific application, an essential element of the planning process is the identification of constituents or technical issues that could hinder degraded water reuse. Protection of public health is a critical objective in all applications. While technological solutions are available to overcome constraints, public acceptance often presents the greatest challenge to reuse programs. The following briefly summarizes some of the major issues commonly associated with implementing safe and successful reuse programs for degraded water resources.

Salinity

Salinity has long been a concern associated with irrigation and is frequently the single most important parameter determining the suitability of reuse water for agricultural irrigation (USEPA, 2004). The issues of concern are related to impacts associated with various dissolved components, either singly or in combination. The impact of dissolved constituents in irrigated reuse water is generally associated with three issues: salinity, sodicity, and toxicity by specific ions. Trace elements (particularly B, Mo, and Se) are a growing concern.

The same water characteristics that determine the suitability of fresh waters for irrigation (Ayers and Westcot, 1985) apply to degraded waters. General guidelines for irrigation water quality are given in Table 3 (Metcalf & Eddy, 2007). Because plants and soils vary widely in their tolerances to many of these salinity-related effects, the guidelines should be interpreted in the context of the local climatic, agronomic, and management characteristics.

Salinity or specific ion toxicity issues may require special management procedures. Measures can be taken to reduce the proportion of Na^+ relative to other cations, often by adding Ca to the reuse water. Blending degraded water with a higher quality water source can also be used to mitigate salt-related impacts. Table 4 shows typical trace element concentrations in wastewater effluents in comparison to EPA's recommended limits for irrigation waters.

Irrigation management strategies are also an important part of mitigating the salinity impacts of degraded waters. For salinity management, adequate water must be applied to leach salts below the root zone and maintain an EC below the maximum tolerable level for the growing vegetation. The LR is that fraction of water entering the soil that must pass through the root zone to prevent soil salinity from exceeding a specific threshold value that will impact crop yield (Corwin et al., 2008a). Maintaining an adequate LR is essential for long-term success of irrigating with reuse water (Devitt et al., 2007). Dudley et al. (2008) reported that high frequency drip irrigation is effective in reducing the salt load in drainage waters.

Nutrients

Degraded waters contain a number of plant essential nutrients; nitrogen (N) and phosphorus (P) are important macronutrients for plant growth, and reuse waters often contain sufficient N and P to satisfy the needs of the vegetation on the site. Potassium is also a major crop nutrient, but often needs to be supplemented for maximum yields when wastewater effluent is used for irrigation. Reuse waters can also supply adequate levels of other plant-essential nutrients (S, B, and trace elements).

The application of treated or partially-treated wastewater effluents to cropland has long been practiced to avoid nutrient discharges to water bodies. However, if not carefully managed, increased recharge of nitrate in ground water or runoff and leaching of P may also accompany the applications of degraded water to the soil. Calculating the wastewater loading rate in the design of effluent irrigation systems is normally based on the more restrictive of two limiting conditions: the capacity of the soil profile to transmit water or the nitrate concentration of water percolating below the root zone. The latter is complicated by uncertainty in quantifying the amount of N in the reuse water that is actually available to the growing vegetation. To balance N supply with crop needs, changes in wastewater treatment processes (e.g., nitrification–denitrification) are used to lower the total N concentration or change the N speciation in the effluent water.

Phosphorus in degraded waters can be high enough to meet (and, often, exceed) crop needs depending on the P concentration, hydraulic loading rate, and needs of the specific crop. For 5 cm per week loading rate and the typical P levels in secondary effluent (Table 4), continuous irrigation with wastewater effluent will satisfy the P needs of most commercial crops. Concerns over water quality in agricultural watersheds have elicited various national and state initiatives for addressing the impact of soil P on aquatic resources (Sharpley et al., 2003). Most states have developed a P indexing approach to evaluate and manage P loss from fields by runoff and leaching. The indices focus on soils amended with manures and fertilizers. Although P indices are supposed to consider all P containing soil amendments, most do not explicitly address land applied wastewater effluents. The P-related agronomic and environmental implications of continuous application of degraded water sources to soils have received limited study, and remain important research needs.

Pathogens

Humans and animals can potentially be exposed to disease-causing organisms (pathogens) through soil application of some degraded waters. The risk of exposure is greatest when the reuse water has been degraded through contact with human and animal wastes, for example, partially treated domestic or CAFO wastewaters. Humans can come in contact with pathogens by ingestion of crops or drinking water contaminated by degraded water. Aerosols can be generated by land application of municipal wastewater effluents through sprinklers, and individuals living near application sites potentially can be exposed to pathogens contained in the aerosols.

