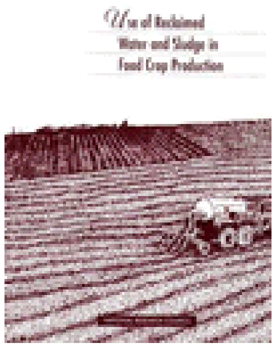

Use of Reclaimed Water and Sludge in Food Crop Production

Committee on the Use of Treated Municipal Wastewater Effluents and Sludge in the Production of Crops for Human Consumption, National Research Council

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Water Science and Technology Board
Commission on Geosciences, Environment, and Resources
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Cover depicts a farm field with a specialized truck for injecting sludge into the soil. A wastewater treatment plant is in the background. Art by Ellen Hill-Godfrey of Kensington, Maryland.

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Preface

In early 1993, the U.S. Environmental Protection Agency's (EPA) Office of Wastewater Compliance and Enforcement suggested to the National Research Council's Water Science and Technology Board (WSTB) that it should consider undertaking a study of public health and public perception issues associated with the use of treated municipal wastewater and sludge in the production of crops for human consumption. At the time, EPA was just finalizing the Part 503 Sludge Rule, *Standards for the Use or Disposal of Sewage Sludge*, and one of the major implementation concerns was with the food processing industry's reluctance to accept the practice. When EPA first promulgated criteria for land application of municipal wastewater sludges to cropland in 1979, some food processors questioned the safety of selling food crops grown on sludge-amended soils and their liability. In response, the principal federal agencies involved—EPA, the U.S. Food and Drug Administration (FDA), and the U.S. Department of Agriculture (USDA)—developed a Joint Statement of Federal Policy in 1981 to assure that current high standards of food quality would not be compromised by the use of high quality sludges and proper management practices. Nevertheless, the food processing industry remains concerned about safety and market acceptability, and at least one company has adopted an official policy that bans the purchase of any crops grown on fields receiving municipal sewage sludge or treated municipal wastewater. With the issuance of the Part 503 Sludge Rule in 1993, public concerns with a number of technical, regulatory, and environmental issues have surfaced. Because cropland application of both sludge and wastewater represent important management options, municipal wastewater management officials have a vital interest in the feasibility of these practices.

Therefore, in mid-1993, WSTB formed a committee representing diverse expertise and perspectives to conduct an independent study of the safety and practicality of the use of these materials for the production of crops for human consumption. The study sought to review (1) the historical development, rationale, and scope of the practice of treating municipal wastewater and sludge in the United States; (2) wastewater treatment technologies and procedures for agricultural use of these materials; (3) effects on soils, crop production, and ground water; (4) public health concerns about microbiological agents and toxic chemicals; (5) existing regulations and guidelines; and (6) economic, liability, and institutional issues. The committee based its review on existing published literature and discussions with experts in the field. The committee was not constituted to conduct an independent risk assessment of possible health effects, but instead to review the method and procedures used by EPA in its extensive risk assessment, which was the basis for the Part 503 Sludge Rule.

The committee met five times over a 17-month period including field visits to the Irvine Ranch Water District in California, the CONSERV II Water Reclamation Program of Orange County and Orlando, Florida, and the Disney World, Florida reuse programs. The committee also held a one-day workshop at Rutgers University in New Brunswick, New Jersey to hear from researchers, public interest groups, farm credit bureaus, farmers, and state and city planners on land application of municipal sludge in the Northeast.

The committee focused primarily on the issues surrounding the use of treated municipal wastewater effluents and treated sludge in food crop production, concentrating on the uptake of chemical constituents and pathogens by food crops. The study did not include an investigation of what happens after the crops are harvested (e.g., processing of food products). Further, the committee was not constituted to evaluate site-specific implementation of wastewater effluent and sludge reuse projects, or to compare the relative merits and risks of various other forms of disposal or beneficial uses. However, the committee recognized that in addition to the safety and practicality of using these materials on food crops, there are many implementation issues involved with the agricultural use of municipal wastewater and sludge including the degree to which the regulations are implemented and enforced, the public confidence in local reuse programs, local nuisance and traffic problems, environmental and product liability issues, and overall public perceptions. In several of these areas, this report notes particular findings that should receive the attention of federal, state, and local authorities responsible for implementing reuse projects.

It is hoped that this report will be particularly useful to food processors, states, and municipalities in assessing the use of treated municipal wastewater and sludge in producing crops for human consumption. It highlights public concerns and regulatory issues likely to be faced, and also identifies some additional areas for research.

The Committee on the Use of Treated Municipal Wastewater Effluents and Sludge in the Production of Crops for Human Consumption consisted of 14 members with experience in soil and crop science, agricultural engineering, wastewater and sludge treatment, soil microbiology, toxicology, ecology, infectious disease, public health, economics, law, and other relevant fields. The committee gained insights from a far larger group by inviting guests to its meetings, participating in field trips, and reviewing the literature. My great appreciation goes to the committee, each of whom gave significant time and energy to create this report. Additionally, I would like to thank Rufus Chaney and Richard Bord for providing their time and resources to the study. I want to thank the staff of the WSTB, especially Gary Krauss, study director, and Mary Beth Morris, project assistant. I would also like to thank the study sponsors: the EPA, the U.S. Bureau of Reclamation, the USDA, the FDA, the National Water Research Institute, the Water Environment Research Foundation, the National Food Processors Association, the Association of Metropolitan Sewerage Agencies, California's Eastern Municipal Water District, the Metropolitan Water Districts of Southern California, Bio Gro Division of Wheelabrator Water Technologies, and N-Viro International Corporation. Without this support, the study would not have occurred.

Albert Page

University of California, Riverside

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BACKGROUND

The use of treated municipal wastewater effluent for irrigated agriculture offers an opportunity to conserve water resources. Water reclamation can also provide an alternative to disposal in areas where surface waters have a limited capacity to assimilate the contaminants, such as the nitrogen and phosphorus, that remain in most treated wastewater effluent discharges. The sludge that results from municipal wastewater treatment processes contains organic matter and nutrients that, when properly treated and applied to farmland, can improve the physical properties and agricultural productivity of soils, and its agricultural use provides an alternative to disposal options, such as incineration, or landfilling.

Land application of municipal wastewater and sludge has been practiced for its beneficial effects and for disposal purposes since the advent of modern wastewater management about 150 years ago. Not surprisingly, public response to the practice has been mixed. Raw municipal wastewater contains human pathogens and toxic chemicals. With continuing advances in wastewater treatment technology and increasingly stringent wastewater discharge requirements, most treated wastewater effluents produced by public treatment authorities in the United States are now of consistent, high quality. When treated to acceptable levels or by appropriate processes to meet state reuse requirements, the effluent is referred to as "reclaimed water." Sewage sludge can also be treated to levels that allow it to be reused. With the increased interest in reclaimed water and the promotion of agricultural use for treated sludge, there has been increased public scrutiny of the potential health and environmental consequences of these reuse practices. Farmers and the food industry have expressed their concerns that such practices—especially the agricultural use of sludge—may affect the safety of food products and the sustainability of agricultural land, and may carry potential economic and liability risks.

Reclaimed water in the United States contributes a very small amount (probably much less than one percent) of water to agricultural irrigation, mainly because the extent of the practice is limited both by regional demands and the proximity of suitable agricultural land to many municipal wastewater treatment plants. Most reclaimed water goes towards various nonpotable urban uses such as irrigating public landscapes (parks, highway medians, lawns, etc.), air-conditioning and cooling, industrial processing, toilet-flushing, vehicle-washing, and construction. Irrigation of residential lawns and/or gardens with reclaimed water is becoming increasingly popular where dual plumbing systems to facilitate water reuse have been installed; however, this report concentrates on agricultural uses of reclaimed water, and not residential use.

Sewage sludge (or simply, "sludge") is an inevitable end product of modern wastewater treatment. Many of the organic solids, toxic organic chemicals, and inorganic chemicals (trace elements) are removed from the treated wastewater and concentrated in the sludge. An estimated 5.3 million metric tons per year dry weight of sludge are currently produced in the United States from publicly owned treatment plants. This amount will surely increase as a larger population is served by sewers and as higher levels of wastewater treatment are introduced.

Sludge disposal has always represented a substantial portion of the cost of wastewater management. Over the past 20 years, restrictions have been placed on certain sludge disposal practices (e.g., ocean dumping and landfill disposal), causing public wastewater treatment utilities to view the agricultural use of sludge as an increasingly cost-effective alternative. Currently, 36 percent of sludge is applied to the land for several beneficial purposes including agriculture, turfgrass production, and reclamation of surface mining areas; 38 percent is landfilled; 16 percent is incinerated; and the remainder is surface disposed by other means.

The Midwest has a long history of using treated sludge on cropland. Much of the cropland that receives sludge is used to grow hay, corn, and small grains for cattle feed, and public acceptance generally has been favorable. In Madison, Wisconsin, for example, the demand for sludge as a soil amendment exceeds the local supply. With ocean disposal of sludge no longer allowed, New York City and Boston—among other coastal cities—ship much of their sludge to other parts of the country. A portion of the sludge produced in the Los Angeles Basin is transported to a large farm near Yuma, Arizona.

If all the municipal sludge produced in the United States were to be agriculturally applied at agronomic rates, it would only be able to satisfy the nitrogen needs of about 1.6 percent of the nation's 1,250 million hectares (309 million acres) of cropland. About one quarter of this cropland is used to grow food for human consumption, of which 2 percent grows produce crops that can be consumed fresh. Thus, in a national context, the amount of food crops produced on fields receiving sludge would remain very small. Nevertheless, the local availability of agricultural land, combined with other regional and local concerns, is an important factor in sludge management decisions. While many western and midwestern states have ample agricultural land relative to the amount of sludge produced, land is less available in other regions. In New Jersey, for example, over half the state's cropland would be needed to receive sludge application to avoid other forms of disposal or out-of-state disposal. Rhode Island would need essentially all of its cropland to satisfy its sludge disposal needs through in-state agricultural use. The level of public acceptance for agricultural use of sludge varies considerably. Nuisance (e.g. odors and traffic), environmental, and safety issues are legitimate concerns that must be addressed by regulatory policy and management programs.

In February 1993, the U.S. Environmental Protection Agency (EPA) promulgated *Standards for the Use or Disposal of Sewage Sludge* (Code of Federal Regulations Title 40, Parts 257, 403, and 503, and hereafter referred to as the "Part 503 Sludge Rule"). The rule builds on a number of federal and state regulations that aim to reduce pollutants entering the municipal waste stream through source controls and industrial pretreatment programs that have reduced the levels of contaminants in the sludge as well as in the final effluent. The Part 503 Sludge Rule defines acceptable management practices and provides specific numerical limits for selected chemical pollutants and pathogens applicable to land application of sewage sludge. In this context, sewage sludge—traditionally regarded by many groups as an urban waste requiring careful disposal—is now viewed by the wastewater treatment industry, the regulatory agencies, and participating farmers as a beneficial soil amendment.