Table 3. Guidelines for interpretation of water quality irrigation (adapted from Ayers and Westcot, 1985).

Potential irrigation problem	Units	Degree of restriction on use None	 Slight to moderate	 Severe
		Salinity		
EC†	dS m^{-1}	<0.7	0.7–3.0	>3.0
TDS	mg L^{-1}	<450	450–2000	>2000
Sodicity				
SAR, 0–3 and EC	dS m^{-1}	≥0.7	0.7–0.2	<0.2
3–6 and EC	dS m^{-1}	≥1.2	1.2–0.3	<0.3
6–12 and EC	dS m^{-1}	≥1.9	1.9–0.5	<0.5
12–20 and EC	dS m^{-1}	≥2.9	2.9–1.3	<1.3
20–40 and EC	dS m^{-1}	≥5.0	5.0–2.9	<2.9
		Specific ion toxicity		
Sodium (Na)				
Surface irrigation	SAR	<3	3–9	>9
Sprinkler irrigation	mg L^{-1}	<70	>70	
Chloride (Cl)				
Surface irrigation	mg L^{-1}	<140	140–350	>350
Sprinkler irrigation	mg L^{-1}	<100	>100	
Boron (B)	mg L^{-1}	<0.7	0.7–3.0	>3.0
		Miscellaneous effects		
Nitrogen (total N)	mg L^{-1}	<5	5–30	>30
Bicarbonate (HCO_3) (overhead sprinkling only)	mg L^{-1}	<90	90–500	>500
pH	unitless		Normal range of 6.5–8.4	
Residual chlorine (overhead sprinkling only)	mg L^{-1}	<1.0	1.0–5.0	>5.0

† EC = electrical conductivity; TDS = total dissolved solids; SAR = sodium adsorption ratio.

Despite the variety of potential pathogens in degraded water, no states have set limits on specific microorganisms. Rather, regulations to protect public health are largely established on total or fecal (thermo-tolerant) coliform (FC) levels

Table 4. Typical constituent concentrations (mg L^{-1}) of treated wastewater effluents (adapted from Metcalf & Eddy, 2007).

Constituent	After secondary treatment	After tertiary treatment	After reverse osmosis	EPA Recommended levels for irrigation Long term	 Short term
As	< 0.005–0.023	< 0.001	0.00045	0.10	10.0
B	< 0.1–2.5	0.3	0.17	0.75	2.0
Cd	< 0.005–0.15	< 0.0004	0.0001	0.01	0.05
Cr	< 0.005–1.2	< 0.01	0.0003	0.10	20.0
Cu	< 0.005–1.3	< 0.01	0.015	0.20	5.0
Hg	< 0.0002–0.001	0.0001	–	–	–
Mo	0.001–0.018	–	–	0.01	0.05
Ni	0.003–0.6	< 0.02	0.002	0.2	2.0
Pb	0.003–0.35	< 0.002	0.002	5.0	20.0
Se	< 0.005–0.02	< 0.001	0.0007	0.02	0.05
Zn	0.004–1.2	0.05	0.05	2.0	10.0
Total N	15–35	2–12	< 1		
Nitrate-N	10–30	1–10	< 1		
Total P	4–10	< 2	< 0.05		

and vary with the expected degree of human contact for the particular reuse scenario. The WHO recommended standard is <1000 FC 100 mL^{-1} for use of degraded water for irrigating crops eaten raw (WHO, 2006). State standards for unrestricted urban use are more stringent, typically varying from non-detectable to 200 FC 100 mL^{-1} (USEPA, 2004).

Disease outbreaks in some countries have been reported from irrigation of untreated wastewater (WHO, 2006). But studies and experience (USEPA, 2004) suggest that functioning wastewater treatments plants produce effluents with minimal pathogenic risk. Brooks et al. (2004) conclude that spray irrigation of wastewater effluent poses little risk to the public of infection from bioaerosols. Pepper et al. (2008) summarize years of study that similarly point to minimal risk from land application of Class B biosolids.

Animal manures, however, may receive little to no treatment to reduce pathogen loads, and frequently contain pathogenic viruses, bacteria, and protozoa that pose a risk to human and/or animal health (Gerba and Smith, 2005; Bradford et al., 2008). There have been highly publicized outbreaks of food-borne illnesses and deaths, as well as major economic impacts associated with manure-contaminated water use on fresh produce (USFDA, 2007). Various animal husbandry and manure handling practices can be implemented to mitigate manure pathogen risks (Bradford et al., 2008), but such practices are not widely used.

Pathogen-related issues still are a major concern, particularly emerging infectious disease agents. New organisms of concern include bacteria (e.g., *E. coli* 0157:H7, *Listeria*, *Heliocobacter*), viruses (e.g., poliovirus, coxsackievirus, echovirus, hepatitis A, rotavirus, Norwalk viruses), and parasites (e.g., *Cryptosporidium*, *Cyclospora*, *Toxoplasma*, *Microsporidia*, and *Giardia*) (Gerba and Smith, 2005). The 2006 outbreak of *E. coli* 0157:H7 on spinach from the Salinas Valley (USFDA, 2007) underscores the need for additional understanding and management of emerging pathogens in degraded water reuse.

Emerging Pollutants of Concern

Management and regulation of soil-based water reuse applications has traditionally focused on specific pesticides or nutrients with potential adverse impacts on health and environment. Reuse of degraded water also results in application of numerous other organic compounds to agricultural fields, which can be transported off-site via runoff and drainage (Pedersen et al., 2003). These "other organics" are currently unregulated, but their presence is of growing notoriety and concern.

Collectively, the unregulated substances are referred to as ECOCs, substances previously undetected or that had not been considered as a risk (Daughton, 2001). The main source of ECOCs in the environment is wastewater treatment plant effluents, which were not designed to eliminate the compounds. Compounds include personal care products, pharmaceuticals, surfactants, flame retardants, industrial chemicals, and disinfection by-products; most occur in effluents at trace levels ($\mu g\ L^{-1}$ to $\eta g\ L^{-1}$). Some ECOCs are easily removed and degraded during sewage treatment, whereas others move through the wastewater treatment plants conservatively (Polar, 2007). Advanced treatment (e.g., reverse osmosis, ozone treatment) can improve ECOC removals (Metcalf & Eddy, 2007), but is not widely practiced, and some chemicals nevertheless escape removal.

Animal wastes (manure, lagoon effluents) can also contain ECOCs (veterinary therapeutics feed additives, and natural hormones) and serve as sources to agricultural systems and the environment (Pedersen et al., 2003). Emerging chemicals of concern in wastewater effluents and their effects on aquatic organisms have attracted the most research attention (e.g., Pedersen et al., 2003; Kinney et al., 2006), but a significant body of work exists on manure-borne ECOCs and their behavior in soil systems (Bradford et al., 2008).

The bioactive properties of pharmaceuticals and other ECOCs introduced into surface and ground waters and soils can adversely affect humans and ecosystems. The risks remain inadequately quantified, but numerous effects have been documented or hypothesized, including:

Antibiotic resistance in humans, animals, and soil microbes exposed to subtherapeutic concentrations of antibiotics and anti-microbials,

Endocrine disrupting activity, associated with synthetic or natural estrogens, or numerous other chemicals that mimic natural hormones or alter hormone production,

Immune system effects,

Unknown effects of long-term exposure at very low dosages (lifetime ingestion via drinking water) to a host of individual and combinations of chemicals sharing a specific mode of action,

Side effects on non-target receptors for which there are, as yet, no data,

Cancer,

Ecological effects on aquatic organisms, plant communities, and soil microbial populations.

The list of chemicals of concern (detected because of advances in analytical techniques) and the potential impacts is almost endless, and the risk and the magnitude of effects are largely unknown. According to Miller (2006), removing exotic chemicals via appropriate treatment technologies is the biggest challenge in reuse of wastewater effluents.

Public Acceptance

Science and technical information is only part of developing and managing sustainable degraded water reuse programs. An important conclusion from an early conference on land application of biosolids was that "unless political and institutional constraints on the land application of effluents and sludges are recognized, identified, and resolved, projects will likely fail, regardless of their technical, scientific, and economic feasibility" (NASULGC, 1973). Experience with degraded water reuse reflects a similar imperative to engage the public in planning and implementing reuse programs. A key feature is assuring the public of the chemical and microbiological safety of water reuse projects.