EPA believed that both water reclamation and sludge beneficial use programs could benefit from an independent assessment of the public health and environmental concerns that have been raised by the food processors concerning land application of treated municipal wastewater and sludge. In mid-1993, at the suggestion of EPA, and with support of a number of co-sponsors, the National Research Council (NRC) undertook this study to examine the use of treated municipal wastewater and sludge in the production of crops for human consumption. The study reviews the current state of the practice, public health concerns, existing guidelines and regulations, and implementation issues. The report makes a number of recommendations resulting from the study that are summarized below.

CONCLUSIONS AND RECOMMENDATIONS

Irrigation of food crops with treated municipal wastewater has been effectively and safely practiced in the United States on a limited scale. The public has generally accepted the concept of wastewater irrigation as part of larger and more comprehensive water conservation programs to reclaim wastewater for a variety of nonpotable uses. Where reclaimed water has been used for food crop production, the state standards for wastewater treatment and reuse, along with site restrictions and generally good system reliability, have insured that food crops thus produced do not present a greater risk to the consumer than do crops irrigated from conventional sources.

The beneficial reuse of municipal sludge has been less widely accepted. Federal regulations are designed to assure that sludge application for the production of food crops does not pose a significant risk from the consumption of foods thus produced. However, the parties affected by these reuse programs—local communities, crop growers, food processors, and the consumer—remain concerned about the potential for exposure to contaminants, nuisance problems, liability, and adequacy of program management and oversight. Sludge management programs based on agricultural sludge use can involve many potentially responsible parties, and can cross agency, state, and federal jurisdictional boundaries. Therefore, municipalities, public utilities, crop growers, and food processors must be able to provide well-managed and reliable programs that address, and are open to, community, business, health, agronomic, and environmental concerns.

Adequacy of Existing Regulations for Pathogens in Reclaimed Water and Sludge

Municipal wastewater contains a variety of pathogenic (infectious) agents. When reclaimed water or sludge is used on fields producing food crops, the public health must be protected.

This can be achieved by proper wastewater or sludge treatment and site management that reliably reduces the pathogens to acceptable levels.

There are no federal regulations directly governing the use of municipal wastewater to irrigate crops. However, EPA provided guidelines for reclaimed water quality and its use for crop irrigation in its 1992 *Guidelines for Water Reuse*. There are currently 19 states that regulate the practice by setting criteria for reclaimed effluent quality, such as microbiological limits or process standards; crop restrictions; or by waiting periods for human or grazing animal access or before crop harvest. State regulations vary; some require very high-quality effluents to reduce the concentration of pathogens to levels acceptable for human contact prior to irrigation. Others depend on the use of crop restrictions and site limitations, thus allowing required time for pathogens to decrease to acceptable levels. In general, modern wastewater treatment procedures incorporate monitoring and technical redundancies that provide system reliability and protection against exposure to pathogens.

The strategy for regulating pathogens in the agricultural use of sludge is similar. The Part 503 Sludge Rule requires the use of either Class A pathogen criteria, in which the sludge is considered to be safe for direct public contact, or Class B pathogen criteria, in which site and crop restrictions are required.

Class A (safe for public contact) microbial standards or process standards for sludge appear to be adequate for public health protection. The Part 503 Sludge Rule allows for direct testing of pathogens (bacteria, viruses, and helminths), and the use of salmonella or fecal coliform testing as alternative indicators to determine Class A sludge quality. The prescribed methods for the testing of salmonella are of questionable sensitivity. Until such time as more precise methods are developed and accepted, the present test for salmonella should not be used as a substitute for the fecal coliform test; rather, it should be run in concert with that test or in situations in which the fecal coliform results are in question, such as may happen under some operating conditions. The salmonella test is less precise because of the relatively low numbers of salmonella present compared to fecal coliform.

Restrictions on the use of Class B sludge require allowing a suitable length of time for die-off of helminth ova, which can be transmitted to humans via improperly cooked, contaminated meat. The control of helminth parasites is achieved largely through public health education (e.g., the need for thorough cooking of meat) and government meat inspection, as well as controls over applications of wastewater and sludge to land. Based on a review of U.S. studies, the Part 503 Sludge Rule requires a 30-day waiting period before cattle can graze on Class B sludge-amended fields. A recent investigation in Denmark indicates that the beef tapeworm (*Taenia* sp.), one of the helminth group, may survive in sludge-treated fields for up to one year. Although the evidence comes from a single study, there is reason to believe that the length of the waiting period for grazing following sludge application to pastures needs to be re-examined.

There have been no reported outbreaks of infectious disease associated with a population's exposure—either directly or through food consumption pathways—to adequately treated and properly distributed reclaimed water or sludge applied to agricultural land. Reports and available epidemiological evidence from other countries indicate that agricultural reuse of *untreated* wastewater can result in infectious disease transmission. The limited number of epidemiological studies that have been conducted in the United States on wastewater treatment plant workers or populations exposed to various reclaimed water or treated sludge via land application projects indicate that exposure to these materials is not a significant risk factor. However, the value of prospective epidemiological studies on this topic is limited because of a number of factors, including a low illness rate—if any—resulting from the reuse practice, insufficient sensitivity of current epidemiological techniques to detect low-level disease transmission, population mobility, and difficulty in assessing actual levels of exposure.

Infectious diseases of the types potentially associated with municipal wastewater are under-reported and exposures are scattered, so that some effects may well go unrecorded. From a public health point of view, the major microbiological considerations for evaluating any reuse management scheme are the ability to effectively monitor treatment efficacy and the reliability of the process used to reduce pathogens to acceptable levels.

Recommendations

- **Until a more sensitive method for the detection of salmonella in sludge is developed, the present test should be used for support documentation, but not be substituted for the fecal coliform test in evaluating sludge as Class A.**
- **EPA should continue to develop and evaluate effective ways to monitor for specific pathogens in sewage sludge.**
- **EPA should re-evaluate the adequacy of the 30-day waiting period following the application of Class B sludge to pastures used for grazing animals.**

Adequacy of Existing Regulations for Harmful Chemicals in Reclaimed Water and Treated Municipal Sludge

Reclaimed Water

States that regulate the use of reclaimed water for crop irrigation have focused on its microbiological quality and have not typically set human health criteria for harmful inorganic (trace elements) and organic chemicals in the reclaimed water. Instead, reliance is placed on the wastewater treatment processes to reduce these constituents to acceptable levels in reclaimed water.

Potentially harmful trace elements, such as arsenic, cadmium, cobalt, copper, lead, mercury, molybdenum, nickel, selenium, and zinc are found in treated municipal wastewater effluents. In 1973, the National Academy of Sciences issued a report on water quality criteria that recommended limits on the concentration of trace elements in irrigations water regard to their effects on crop production. These agricultural irrigation guidelines have been generally accepted by EPA and others. Reclaimed water that has received a minimum of secondary treatment normally falls within these guidelines. While wastewater treatment processes typically used in the United States are not usually intended to specifically remove trace elements from the waste stream, most of the trace elements are only sparingly soluble and tend to become concentrated in the residual solids or sludge fraction. Chemical production and use bans, industrial pre-treatment programs, and municipal wastewater treatment have been effective in reducing the levels of toxic constituents in wastewater effluents to acceptable levels.

Wastewater treatment processes also remove many toxic organic chemicals in the wastewater stream through volatilization and degradation. Those that remain in the final effluent may volatilize or decompose when reclaimed water is added to soil. Consequently, only negligible quantities of toxic organic chemicals from municipal wastewater systems—those relatively resistant to decomposition—will persist in soils for an extended period. In general, toxic organic chemicals, especially those that persist in the soil, are not taken up by plants when the water application rates are commensurate with crop needs. Therefore, the immediate or long-term threat from organic chemicals to humans consuming food crops irrigated with reclaimed water is negligible.

Treated Municipal Sludge

Potentially harmful chemicals (largely, trace elements and persistent organics) become concentrated in the sludge during the wastewater treatment process. Following repeated land applications, trace elements, except for boron, will accumulate in the soil to, or slightly below, the depth of sludge incorporation. The persistent organic chemicals degrade over time in soils. Degradation rates are dependent on the chemical in question and on soil properties.

The Part 503 Sludge Rule for the agricultural use of sludge sets criteria for concentrations of 10 trace elements in sludge; arsenic, cadmium, chromium[1], copper, lead, mercury, molybdenum[1], nickel, selenium[1], and zinc. The rule is based on a risk-assessment approach that considered the effects of these trace elements and organic chemicals of concern on crop production, human and animal health, and environmental quality. Except for cadmium, these trace elements are not ordinarily taken up by crop plants in amounts harmful to human consumers. EPA regulations for cadmium in sludge are sufficiently stringent to prevent its accumulation in plants at levels that are harmful to consumers.

In deriving pollutant loading rates for land application of sewage sludge, EPA considered 14 transport pathways and, in all cases, selected the most stringent value as the limit for each pollutant. For the 10 regulated inorganic pollutants, the most stringent loading rates were derived from pathways that involved a child directly ingesting sludge or from pathways involving effects on crops. This resulted in significantly lower pollutant limits than would have been the case had they been set by human food-chain pathways involving human consumption of food crops, meat or dairy products. Therefore, when sludges are applied to land according to the Part 503 Sludge Rule, there is a built-in safety factor that protects against human exposure to chemical contaminants via human food-chain pathways.

Available evidence indicates that most trace organic chemicals present in sludge are either not taken up or are taken up in very low amounts by crops after sludge is applied to land. The

[1]Selected criteria have since been rescinded or are under review by EPA.

wastewater treatment process removes most of these organic chemicals, and further reduction occurs when sludge is processed and after it is added to soil. Consequently, only negligible quantities of toxic organic chemicals from municipal wastewater systems will persist in soils for an extended period. Recent studies suggest that plant tissues may absorb volatile toxic organic chemicals from the vapor phase of volatile compounds; however, the aeration that occurs during treatment of wastewater and during many sludge treatment processes removes most of the volatile organic chemicals at the treatment plant.

This study revealed some inconsistencies in EPA's approach to risk assessment and its technical interpretation for development of the Part 503 Sludge Rule, although the inconsistencies do not affect food safety. To improve the overall integrity of the regulation, EPA should address the exemption of organic pollutants and the marketing of sludge products to the public.

Exempting Organic Pollutants EPA chose not to regulate organic pollutants in the Part 503 Sludge Rule because all priority organic pollutants that were considered fell into at least one of the three exemption categories: (1) the pollutant has been banned in the United States and is no longer manufactured, (2) the pollutant was detected by EPA in less than 5 percent of the sludge from wastewater treatment plants sampled in a national sewage sludge survey, or (3) the concentration of the pollutant was low enough that it would not exceed the risk-based loading rates. Nevertheless, PCBs and aldrin/dieldrin occurred at higher than 5 percent detection frequency, and the concentrations of PCBs, hexachlorobenzene, benzo(a)pyrene, and N-nitrosodimethylamine would result in pollutant loadings exceeding EPA's risk-based limits in a small percentage of sludges. Some of these have been banned but persist in the environment. While the probability that the compounds would affect human-consumed crops is very low, the potential for human exposure to these chemicals through other pathways as defined in the Part 503 Rule should be re-evaluated.

The basis for exempting organic chemical pollutants rests, in part, on the integrity of the 1990 National Sewage Sludge Survey (NSSS)—the data base used by EPA to determine concentrations of pollutants in sludge. The survey has been criticized because sludge samples analyzed from the treatment plants varied in their water content which caused inconsistencies when deriving standardized detection limits of chemicals. As a result, estimates of frequencies and concentrations for certain organic chemicals may not be reliable. A credible data set of toxic chemical concentrations in sewage sludge based on a nationwide survey is essential. To update its information on sludge quality, EPA plans to repeat the survey in the near future. In conducting a second NSSS, EPA should strive to improve the integrity of the data by using more consistent sampling and data-reporting methods.

Recommendation

- **A more comprehensive and consistent survey of municipal wastewater treatment plants is needed to show whether or not toxic organic compounds are present in sludges at concentrations too low to pose a risk to human and animal health and to the environment. In conducting a second NSSS, EPA should strive to improve the integrity of the data by using more**

consistent sampling and data-reporting methods. The EPA should not exclude chemicals from regulatory consideration based solely on whether or not those chemicals have been banned from manufacture in the United States (e.g., PCBs) since they are still found in sludges from many wastewater treatment plants.

Marketing Sludge Products to the Public In addition to its use on agricultural land, sludge can be marketed and distributed to the public for home gardening and landscaping purposes. EPA has used the term "Exceptional Quality" (EQ) to refer to sludge that meets specified low pollutant and pathogen limits and that has been treated to reduce the level of degradable compounds that attract vectors. EQ sludge is a product that required no further regulation. EPA allows sludge that is sold or given away to the public to exceed the EQ chemical pollutant concentrations with the stipulation that prescribed application limits not be exceeded. However, there is little assurance that the home gardener or landscaper will either be aware of or be able to follow these requirements, nor is there a method for tracking the disposition of sludge marketed to the public. Allowing sludge with less than the highest quality chemical pollutant limits to be used by the public opens the door to exceeding regulatory limits, and thereby undermines the intent of Part 503 and public confidence in the law.

Recommendation

- **The Part 503 Sludge Rule should be amended to more fully assure that only sludge of exceptional quality, in terms of both pathogen and chemical limits, is marketed to the general public so that further regulation and management beyond the point of sale or give-away would not be necessary.**

Soil, Crop, and Ground Water Effects

Reclaimed Water

Guidelines for the chemical quality of water used in agricultural irrigation have been generally accepted since recommended limits were set by a National Academy of Sciences report in 1973. These guidelines concern potential toxicity to plants or to crop productivity. Where industrial pretreatment programs are effectively implemented (or where industrial input is low), reclaimed water that has received a minimum of secondary treatment will normally meet these recommended limits for irrigation water quality.

While the plant nutrients in treated effluents are generally considered a supplemental fertilizer source, the application rates are not easily controlled compared to commercial fertilizer operations. Wastewater irrigation could exceed the nitrogen and phosphorus requirements of many crops during the growing season. Further, plants require nutrients and water at different stages in the growth cycle and the timing of irrigation may not correspond to times when plant nutrients are needed. Wastewater applications at times when the plant nutrient needs are low can lead to excessive vegetative growth, can affect crop maturity, and can cause leaching of nitrate nitrogen and possible nitrate contamination of ground water.

The application of wastewater effluents to soils may pose some risk of ground water contamination by viruses and bacteria; however, that risk can be minimized by adequate disinfection of reclaimed wastewater and by slow infiltration rates.

Recommendation

- **Those who irrigate crops with treated municipal wastewater should be aware of the concentration of nutrients (nitrogen and phosphorus) in the reclaimed water and should adjust fertilizer practices accordingly in order to avoid undesirable vegetative growth or potential contamination of ground water.**

Treated Municipal Sludge

Municipal sewage sludge is a source of nitrogen and phosphorus in crop production. The addition of organic matter through successive sludge applications improves the physical properties and productivity of soils. When used at agronomic rates for nitrogen and phosphorus, sewage sludge can usually satisfy crop requirements for many other nutrients as well, with the possible exception of potassium. EPA's Part 503 Sludge Rule specifies the annual and cumulative loadings of trace elements in sludge-amended soils, and, based on currently available information, these limits are adequate to protect against phytotoxicity and to prevent the accumulation of these elements in crops at levels harmful to consumers.

Because repeated sewage sludge applications lead to accumulations of trace elements in soil, concern has been expressed over possible adverse effects associated with the use of sludge on soils that are acidic or may become acidic. However, as long as agricultural use of treated sludge is in keeping with current regulations and acid soils are agronomically managed, no adverse effects are anticipated. The Part 503 Sludge Rule is based on approximately 20 years of research and experience in applying sewage sludge to cropland. While this has provided an adequate knowledge base for developing the regulations, continued monitoring of trace elements in soils over longer time periods is desirable.

As in all farm operations, proper management is needed to avoid the buildup of nitrates. Typically, sludges comprise approximately 1 to 6 percent organic and inorganic nitrogen on a dry weight basis. The soluble inorganic forms are immediately available to plants, but the organic forms must first be mineralized to plant-available forms. For sludge to be efficiently used as a source of available nitrogen, the mineralization of organic nitrogen must be taken into account to avoid overfertilization and potential leaching of excess nitrate-nitrogen into ground water.

Most sludges supply more than enough phosphorus to satisfy crop needs when applied as a source of nitrogen. In certain soils, available phosphorus may be excessive, particularly where animal manure is plentiful and where impacts to surface water quality are of concern. In these situations, soil phosphorus levels should be monitored and sludge application rates be adjusted to correspond to crop phosphorus rather than nitrogen needs.

Heavy metals are not mobile in soils, and their transport to ground water as a result of sewage sludge application at agronomic rates is unlikely. Likewise, toxic organic compounds in sludge are not likely to contaminate ground water because their concentrations are low, because they are volatilized or biodegraded in soils, or because they are strongly sorbed to soil particles. Because of predictable pathogen die-off and because of the immobilization of micro-organisms on sludge and soil particles, the risk of transporting viruses, bacteria, and protozoa to ground water due to sludge application is negligible as long as sludge is properly treated and applied to or incorporated into unsaturated soils. As with all agricultural soil amendments, sludge use must be managed properly to avoid contamination of surface or ground waters.

Recommendations

- **When determining sludge and fertilizer application rates, an analysis of the rates of organic nitrogen mineralization should be performed in order to avoid buildup of excess nitrate-nitrogen. Nitrate-nitrogen that is not taken up by plants may contribute to excess fertilization and leaching. Where excess phosphorus is of concern, soil phosphorus levels should be monitored and sludge application rates should be adjusted to correspond to crop phosphorus rather than nitrogen needs.**
- **As more croplands are treated with municipal sludges and reach their regulatory limit of chemical pollutant loading from sludge applications, additional information will be needed to assess potential, long-term impacts of sludge on ground water quality and on the sustainability of soils for crop production.**

Economic, Legal, and Institutional Issues

In addition to human health and environmental concerns, there are other barriers to increased acceptance of treated municipal wastewater and/or sludge application in the production of food crops. In general, however, barriers to acceptance apply more to agricultural use of sludge than to crop irrigation with reclaimed water. These potential barriers include lack of economic incentives for the farmer, lack of public confidence in the adequacy of regulatory systems to ensure compliance, agribusiness concerns with potential liability or economic losses due to decreases in both land value and crop value, and public concerns over nuisance factors.

Economic Considerations

There are negligible economic incentives for food processors to accept crops produced with reclaimed water or treated sludge. Benefits in terms of lower raw food costs are likely to be minimal, potential risks could lead to liability, and the negative public perception of food crops produced using these materials could have a detrimental impact on consumer demand.

Even though the value of the water and nutrients represents only a small percentage of total farm production costs, there are many cases of clear economic incentives for society as a whole as well as for municipal wastewater treatment plants to pursue cropland reuse options. In water-scarce areas, reclaimed water should have value comparable to that of irrigation water from conventional sources. Where alternative irrigation water is cheaply available, there are only limited incentives for farmers to apply reclaimed water. Limited economic incentives exist for farmers to use sludge because fertilizer is relatively inexpensive and sludge use may entail additional management concerns. It may be appropriate to pay the farmer where the regulatory compliance costs associated with using reclaimed water or treated sludge exceed their beneficial use values. However, payments should not encourage excessive application rates that would interfere with the proper agronomic use of these materials.

Recommendation

- **Any payment program designed to promote agricultural use of treated effluents or treated sludge should be carefully structured to avoid the creation of incentives to apply reclaimed water or sludge at rates in excess of agronomic rates, and to avoid undermining farm management practices needed to protect public and occupational health and the environment.**

Public Perception and Liability

The public is concerned about the health and environmental risks associated with beneficial land application of sludge, particularly in areas where land application has only recently been implemented or considered. Some of this concern is not scientifically supportable, and should be addressed with education programs and early public involvement in the design of land-application programs. In addition, private-sector forces can deter violations of the law and mismanagement by the various parties involved in reuse programs. Private-sector forces include common-law liability, market forces, and voluntary self-regulation such as codes of conduct, worker training and certification, and audits. Although insurance coverage and indemnification contracts for the farmer are useful means of self-regulation and protection against certain kinds of economic harm, it is unlikely that they will be sufficient to satisfy all concerns of the farmer, food processors, general public, and the affected community. Thus, public concerns about real or perceived residual risks create business risks and militate against agricultural use of sludge and reclaimed water despite the federal or state regulatory safeguards. Proponents of cropland application of sludge and wastewater must, therefore, address such public concerns if they are to achieve their goals.

Recommendations

- **States and municipalities that wish to implement a beneficial-use program need to address public concerns and provide assurances that the new uses of sludge and wastewater do not endanger health or the environment in application areas. The public and local officials should be involved in the decision-making process at an early stage.**
- **The operators of municipal wastewater treatment facilities and the parties using sludge and wastewater should implement visible, stringent management and self-regulation measures, including monitoring and reliable reporting by farmers, and should support vigilant enforcement of appropriate regulations by local or state agencies. Implementation of these measures will be credible means of preventing nuisance risks and harm to people, property, and highly valued nearby resources.**
- **The municipal utility should carry out demonstration programs for public education, and to verify the effectiveness of management and self-regulatory systems. In addition, the utility should be prepared to indemnify farmers against potential liabilities when farmers' financing by banks or other lenders may hinge on this assurance.**

Other Regulations and Institutional Controls

From a regulatory perspective, it is important to remember that EPA's Part 503 Sludge Rule augments a wide array of existing institutional programs and controls over the disposition of municipal wastewater and sludge. For example, federal and state regulations govern the handling and treatment of toxic waste and the protection of surface and ground waters. These regulatory mandates appear adequate to manage most of the risks associated with land application, but they must be funded and implemented to be meaningful safeguards.