Community acceptance of degraded water reuse depends on the type and source of the reuse water, the specific reuse application, and cultural and local issues. Perceived human health risks are often the main criteria determining public acceptance. Thus, reuse of stormwater is generally more accepted than wastewater effluent (Fletcher et al., 2008). Residents of San Francisco gave the following positive responses to acceptable uses of wastewater effluent: concrete production (90%), irrigation of crops for direct human consumption (30%), and direct potable reuse (18%) (USEPA, 2004).

Consideration of stakeholder issues must occur, not as an afterthought, but early on in the conceptualization of a reuse program. Public participation is essential. In areas with abundant rainfall, the benefits of water reuse are not fully appreciated. Education of the public and local decision-makers is a key consideration for success (Miller, 2006). Endeavors to promote the degraded water reuse systems will largely be wasted without due consideration and active implementation of stakeholder concerns. The vital societal importance of the water reuse makes such efforts imperative.

Technology Requirements

Treatment Systems

Reuse programs are critically dependent on a degraded water source with quantity and quality to consistently meet the required criteria of the intended use. Depending on the type and level of constituent removal, a variety of treatment processes, used singly or in combination, can be used for degraded water supplies. Some reuse water sources are already high quality. Municipal and industrial wastewater effluents must meet Clean Water Act standards before discharge. Other sources, like lagoon waters from CAFOs, may contain high levels of nutrients, salts, and oxygen-demanding materials that must be addressed to avoid adverse impacts on soil and water quality (Bradford et al., 2008).

The level of pretreatment before degraded water reuse varies widely for different end uses. For example, for scenarios where ground water recharge is the objective, the reuse water should not contain measurable levels of viable pathogens (USEPA, 2004). In contrast, the microbial recommendation for silviculture sites where public access is prohibited is 200 FC 100 mL^{-1}. Processes can range from little or no treatment before reuse, to advanced biological wastewater treatment coupled with membrane technologies. Conventional stormwater harvesting, for example, normally involves simple collection and storage before use for urban irrigation (Fletcher et al., 2008). In many states, unrestricted urban reuse of wastewater requires secondary treatment, filtration, and high-level disinfection. Advanced technologies, like reverse osmosis, membrane filtration, and membrane bioreactors are effective in wastewater reuse applications (Sorgini, 2007). Pollution prevention strategies can be used to reduce the introduction of contaminants to the reuse water during its initial degradation. For example, manipulation of animal diets and veterinary practices may be a simple and cost effective way to keep some contaminants out of CAFO lagoon waters destined for reuse (Bradford et al., 2008).

Some reuse water must meet more than one quality standard, and some facilities produce several “designer” classes of wastewater effluent for various applications (Sorgini, 2007). Multiple technologies may be necessary where multiple grades of water cannot be produced from a single process. Alternatively, a single treatment system could be used to treat the degraded water to the most stringent quality standards. Another strategy is to treat water to meet a lower quality standard and have local point-of-use treatment at the application site. This avoids multiple distribution pipelines (Metcalf & Eddy, 2007).

Storage, Distribution, and Site Requirements

By and large, the storage, distribution, and site requirements for reuse options are similar for degraded waters and fresh surface or ground water sources (Metcalf & Eddy, 2007). However, there are considerations specific to degraded water that must be addressed.

Storage is often needed to satisfy the variable demand for the reuse water regardless of the degraded water source. This is particularly evident in irrigation systems, where a reliable supply of water must be matched with diurnal and seasonal demands. But the quality of degraded water sources may impose additional constraints on storage. Increased retention times may be needed to reduce suspended solids, or allow degradation or mineralization of contaminants (Bradford et al., 2008). Regrowth or introduction of pathogens during storage may necessitate post-storage chlorination of wastewater effluents. When surface or ground water sources are used for irrigation, there may be no restrictions on runoff discharge from the application site. For sites irrigated with wastewater effluent, however, regulations may prohibit or otherwise restrict discharge of runoff to surface waters. This may require storage capacity during seasons with high precipitation or when crop consumptive use is low.

Delivery and distribution systems needed to covey the reuse water to the site of application may involve special considerations. Depending on reuse water composition, these systems may require additional devices and more regular maintenance to ensure reliable service to the reuse site. Greater corrosion of pipelines is typically experienced with wastewater effluent than fresh water sources (USEPA, 2004). Periodic flushing of pipes, cross-connection control, and regular use of valves and hydrants are needed for distribution facilities for wastewater effluent irrigation (Metcalf & Eddy, 2007). Low water velocities associated with drip irrigation systems may be more prone to clogging by biological growth and chemical precipitation when degraded water is used. Periodic chlorination, chemical modification, and flushing may be necessary.