Sludges that do not meet beneficial use criteria standards as defined by the Part 503 Sludge Rule must be disposed of according to federal and state regulations as applicable. Both the general public and state and local regulators should be aware that the Part 503 Sludge Rule is not the only control over agricultural use of sewage sludge.

Recommendation

- **Management of sludge for beneficial use should be more visibly linked to existing regulations governing its disposal. Program credibility may be improved and public concern reduced if federal, state, and municipal**

regulators clearly assign authority to local governments for responding to any reports of adverse consequences related to beneficial use of sludge, such as ground water contamination, odor, attraction of vermin, or illnesses. The public should be aware that state and local units of government have the necessary regulatory authority to take corrective actions against parties who have violated rules and guidance.

CONCLUDING REMARKS

In summary, society produces large volumes of treated municipal wastewater and sewage sludge that must be either disposed of or reused. While no disposal or reuse option can guarantee complete safety, the use of these materials in the production of crops for human consumption, when practiced in accordance with existing federal guidelines and regulations, presents negligible risk to the consumer, to crop production, and to the environment. Current technology to remove pollutants from wastewater, coupled with existing regulations and guidelines governing the use of reclaimed wastewater and sludge in crop production, are adequate to protect human health and the environment. Established numerical limits on concentration levels of pollutants added to cropland by sludge are adequate to assure the safety of crops produced for human consumption. In addition to health and environmental concerns, institutional barriers such as public confidence in the adequacy of the regulatory system and concerns over liability, property values, and nuisance factors will play a major role in the acceptance of treated municipal wastewater and sewage sludge for use in the production of food crops. In the end, these implementation issues, rather than scientific information on the health and safety risks from food consumption, may be the critical factors in determining whether reclaimed wastewater and sludge are beneficially reused on cropland.

The use of wastewater and sludge in the production of crops for human consumption presents a manageable risk. However, the implementation of regulations and guidelines is where problems are most likely to arise. Municipal wastewater treatment plants, private processors, distributors, and applicators must not only comply with all regulatory requirements and management practices, they must take extra steps to demonstrate to various stakeholders (e.g., neighbors, farmers, food processors, and consumers) that such compliance is occurring. This must be done through full public participation opportunities, self-monitoring and reporting programs, and public education campaigns. This is particularly true if monitoring by state or local entities is likely to be minimal. General acceptance of sludge application for food crop production probably hinges most on the development of successfully implemented projects that meet state and federal regulations and address local public concerns.

1

Introduction

Municipal wastewater treatment processes used in the United States were designed to receive raw municipal wastewaters from both domestic and industrial sources and produce a liquid effluent of suitable quality that can be returned to natural surface waters with a minimal impact to the environment or to public health. A byproduct of this process, called sludge or sewage sludge, contains the solid fraction from the raw wastewater and the solids produced during the wastewater treatment processes. Both the effluent and sludge are treated to quality levels suitable for disposal or recycling purposes. As described in Chapter 3, secondary treatment is the national standard for discharge to surface waters (although local conditions can dictate either higher or lower treatment depending on the assimilative capacity of receiving waters). When treated to acceptable levels or by appropriate processes to meet state water reuse requirements, the effluent is generally referred to as "reclaimed water." In an effort to distinguish sewage sludge that is treated and managed for beneficial purposes, the wastewater treatment industry now refers to sewage sludge as "biosolids." However, for the purposes of this report, it is called "sewage sludge," or simply "sludge." The rising volume of municipal wastewater, propelled by growing population and urbanization (see Figure 1.1), has inevitably increased the volume of treated effluent and treated sludge. During the past decades, some disposal practices have been restricted. Landfill space is scarce, sitings of incineration facilities are difficult, and certain types of surface waters are adversely impacted by excess nutrient load and contaminants from treated effluents. Because of the wide range of environmental and societal problems associated with municipal wastewater and sludge disposal, municipalities have a need to find new ways to dispose of—or better, make use of—these materials. For coastal cities in particular, regulations requiring elimination of ocean disposal of sludge have precipitated the need for other management alternatives.

Fortunately, these materials have the potential for use in agriculture. The simultaneous increase in the demand for water, coupled with tighter regulation over the safety of sludge, widens an opportunity to use treated effluent for irrigation, and to use treated sludge as a supplemental source of fertilizer and soil conditioner. The similarities of effluent to irrigation water and of sludge to fertilizer are further described in Chapter 2 (see Tables 2.1 and 2.2). Capturing and reusing the water and nutrient value of these materials help to conserve resources.

However, a pressing question is whether the use of these materials in an agricultural setting

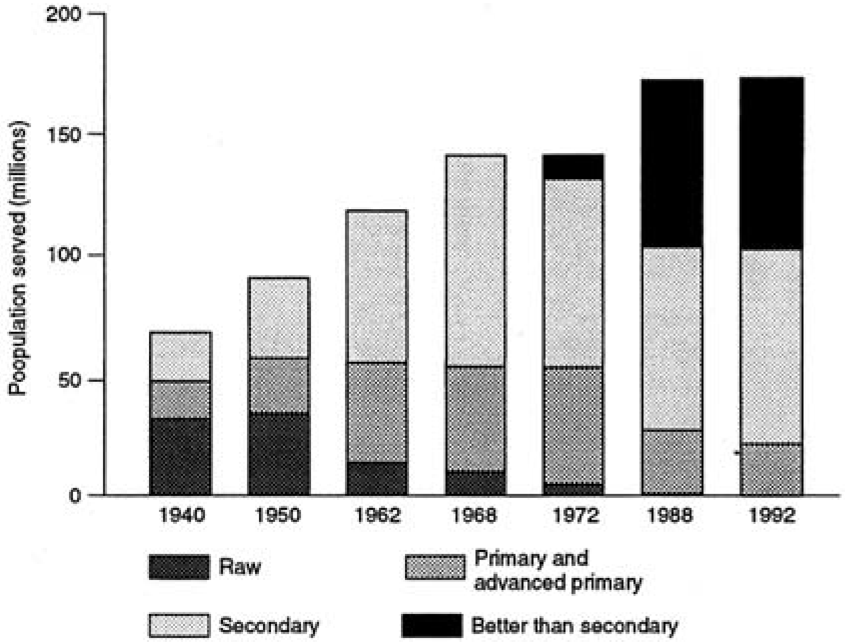

FIGURE 1.1 Increasing proportion of the U.S. population served by publicly owned treatment works (POTWs).
SOURCE: EPA, 1995.

is safe and practical. Further, is it safe in all climates, on all soils, and is it sustainable over the long term? Because human health is inevitably the leading criterion for safety, the severest test is whether treated effluents and treated sludge can be safely applied to crops that people eat.

The answer to whether wastewater and sludge can be safely applied to crops that people eat depends on several factors. These include the nature and amounts of potentially toxic or pathogenic constituents in treated effluents and sludges, the fate of these constituents once the materials are applied to an agricultural site, the potential of harmful constituents to migrate into plant tissue, the potential for other environmental impacts on water resources from runoff or infiltration, and whether long-term effects on the environment or future crop production are likely. An important safety consideration is the capability of facilities to produce treated effluent and treated sludge of consistent and reliable quality.

After safety, feasibility will govern the use of these materials in crop production. The distance of agricultural fields from the treatment plants and competition with other effluent and sludge uses or disposal practices may affect the practicality of agricultural use. A critical consideration is whether the recipients of and those affected by recycled effluents and sludge—farmers and their neighbors, the food processing industry, and consumers—will give more weight to the benefits or to the risks of applying these materials to agricultural land.

Irrigation of citrus trees with reclaimed water at the Water Conserv II reclamation project serving the City of Orlando and Orange County, Florida (courtesy of Tom Lothrop, City of Orlando Environmental Services Department).

REFERENCE

EPA. 1995. Impacts of Municipal Wastewater Treatment: A retrospective analysis. Washington, D.C.: U.S. Environmental Protection Agency, Office of Water.

2

Municipal Wastewater, Sewage Sludge, and Agriculture

HISTORICAL PERSPECTIVES

Wastewater

Large-scale cropland application of municipal wastewater was first practiced about 150 years ago after flush toilets and sewerage systems were introduced into cities in western Europe and North America. The wastewater was discharged without any treatment, and receiving watercourses became heavily polluted. The problem is illustrated by the situation in London in the 1850s when the "stink" from the River Thames obliged the House of Parliament to drench their drapes in chloride of lime (Snow, 1936). Water supplies drawn from the river below the sewage outfall were found by Dr. John Snow to be the source of the cholera outbreaks of the period. The partial solution to the problem was the construction by Sir John Bazalgete of a vast interceptor along the north bank of the River Thames, creating the famed Thames Embankment. This gave relief to central London, but moved the pollution problem downstream. Sir Edwin Chadwick, a lawyer and crusader for public health at the time, was a strong advocate of separate sanitary sewers, and he coined the slogan, "the rain to the river and the sewage to the soil." In this spirit, and to reduce pollution of the Thames downstream, "sewage farms" were established to take the discharges from the interceptor. The agricultural benefits from the farms were incidental to their service in the disposal of the wastewater.

The practice of sewage farms quickly spread. By 1875, there were about 50 such farms providing land treatment in England, and many similar farms served major cities in Europe. By the turn of the century, there were about a dozen sewage farms in the United States. However, the need for a reliable outlet for wastewater was not entirely compatible with the seasonal nature of nutrient and water requirements of crop production. While sewage farms alleviated pollution in the receiving streams, they created a different set of environmental sanitation problems. Hydraulic and pollutant overloading caused clogging of soil pores, waterlogging, odors, and contamination of food crops. The performance improved over the years as operators gained experience with balancing the needs of wastewater disposal and crop growth. Nevertheless, the farms were gradually phased out when the land areas required to accommodate wastes from large cities grew too great to be practical and more effective technologies were developed to remove pollutants from wastewater. The processes of primary sedimentation and secondary biological treatment, which were developed in the early part of this century, required much smaller areas for their operations and were capable of producing clarified effluents for direct discharge into a surface water body. These technologies eliminated the need for sewage farms.

In the United States, an estimated 0.69 m^3 (182 gal) per capita per day of municipal wastewater is generated (Solley et al., 1993). Municipal wastewater treatment plants (otherwise known as publicly-owned treatment works or "POTWs") currently serve around 75 percent of the U.S. population (EPA, 1995). The remainder are largely served by individual household septic systems. For those served by centralized facilities, the municipal wastewater is collected through a sewer network and centrally treated in a wastewater treatment plant. The collected wastewater contains pollutants originating from households, business and commercial establishments, and industrial production facilities. The general composition of municipal wastewater is well understood. For the purpose of water-quality management, pollutants in municipal wastewater may be classified into the following five categories:

- Organic matter (measured as biochemical oxygen demand or BOD),
- Disease-causing microorganisms (pathogens),
- Nutrients (nitrogen and phosphorus),
- Toxic contaminants (both organic and inorganic), and
- Dissolved minerals.

Although the exact composition may differ from community to community, all municipal wastewater contains constituents belonging to the above categories. Pollutants belonging to the same category exhibit similar water quality impacts. The objective of wastewater treatment is to remove pollutants so that the effluent meets the water quality requirement for discharge or reuse.

In modern society, thousands of potentially hazardous chemicals are used in household products and commercial and industrial activities. They may be inadvertently or intentionally discharged into the wastewater collection system. Municipal wastewater also contains many types of infectious, disease-causing organisms that originate in the fecal discharge of infected individuals.

In wastewater treatment, the physical and chemical state of pollutants determine the approaches that are employed to remove impurities. For this purpose, pollutants may be further classified (as per Camp and Messerve, 1974) into:

- Settleable impurities,
- Suspended impurities,
- Colloidal impurities, and
- Dissolved impurities.

Pollutants sharing the same physical state behave similarly during conventional wastewater treatment.

With more than one hundred years of continuous development, municipal wastewater treatment technology in use today can achieve almost any degree of treatment and removal of impurities desired. The conventional municipal wastewater treatment system consists of a series of processes, through which pollutants are removed, step by step, from the water and are concentrated into the solid fraction or sludge (see Chapter 3 for a further description of municipal wastewater and sludge treatment).

Treated effluents are customarily discharged into a surface water body. With advances in wastewater treatment technology, wastewater effluents can achieve consistently high quality and are increasingly reclaimed for reuse. The value of reclaimed water in crop irrigation has long been recognized, particularly where fresh water resources are limited (Webster, 1954; Mertz, 1956; Sepp, 1971). Some wastewater reclamation programs (e.g., in Florida) are also motivated by the need to avoid nutrient overload to sensitive receiving waters. In these cases, beneficial reuse can be more economical and/or technically feasible than employing the advanced wastewater treatment needed to meet the requirements for surface water disposal.

In the United States, irrigating crops with reclaimed wastewater has been generally well accepted, both in the semiarid western states and in Florida. The suitability of water for reuse is influenced by the chemical composition of the source water, mineral pickup due to water use, and the extent of wastewater treatment. These characteristics vary seasonally and from one municipality to another (Pettygrove and Asano, 1985). Dowdy et al. (1976) derived a "typical" chemical composition of treated wastewater effluent from a selected number of cities. This "typical" composition is compared to that of water from the Colorado River—a source for crop production in several western states—for many of the water quality criteria important in irrigation (Table 2.1). Judged against existing guidelines for irrigation water quality criteria (National Academy of Sciences, 1973; Westcot and Ayers, 1985), the chemical composition of treated wastewater effluents, although widely varied, is acceptable for crop irrigation. In addition, treated effluents contain significantly higher amounts of nitrogen and phosphorus—fertilizer elements essential for plant growth.

There are numerous examples of successful agricultural reuse projects in the United States. The wastewater from Bakersfield, California has been used for irrigation since 1912 when raw sewage was used (Pettygrove and Asano, 1985). Currently, reclaimed water from Bakersfield irrigates approximately 2,065 ha (5,100 acres) of corn, alfalfa, cotton, barley, and sugar beets productions with more than 64,000 m3/day (16.9 million gal/day) of primary and secondary effluents from three treatment plants (Pettygrove and Asano, 1985). To avoid wastewater discharge to sensitive receiving waters, the city of Tallahassee, Florida has been using treated effluent for agricultural irrigation on city-owned farmland since 1966. About 68,000 m3/day (18 million gal/day) of secondary effluent are pumped approximately 13.7 km (8.5 miles) and irrigate about 700 ha (1,729 acres) (Roberts and Bidak, 1994).

A seven-year agricultural wastewater reclamation demonstration study was conducted at Castroville, California, and completed in 1987. This study used a wastewater treatment process of secondary (biological) treatment, coagulation, filtration, and disinfection, with the final effluent meeting a quality standard of 2.2 total coliform/100 ml (the standard enforced by California's regulations for wastewater reclamation). The study concluded that the treatment process was acceptable for the spray irrigation of food crops to be eaten raw (Sheikh et al., 1990). The study detected no pathogenic organisms in the treated effluent, and spray irrigation with the treated effluent did not adversely affect soil permeability, did not result in heavy metal accumulation in the soil or plant tissue, and did not adversely affect crop yield, quality, or shelf

TABLE 2.1 Composition of Secondary Treated Municipal Wastewater Effluents and Irrigation Water

	Secondary Effluent[a]			
Parameter	Range	Typical	Colorado River[b]	Irrigation Water Quality Criteria[c]
Total Solids	U	425	U	NA
Total Dissolved Solids	200–1300	400	668.0	<2000
pH	6.8–7.7	7.0	7.9	6.5–8.4
Biochemical Oxygen Demand	2–50	25	U	NA
Chemical Oxygen Demand	25–100	70	U	NA
Total Nitrogen	10–30	20	U	<30
Ammonia Nitrogen	0.1–25	10	U	NA
Nitrate Nitrogen	1–20	8	0.1–1.2	NA
Total Phosphorus	5–40	10	<0.02	NA
Chloride	50–500	75	55–77	<350
Sodium	50–400	100	71–97	<70
Potassium	10–30	15	4–6	NA
Calcium	25–100	50	66–163	NA
Magnesium	10–50	20	23–28	NA
Boron	0.3–2.5	0.5	0.10–0.54	<3.0
Cadmium (*ug*/L)	<5–220	<5	<1–69	10
Copper (*ug*/L)	5–50	20	<10–10	200
Nickel (*ug*/L)	5–500	10	<1–4	200
Lead (*ug*/L)	1–200	5	<5	5000
Zinc (*ug*/L)	10–400	40	<3–12	2000
Chromium (*ug*/L)	<1–100	1	<1	100
Mercury (*ug*/L)	<2–10	2	<0.1–0.1	NA
Molybdenum (*ug*/L)	1–20	5	2–8	10
Arsenic (*ug*/L)	<5–20	<5	4–16	100

All units in milligrams per liter unless otherwise noted as micrograms per liter (*ug*/L). U: unavailable. NA: not applicable.
[a] Adapted from Asano et al., 1984 and Treweek, 1985
[b] Radtke, et al., 1988
[c] from Westcot and Ayers, 1985 and National Academy of Sciences, 1973

life. Over a 10-year period, Yanko (1993) assayed 590 filtered and chlorine-treated secondary effluent samples from wastewater treatment plants in Los Angeles County for enteric viruses. All of the effluent samples had met California's wastewater reclamation standard of 2.2 coliform/100 ml, and only one was found positive for virus (Coxsackie B3).

State regulations of the use of reclaimed wastewater on food crops are aimed at protecting consumers from possible exposure to pathogens (discussed in Chapter 7). The potential health hazard of trace elements (including heavy metals) and toxic organic chemicals has been addressed for a variety of end used of reclaimed wastewater, but they have not been regulated for purposes of agricultural irrigation. As mentioned, concentrations of trace elements in wastewater effluents that have undergone secondary or higher levels of treatment are normally within existing guidelines for irrigation water quality criteria (see Chapter 4 for a discussion of trace elements and organic chemicals).

Sewage Sludge

Before the era of wastewater treatment, municipal wastewater was untreated and sludge did not exist. Sewage sludge is an end product of municipal wastewater treatment and contains many of the pollutants removed from the influent wastewater. Sludge is a concentrated suspension of solids, largely composed of organic matter and nutrient-laden organic solids, and its consistency can range in form from slurry to dry solids, depending on the type of sludge treatment. Agricultural utilization of sewage sludge has been practiced since it was first produced. Given agricultural experience with the use of human excrement, sewage, and animal manure on croplands, the application of municipal wastewater sludge to agricultural lands was a logical development. As an early example, municipal sludge from Alliance, Ohio was used as a fertilizer as early as 1907. During the same period, Baltimore, Maryland used domestic septage in agricultural production (Allen, 1912). The plant nutrient value of sludge has been evaluated by many investigators (Rudolfs and Gehm, 1942; Sommers, 1977; Tabatabai and Frankenberger, 1979), and the nutrient composition is considered to be similar to other organic waste-based soil amendments that are routinely applied on cropland, such as animal manures (as shown in Table 2.2). In addition to major plant nutrients, sludge also contains trace elements that are essential for plant growth. Soils which have been tilled for decades are often deficient in certain trace elements, such as zinc and copper (Martens and Westermann, 1991). Certain calcareous soils are deficient in iron (Martens and Westermann, 1991). Land applications of municipal sludge can help to remedy these trace metal deficiencies (Logan and Chaney, 1983).

Early agricultural sludge use projects were often carried out with little regard for possible adverse impacts to soil or crops (Allen, 1912). A common goal was to maximize the application rate to minimize the cost of sludge disposal. Since the early 1970s, more emphasis has been placed on applying sludge to cropland at an agronomic rate (Hinesly et al., 1972; Kirkham, 1974).

Wastewater treatment authorities attempt to manage the volume of wastewater and type of pollutants discharged into sewers to protect the integrity of the infrastructure, health and well-being of sanitation workers, the performance of wastewater treatment processes, and the impact on receiving waters. Federal and state regulations exert control over the quality of the treated effluent in order to keep contaminants below concentrations that would be harmful to humans and the environment.

TABLE 2.2 Chemical Composition of Sewage Sludge and Animal Manure

Constituent (Unit)	Animal Manure[a]	Sewage Sludge	
	Range	Range	Typical
Nitrogen (% dry weight)	1.7–7.8	<0.1–17.6[b]	3.0
Total phosphorus (% dry weight)	0.3–2.3	<0.1–14.3[b]	1.5
Total sulfur (% dry weight)	0.26–0.68	0.6–1.5[b]	1.0
Calcium (% dry weight)	0.3–8.1	0.1–25[b]	4.0
Magnesium (% dry weight)	0.29–0.63	0.03–2.0[b]	0.4
Potassium (% dry weight)	0.8–4.8	0.02–2.6[b]	0.3
Sodium (% dry weight)	0.07–0.85	0.01–3.1[b]	-
Aluminum (% dry weight)	0.03–0.09	0.1–13.5[b]	0.5
Iron (% dry weight)	0.02–0.13	<0.1–15.3[b]	1.7
Zinc (mg/kg dry weight)	56–215	101–27,800[b]	1200
Copper (mg/kg dry weight)	16–105	6.8–3120[c]	750
Manganese (mg/kg dry weight)	23–333	18–7,100[b]	250
Boron (mg/kg dry weight)	20–143	4–757[b]	25
Molybdenum (mg/kg dry weight)	2–14	2–976[b]	10
Cobalt (mg/kg dry weight)	1	1–18[b]	10
Arsenic (mg/kg dry weight)	12–31	0.3–316[c]	10
Barium (mg/kg dry weight)	26	21–8,980[b]	-

[a] Data summarized from Azevado and Stout, 1974
[b] Data summarized from Dowdy et al., 1976
[c] Data summarized from Kuchenrither and Carr, 1991

Nevertheless, toxic chemicals in low concentrations are introduced into municipal wastewater. Many of these toxic chemicals are removed from the wastewater and concentrated into the sewage sludge by the wastewater treatment process. Sewage sludge also contains human pathogens, although it can be treated to significantly reduce the number of pathogens present. Pathogens and toxic chemical pollutants may be introduced into sludge-amended soil.