Regulations

Before implementing a degraded water reuse program, legal and regulation issues at several governmental levels need to be addressed (Metcalf & Eddy, 2007). No federal regulations currently exist that govern wastewater effluent reuse practices in the USA (USEPA, 2004), and lack of uniform regulations and standards can be a barrier to implementing water reuse programs (Miller, 2006). Many states have enacted enforceable rules regarding use of degraded water, particularly wastewater effluents. Other states have guidelines that are not directly enforceable, but that are to be used in development of reuse programs. Lack of regulations or guidelines may restrict reuse applications if programs need to be permitted on a case-by-case basis. Fletcher et al. (2008) note that stormwater harvesting, despite public support, often involves a time-consuming and resource intensive approval process due to the lack of policies on the part of permitting authorities. The absence of regulations or guidelines does not mean that reuse is prohibited, but generally there will be a requirement to demonstrate that a proposed reuse program is protective of public health (USEPA, 2004).

Legislation like the Clean Water and Safe Drinking Water Acts may constrain the use of wastewater effluents for indirect potable reuse (Metcalf & Eddy, 2007). For irrigation systems using wastewater effluent, a National Pollutant Discharge Elimination System (NPDES) permit may be required for surface water discharge of runoff water. Many states have established buffer zones between the wetted area of effluent irrigation sites and residential areas, roadways, and water supply wells. This may necessitate taking formerly productive cropland out of cultivation. Some states specify maximum hydraulic loading rates for irrigation with reuse water, for example, no more than 5 cm per week (USEPA, 2004).

Most state regulations for wastewater effluent reuse include monitoring requirements that stipulate that reuse water be sampled for specific constituents at specified intervals. Although most states have a limited list of specified constituents (e.g., TSS, N, total organic carbon, turbidity, total coliforms), the number of regulated constituents can be extensive. Ground water monitoring may also be required for agricultural irrigation sites, depending on the quality of the water and the site hydrogeology. Separate water quality requirements may exist for other reuse scenarios. Some states provide regulations specific to the use of wastewater effluent in wetlands. For example, where wastewater effluent is used for augmenting flow in natural wetlands, the Florida Administrative Code (F.A.C. Chap. 62–611) requires that BOD and TSS be ≤ 5mg L^{-1}, total $N \leq 3$mg L^{-1}, and total $P \leq 1$ mg L^{-1} (Metcalf & Eddy, 2007).

With the increasing importance of water resource issues providing the impetus for greater water reuse, states are establishing and revising existing regulations and guidelines. Continued research is needed to ensure that such policies promote water reuse while protecting public health and the environment.

The Future of Degraded Water Reuse

Communities around the world face increasingly severe fresh water supply challenges, largely due to expanding populations and associated food supply, economic development, and health issues. Extended regional droughts and drought due to long-term changing weather patterns can exacerbate the problem. Intentional reuse of degraded waters (wastewater effluents, irrigation return flows, CAFO effluents, stormwater, and graywater) can be one solution to the challenge. The future potential for wastewater effluent reuse, in particular, is enormous (Miller, 2006), but other degraded waters represent major reuse resources as well. Increased reuse of degraded waters is feasible and sustainable if various barriers (e.g., public acceptance, stricter discharge barriers, innovative technologies and better water management to ensure protection of health and the environment, political support) can be addressed (NRC, 1996; USEPA, 2004; Metcalf & Eddy, 2007).

Areas with limited water resources, such as the arid Southwest of the USA, already have well-established wastewater effluent reuse programs in place (USEPA, 2004) and years of experience utilizing irrigation return flows. As populations have increased, reuse of wastewater effluents has also grown rapidly even in normally wet areas (e.g., FL), primarily for urban irrigation. Stricter discharge regulations for wastewater treatment plants and CAFOs and increased stormwater runoff from non-porous surfaces associated with increased urbanization promise greater supplies of degraded waters suitable for both restricted and unrestricted reuse.

There are no federal regulations directly governing wastewater reuse practices in the USA. Regulations and guidelines have been developed by individual states, but they vary considerably from state to state. The USEPA has developed suggested guidelines for reuse that serve as the basis for some state regulations. Similarly, few states have regulations governing the reuse of other degraded waters (e.g., stormwater, graywater) and often address proposed reuse programs on a time-consuming case-by-case basis. The absence of state guidelines or regulations likely fosters public perception that degraded water reuse is inadequately understood or nonprotective of health and should not receive official endorsement. Federal reuse regulations, similar to the 40CFR Part 503 biosolids rule, would establish minimum standards and possibly increase public acceptance.