Since about 1970, there has been an intense and concerted effort of scientific research world-wide to better understand the fate of potentially toxic and pathogenic constituents in sludge when sludge is applied to agricultural soils. A search of agricultural research articles (from the computer database, AGRICOLA) revealed more than 2,300 articles published since 1970. The surge of technical information regarding agricultural application of sewage sludge has led to the development of pollutant loading guidelines by the United States and western European countries (McGrath et al., 1994). The World Health Organization is also investigating ways to develop human health-related chemical guideline for using treated municipal wastewater effluents and sewage sludge in agriculture production (Chang, et al., 1993).

Since the late 1970s and early 1980s, source control and industrial wastewater pretreatment programs have been initiated to limit the discharge of industrial pollutants into municipal sewers, and these programs have resulted in a dramatic reduction of toxic pollutants in wastewater and in sludge (see Chapter 3 for a discussion of industrial pretreatment). Municipal wastewater sludge, particularly from industrialized cities, now has significantly lower levels of toxic contaminants—specially heavy metals—than in earlier decades when much of the research on sludge application to cropland was conducted. Tables 2.3, 2.4, and 2.5 show decreasing levels of metals in wastewater or sludge for municipal sewage treatment facilities in Chicago, Baltimore, and Philadelphia from about 1970 through 1985. More recently, a comparison of sludge quality was made between two EPA surveys (Kuchenrither and McMillan, 1990): a study of 40 cities conducted in the late 1970's (EPA, 1982) and the National Sewage Sludge Survey (NSSS) conducted in the late 1980s (EPA, 1990). While the two studies used different sampling and analytic techniques, the comparison (in Table 2.6) shows that most metals have significantly lower concentrations in the NSSS than in the 40-city study, largely as a result of industrial pretreatment programs. The data on organic compounds is difficult to compare as the limits of detection between the two studies varied. EPA's 1991 report to Congress (EPA, 1991) also documents a reduction in sludge metal concentrations from about 1985 to 1990 in a number of POTWs across the country.

For a long time, wastewater treatment authorities in the United States managed land applications of sewage sludge with little governmental attention. Early regulations governing sewage sludge disposal were developed by state public health agencies with the intention of controlling infectious disease. Although federal guidelines for land application of sewage sludge were proposed as early as 1974, comprehensive federal regulations did not exist until 1993. EPA first developed sludge management regulations under the 1972 Federal Water Pollution Control Act to prevent sludge-borne pollutants from entering the nation's navigable waters. In 1977, Congress amended the Act to add a new section, 405(d), that required EPA to develop regulations containing guidelines to (1) identify alternatives for sludge use and disposal; (2) specify what factors must be accounted for in determining the methods and practices applicable to each of these identified uses; and (3) identify concentrations of pollutants that would interfere with each use. In 1987, Congress amended section 405 again and established a timetable for developing sewage sludge use and disposal guidelines. Through this amendment, Congress directed EPA to: (1) identify toxic pollutants that may be present in sewage sludge in concentrations that may affect the public health and the environment and (2) promulgate regulations that specify acceptable management practices and numerical concentration limits for these pollutants in sludge.

TABLE 2.3 Metal Loadings in Raw Wastewater (in kg/day) Entering the Chicago Area Treatment Facilities in Response to Pretreatment Programs

	Cd	Cr	Cu	Pb	Ni	Zn
1971	398	5,197	2,166	2,049	2,443	6,972
1972	343	3,321	1,996	1,793	1,377	4,641
1973	301	2,463	961	1,063	957	4,260
1974	213	1,894	652	735	643	3,403
1975	113	1,522	538	497	386	2,537
1976	132	1,527	685	368	416	2,400
1977	168	1,422	588	536	436	2,587
1984	121	1,185	949	396	702	2,322

Note: Table 2.3 combines data from two different POTWs within the Metropolitan Sewerage District of Greater Chicago. Pretreatment programs began in 1972.
SOURCE: Adapted from Page et al., 1987.

The intent of the 1987 amendment was to "adequately protect human health and the environment from any reasonably anticipated adverse effect of each pollutant" [Section 405 (d)(2)(D)]. Section 405 also states that any permit issued to a POTW or other treatment works for wastewater discharge should specify technical standards for sludge use or disposal. *The Standards for the Use and Disposal of Sewage Sludge,* Code of Federal Regulations, Title 40, Part 503 (EPA, 1993) were promulgated in 1993, and are collectively referred to in this report as the "Part 503 Sludge Rule."

IRRIGATION WITH RECLAIMED WATER

Crop Irrigation

The nation encompasses 930.8 million hectares (2,300 million acres) of land, of which 125 million hectares (309 million acres), or 14 percent were used to grow crops in 1993 (USDA, 1992). Figure 2.1 shows the proportion of cropland devoted to different categories of crops. The category "fresh food" includes such produce crops as broccoli, potatoes, or fruit that are bought and consumed fresh, and this is the smallest category in terms of total acreage. Other food crops, such as small grains, vegetables used for commercial processing (canning and processing), peanuts, sugar beets, and sugar cane, are grown on roughly 24 percent of cropland. Crops for domestic animal consumption—feed and hay—occupy the bulk of cropland. Farmers

TABLE 2.4 Metal Concentrations in Digested Sludge Filter Cake (in mg/kg dry weight) at the Back River POTW, Baltimore, Maryland in Response to Pretreatment Programs

Year	Cd	Cu	Pb	Ni	Zn
1978	51	2,750	680	423	5,000
1979	23	2,540	539	397	3,540
1980	18	2,840	433	381	3,400
1981	19	2,070	493	374	3,410
1982	18	1,110	398	193	2,360
1983	23	1,060	324	214	2,620
1984	26	1,010	372	266	2,750
1985	22	681	346	126	2,030

Note: Source identification began in 1980 and source reduction began in 1981. Based on monthly composites in early years, then biweekly and weekly.
SOURCE: Adapted from Page et al., 1987.

often practice crop rotation, so a variety of crops may be grown on the same piece of land over a period of several years.

Irrigated crop production expanded in the United States from nearly 7.7 million hectares (19 million acres) in 1945 to more than 20.5 million hectares (51 million acres) in 1978. The total amount of irrigated cropland dropped by 1987 to 18.8 million hectares (46 million acres) (Figure 2.2, Council for Agricultural Science and Technology, 1992; USDA, 1992). About 15 percent of harvested crops are grown on the 5 percent of farmland that is irrigated. Irrigation is essential in semiarid and arid regions to produce of many crops including orchard crops, and vegetables (Figure 2.3). Irrigated crops represent 38 percent of the total revenue from crop production in the United States (Bajwa, et al. 1992).

Deemand for Irrigation Water

Much of the nation's water withdrawal is used for crop irrigation. In 1990, crop irrigation accounted for 518 million m3/day (137,000 million gal/day) of water or 41 percent of all fresh water withdrawn for all uses from well and surface water (Solley et al., 1993). Irrigation is also a highly consumptive use of water; about 56 percent of the quantity withdrawn is lost to evaporation and plant transpiration, and so is not available as return-flow to surface waters. By comparison, domestic, commercial, industrial and mining uses consume an average of 17 percent of the water withdrawn for these purposes.

TABLE 2.5 Metal Concentrations in Sludges (in mg/kg dry weight) at Two Philadelphia Wastewater Treatment Plants in Response to Pretreatment Programs

Year	Cd	Cu	Pb	Ni	Zn
	Southwest				
1974	31	825	1,540	100	3,043
1976	27	1,110	2,710	103	2,650
1977	27	1,400	2,170	185	3,940
1978	16	1,020	1,800	275	4,050
1980	18	986	740	98	2,780
1981	25	971	562	117	2,300
1982	20	940	1,030	113	2,440
1983	12.5	736	421	79	1,700
1984	14.3	1,140	427	111	1,830
1985	15.0	880	373	80	1,730
	Northeast				
1974	108	1,610	2,270	391	5,391
1976	97	2,240	2,570	372	5,070
1977	71	2,320	2,680	459	3,920
1978	57	1,240	1,620	319	5,910
1980	26	1,210	728	275	3,890
1982	14	985	423	185	2,570
1983	10.9	1,020	351	130	2,110
1984	12.4	1,200	360	130	1,980
1985	17.3	1,270	382	187	2,100

Note: Source identification began in 1976. Liquid sludge analyzed until 1982, and sludge filter cake from 1983 on.
No data available for 1975 and 1979.
SOURCE: Page et al., 1987.

TABLE 2.6 Comparison of Organics and Trace Elements From the 40-Cities Study Conducted in the Late 1970s and the National Sewage Sludge Survey (NSSS) Conducted in the Late 1980s

Organic Pollutants (μg/kg, unless noted by * = mg/kg)	Percent Detection		Mean Values		
	40 Cities	NSSS	40 Cities	NSSS	
Aldrin	16	3	6.4	1.9	
Benzene	93	0	1782	—	
Benzo(a)pyrene	21	3	138	—	
Bis(2-ethylhexyl)phthalate	100	62	155*	74.7*	
Chlorodane	16	0	6.4	—	
Dieldrin	16	4	6.4	—	
Heptachlor	16	0	6.4	—	
Hexachlorobenzene	16	0	155	—	
Hexachlorobutadiene	5	0	23	—	
Lindane	16	0	6.4	—	
Dimethylnitrosamine	5	0	57	—	
PCB's	N/A	N/A	—	—	
Toxaphene	16	0	6.4	—	
Trichloroethene	84	1	8139	—	
DDD/DDE/DDT	N/A	N/A	—	—	
Trace Elements (mg/kg, values in O denote composited means by mass in NSSS)					
Arsenic	100	60	6.7	9.9	(10)
Beryllium	100	23	1.67	0.4	(1)
Cadmium	100	69	69.0	7.0	(22)
Chromium	100	91	429	119	(268)
Copper	100	100	602	741	(730)
Lead	100	80	969	134	(205)
Mercury	100	63	2.8	5.2	(3)
Molybdenum	75	53	17.7	9.2	(11)
Nickel	100	66	135.1	42.7	(70)
Selenium	100	65	7.3	5.2	(5)
Zinc	100	100	1594	12	(1550)

SOURCE: EPA, 1990.

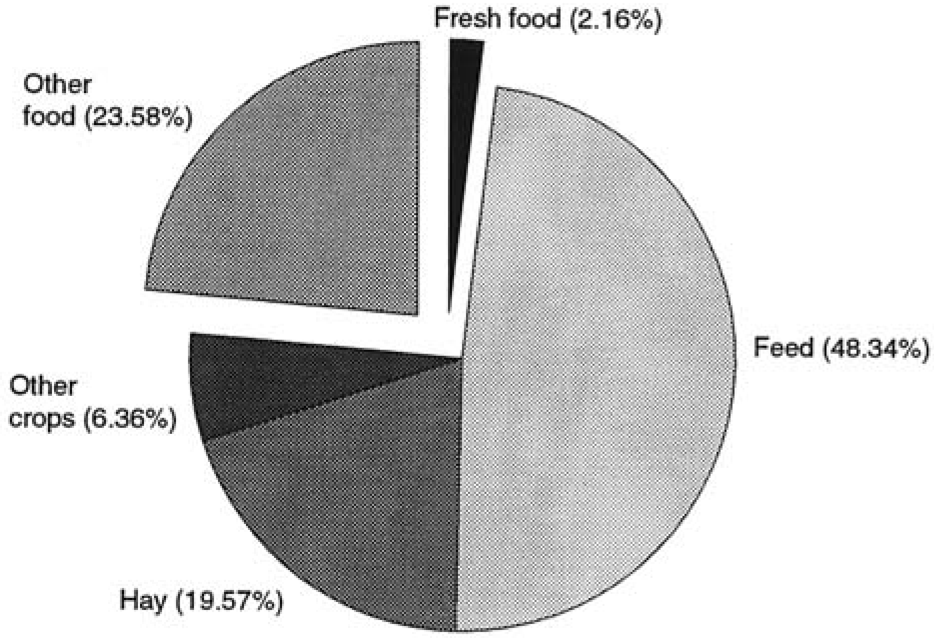

FIGURE 2.1 The proportion of U.S. cropland devoted to different crops. Categories defined by U.S. Department of Agriculture.
SOURCE: USDA, 1992.

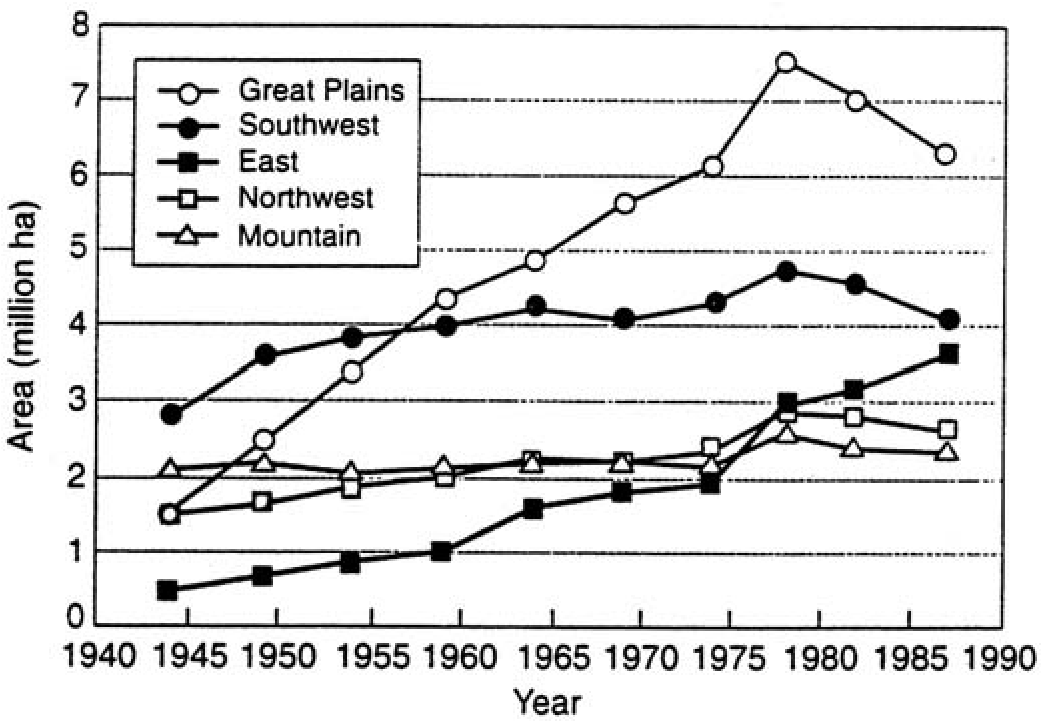

FIGURE 2.2 The expansion and also, in four regions, the contraction of irrigated area of the United States.
SOURCE: Council for Agricultural Science and Technology, 1992.

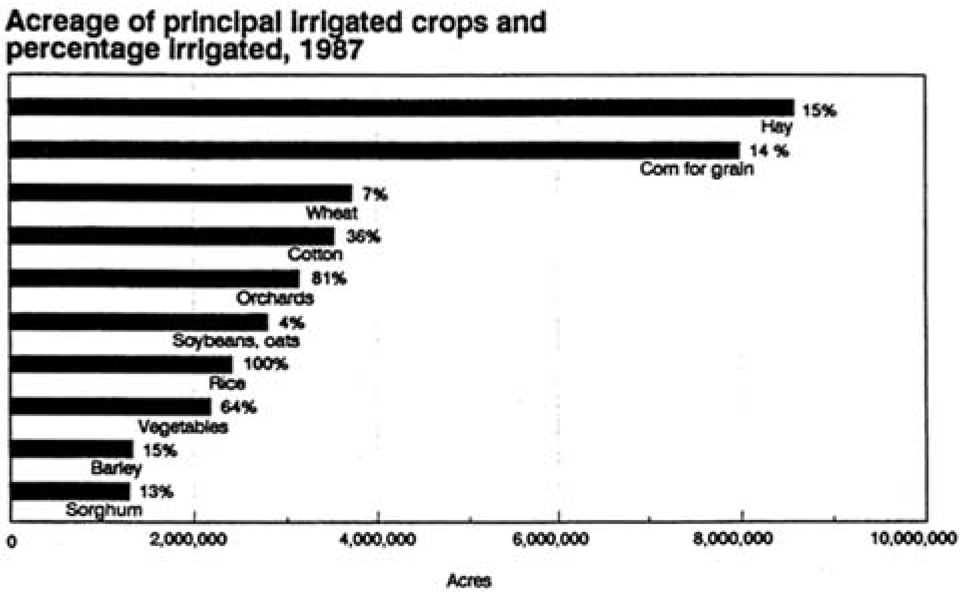

FIGURE 2.3 Irrigated acreage of principal crops in the United States and the percentages of total crop acreage that is irrigated.
SOURCE: Bajwa et al., 1992.

Reclaimed wastewater provides a very small volume of the nation's crop irrigation water although it is a significant source of water in some areas. Nationally, the United States produces 134 million m^3/day (35,400 million gal/day) of municipal wastewater. Approximately 3 percent of this quantity, or 3.5 million m^3/day (925 million gal/day), is reclaimed (Solley et al., 1993). About 70 percent of this reclaimed water goes towards irrigation, but the national estimates do not distinguish between urban and agricultural irrigation. In Florida, agricultural irrigation accounts for approximately 34 percent of the total volume of reclaimed water used within the state (Florida Department of Environmental Regulation, 1992). In California, agricultural irrigation accounts for approximately 63 percent of the total volume of reclaimed water (California State Water Resources Control Board, 1990). Even so, only 5 percent of California's reclaimed water irrigates land used to grow crops classified for human consumption (Figure 2.4, EPA, 1992). It is probable that reclaimed water accounts for less than 0.5 percent of the water used nationally for agricultural irrigation.

Although the total volume of treated wastewater produced in the United States could theoretically satisfy 26 percent of the need for agricultural irrigation, this magnitude of reuse is not likely. The volume of wastewater produced by a community does not often match the volume of water needed for crop irrigation in the nearby vicinity. In fact, much of the wastewater in the United States is produced in areas where crop irrigation is not needed or is only occasionally required. Figure 2.5 shows the distribution of U.S. irrigated agriculture and Table 2.7 illustrate regional imbalances in irrigation needs relative to the amount of wastewater produced. For the purpose of Table 2.7, the 18 water resource regions defined by U.S. Water Resources Council (Solley et al., 1993) have been simplified to six (Figure 2.6).

The Northeast region has about half of the population of the U.S. and produces about half

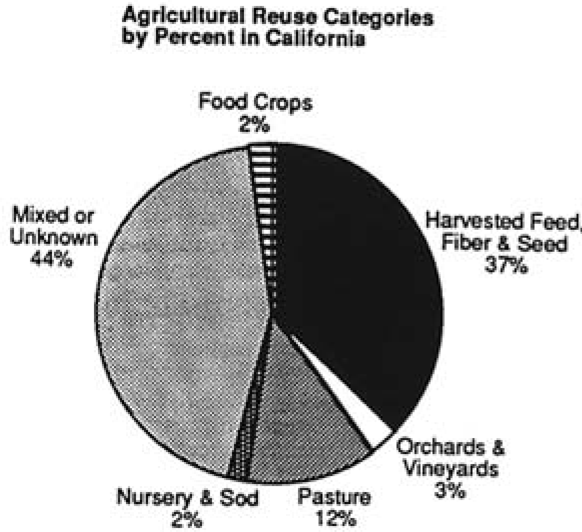

FIGURE 2.4 Proportion of different crop types irrigated by reclaimed water in California.
SOURCE: California State Water Resources Control Board, 1990.

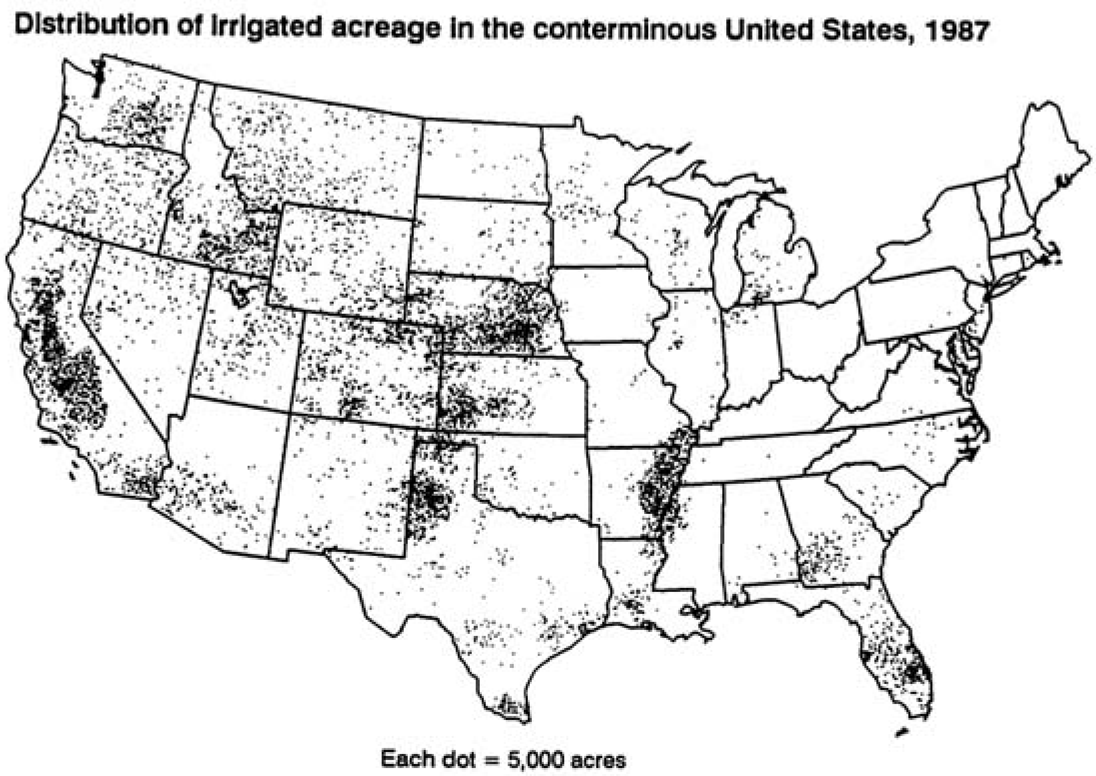

FIGURE 2.5 The distribution of irrigated agriculture in the United States.
SOURCE: Bajwa et al., 1992.