Guidelines for the reuse of degraded waters abound (e.g., USEPA, 2004; AWWARF, 2006; USEPA, 2006; WERF, 2006; WHO, 2006; Metcalf & Eddy, 2007). But, new technologies and the rapidly expanding body of knowledge require frequent updating of reuse guidelines (Bistany, 2006). Some of the issues likely to determine sustainable degraded water reuse are well studied (e.g., salinity, nutrients, trace inorganics, pathogens), but the application of principles learned on these issues from studies with fresh waters have not been fully evaluated in degraded water use scenarios. Examples include:

1. Sustainable irrigation water management techniques developed for traditional field crops irrigated via furrow or overhead sprinkler systems may have to be adapted for ornamentals irrigated via drip systems with water containing excess Na^+ contributed by home water-softeners.
2. Guidance based on nutrient release from solid manures may not be appropriate for nutrient supply in liquid manure or wastewater effluents.
3. Little attention has been given to the risk potential (P-Index characterization) of effluent P land application.
4. The soluble organic C concentration in some degraded waters (e.g., manure effluents, food-processing effluents) may alter the speciation and mobility of metals in soils and the potential for ground water contamination (Fonseca et al., 2007).

5. Available indicator organisms (used to determine wastewater treatment effectiveness) may not be accurate predictors of actual health threats posed to individuals coming in close contact with degraded waters in densely populated urban environments.
6. Reuse of drainage waters on marginally productive, saline-sodic soils may require careful consideration of trace elements (e.g., B, Mo, and Se) to prevent and manage their build up (Corwin et al., 2008a).

Most of these questions are amenable to traditional soil science research approaches and instrumentation.

Other issues, however, (notably emerging chemicals and pathogens of concern) will require nontraditional research approaches and/or instrumentation. A host of chemicals are now being detected in degraded waters of all kinds (owing to greatly enhanced analytical capabilities). The list includes endocrine disruptors, pharmaceuticals, personal care products, fragrances, veterinary medications, etc. The behavior of these chemicals in the environment and the resulting risk to human health is largely unknown. Numerous models are available to predict chemical behavior, based on structural characteristics, chemical and physical properties, fugacity concepts, and risk assessments, but documentation (measurements of effects) is scarce. The scarcity is especially obvious in soil systems; more evidence is available in aquatic systems where soil solid interactions are less. Describing the fate, transport, and risk of ECOCs is an area requiring major research effort.

Similarly, little is known about "emerging pathogens" that could accompany waters contaminated by human or animal manures. The use of surrogate organisms (see above) to evaluate all pathogen behavior is in question and remains incompletely studied.

Ultimately, public (and political) acceptance is the major hurdle to degraded water reuse, especially in urban settings. Major educational programs, based on hard science, are needed to convince the public of the wisdom of reusing degraded waters.

Critical to the public, political, and scientific acceptance of degraded water reuse is evidence of the long-term sustainability of the practice. Carefully conducted, long-term field studies are necessary to validate the short-term lab, greenhouse, and small plot research and demonstration studies that tend to dominate the literature. Evidence of long-term sustainability is most abundant for the reuse of wastewater effluents, including documentation of successful reuse programs that have operated for > 20 yr (USEPA, 2004). Similarly, a recently published WERF report (WERF, 2006) addresses long-term graywater reuse. Published evidence of the long-term sustainability of the reuse of drainage waters (irrigation return flow) is more limited. Goyal et al. (1999) studied the use of drainage waters of various salinities for crop production in a 9-yr field experiment, but focused only on the impact of salinity. Corwin et al. (2008b) broaden the scope of investigation to include salinity, sodicity, and trace elements in a recent field study. Published reports of field studies on the long-term sustainability of CAFO effluents and stormwaters use under real-world conditions are scarce. Thus, a major research need is long-term field studies conducted by interdisciplinary teams that monitor multiple possible impacts and conducted at several locations to address regional differences in source waters, climatic, soil, and geomorphologic conditions. Educational programs based on the results of the field studies should be invaluable in gaining public acceptance. Water scarcity throughout the world demands effective research and educational programs to fully realize the potential for degraded water reuse and to address impending water shortages.

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