TABLE 2.7 Relation of Reclaimed Water Generated to Agricultural Needs by Region

Region	Wastewater Return Flow (bgd)[a]	Reclaimed Water		Water Drawn for Agricultural Irrigation (bgd)	Reclaimed Water as a Percent of Water Drawn for Agriculture Irrigation
		Percent	bgd		
Northeast	20.0	0.3	0.06	1.0	6.0
Southeast	6.0	4.6	0.276	17.0	1.6
California	3.0	8.5	0.255	28.0	0.9
Great Plains	2.3	1.0	0.023	38.0	0.06
Northwest	2.2	0.5	0.011	32.0	0.03
Southwest	1.1	26.2	0.288	19.0	1.5

[a] billion gallons per day
SOURCE: Derived from information in Solley, et al., 1993.

of the wastewater. This region has a relatively short growing season and a humid-climate; thus the demand for crop irrigation is low. In all other regions, the amount of water required by irrigation far exceeds the volume of wastewater produced (Solley, et al., 1993). Water conveyance is a significant cost of a water reuse project and even in the semi-arid and arid western states, the distance between generators and potential users of reclaimed water will determine its feasibility.

Wastewater Reclamation Motivated by Disposal Priorities

In 1976, the city of St. Petersburg, Florida initiated a wastewater reuse program which included diverting its treated wastewater effluent to urban reuse purposes to avoid the pollution of Tampa Bay (EPA, 1992). It was considered a pioneering effort then. It is interesting to note that the reclaimed water was initially not metered in St. Petersburg; customers were urged to use as much as they wanted at a flat rate per acre. Currently, reclaimed water is valued for its ability to reduce water demand, and meters are now being retrofitted. The publication of *Quality Criteria for Water* (EPA, 1976) set minimum national in-stream water quality limits that include numerical limits for metals and toxic organics. When effluents are discharged into a large or fast-flowing water body, the water quality standard can more easily be met because of the dilution that occurs in the receiving stream. However, POTWs that discharge into small or intermittent streams are not able to take advantage of dilution, and their discharge limits may be as stringent as the in-stream water quality standards. In many cases, the local or state requirements are even more restrictive than the national requirements. Often, the pollutants of concern are nutrients such as phosphorus rather than toxic chemicals.

To meet these strict in-stream requirements, and to control treatment costs, many communities are considering water reuse to achieve regulatory compliance (Shacker and Kobylinski,

FIGURE 2.6 Water resource regions referred to in Table 2.7. For purposes of Table 2.7, the 18 water resource regions as established by the U.S. Water Resources Council have been simplified to six as follows: "Northeast" includes New England, Mid-Atlantic, Tennessee, Ohio, Great Lakes, Upper Mississippi, and Sorris-Red-Rainey regions; "Southeast" includes South Atlantic-Gulf, Lower Mississippi, and Texas-Gulf regions; "Southwest" includes Lower Colorado, Upper Colorado, and Great Basin regions; "Great Plains" includes Missouri, Arkansas-White-Red, and Rio Grande regions; "Northwest " is the Pacific Northwest region; and "California" is the California region.
SOURCE: modified from Solley et al., 1993.

1994). Therefore, both water shortage and waste disposal are driving forces for the use of reclaimed wastewater, and the dominance of one over the other will depend on local conditions. A recent survey of water reuse projects in California indicated that two thirds of the projects were initiated exclusively for water supply purposes. Only 4 percent of the projects were motivated by the need for pollution control, and the rest were mixed (Water Reuse Association of California, 1993).

Miller (1990) found that urban landscape irrigation (e.g, for golf courses and highway median strips) is one of the fastest growing uses of reclaimed wastewater in the United States In Florida, two-thirds of the reclaimed water is used for urban landscape purposes (Paret and Elsner, 1993). The Irvine Ranch Water District in California irrigates about twice as much urban land as farmland, and the expectation is that water use on urban land will increase as agricultural land is taken out of production and replaced by residential development (Parsons, 1990). Throughout California, nonagricultural use of reclaimed wastewater is expected to increase faster over the next 20 years as achievement of state goals for water reuse is approached, and it is estimated that the proportion of reclaimed water for crop irrigation will shrink from 21 to 13 percent of all reclaimed water uses (Water Reuse Association of California, 1993).

Value of Reclaimed Wastewater

The costs to reclaim wastewater vary depending on the level of treatment required by state water reuse programs. The total cost of reclaiming 1 acre-foot (1,233 m^3) of municipal wastewater are estimated at roughly $500/acre-foot ($406 per 1,000 m^3) in both Denver, Colorado and Orange County, California (Miller, 1990), which is roughly equivalent to the cost that southern California utilities pay to the Metropolitan Water District for imported water. The value of reclaimed water to the farmer will depend on its cost relative to other off-farm water supplies. In 1988, the average cost to the farmer of an off-farm water supply in the United States was $34/acre-foot ($27.50 per 1,000 m^3) and ranged from about $89/acre-foot ($72.10 per 1,000 m^3) in Arizona to $1/acre-foot ($0.81 per 1,000 m^3) in Arkansas (1988 prices from Bajwa et al, 1992). These rates are considerably less than the amortized unit cost for developing and maintaining a water reclamation facility. If the farmers currently obtain irrigation water at low prices, they are not expected to pay more for using reclaimed water. In areas where the motivation for a water reclamation project is pollution abatement rather than water savings, reclaimed water is likely to have a low market value, and farmers may receive the treated effluent free of charge. In these situations, it may be more attractive for POTWs to seek other alternatives, such as reclaiming water for industrial users who are paying higher water rates.

Treated effluent contains plant nutrients and has potential value as a fertilizer. Even so, the value of effluent as a fertilizer is not significant when total farm production costs are considered. Fertilizer comprised about 6 percent of the $108 billion total production expenses of U.S. farming in 1987 (U.S. Bureau of the Census, 1990). Projected 1992 production costs for several high-value food crops predicted fertilizer costs ranging from 0.03 to 11.5 percent (Table 2.8).

For crops to grow properly, the correct fertilizers must be applied at appropriate intervals in the appropriate amounts. When reclaimed water is used, irrigation needs rather than nutrient requirements may determine fertilizer inputs. The nutrients contained in the irrigation water may not be appropriate in terms of type, amounts, and timing. Effluent irrigation takes place during the warmest part of the season, and fertilization will occur even though fertilizer may only be needed during the early, cool part of the season. Heavy fertilization during the warm season can encourage undesirable vegetative growth (Bouwer and Idelovitch, 1987).

TABLE 2.8 The Cost of Fertilizer As a Percentage of All Costs for the Production of Some Food Crops

Crop	Percent of Total Costs	State
Fresh apples	0.6	Pennsylvania
Processing apples	1.3	Pennsylvania
Green tomatoes	2.4	California
Ripe tomatoes	2.6	Pennsylvania
Carrots	3.4	California
Fresh broccoli	4.1	California
Iceberg lettuce	4.9	California
Sweet corn	6.8	California
Tomatoes for processing	10.2	California
Potatoes	11.5	Pennsylvania

SOURCES: University of California Imperial County Cooperative Extension 1992; Harper, 1993.

USE OF SEWAGE SLUDGE IN AGRICULTURE

Potential Role of Sewage Sludge in Crop Production

Based on estimates of the amount of solids produced in typical primary and secondary wastewater treatment processes (Metcalf and Eddy, 1991), the national production of sewage sludge is approximately 7 million metric tons/year. Secondary and higher levels of treatment account for 5.3 million metric tons/year, and the remainder comes from coastal discharges and sewage ponds (EPA, 1993). The quantity of sewage sludge is expected to increase as a greater percentage of the population is served by sewers and as advanced wastewater treatment processes are brought on-line (refer back to Figure 1.1). Currently, 36 percent of sewage sludge is applied to the land for several beneficial purposes, such as agriculture, turfgrass production, or reclamation of surface mining areas. 38 percent is landfilled, 16 percent is incinerated, and the remainder is surface disposed by other methods (EPA, 1993). With the promulgation of the Part 503 Sludge Rule, EPA encouraged agricultural use of sewage sludge.

From a national perspective, sludge has very little impact on agriculture. If all sludge produced in the United States was used agriculturally and applied according to agronomic nitrogen requirements, it would only require an estimated 1.59 percent of the nation's cropland (assuming that the average concentration of available nitrogen in the sludge is 4 percent dry weight and it is applied at 100 kg nitrogen/ha/yr).

Regional and local availability of farmland will, however, affect the potential for increased agricultural use of treated municipal sludge. The ratio of available farmland to sludge produced is an initial consideration in agricultural use of sludge. North Dakota, for example, would require only 0.05 percent of its agricultural land to take up all sludge produced in the state at agronomic rates for nitrogen. The Madison Metro Sewerage District has applied anaerobically digested sludge to private farmland since 1974, and the demand for sludge outstrips the supply (Taylor and Northouse, 1992). Rhode Island, on the other hand, would need to utilize 100 percent of its cropland to use up its sludge supply; because that is unlikely, other use or disposal options are required. Table 2.9 shows a comparison of the amounts of cropland required to accommodate in-state sludge applications at agronomic rates. Unlike wastewater effluents, sludge can be transported further distances. For example, contractors are currently shipping some of New York City's treated sludge to northeastern Texas and eastern Colorado for cropland application. Boston, Massachusetts ships a portion of its sludge in the form of heat-dried pellets to Florida for application to cropland and pastures. Some of the sludge from the Los Angeles Basin is being transported by truck for cropland application in Yuma, Arizona.

The cost of transporting sludge for land application must be weighed against the cost and environmental consequence of other sludge disposal options on a case by case basis. If wastewater treatment authorities in urban centers cannot overcome the variety of obstacles to use sludge within reasonable transportation distances, they face the consequences of long distance transportation and its associated costs. These geographical and economical constraints on land application create uncertainty over how much of the nation's sewage sludge will be applied on cropland in the long run.

From the farmer's perspective, other factors limit agriculture use of sewage sludge. Sewage sludge is inherently more difficult to use than chemical fertilizers. In part, this is because the composition of plant nutrients and trace elements vary due to differences among types of sludges (e.g., different water contents or treatment processes) and differences among municipalities and their industrial contributors. The composition of commercial fertilizers are formulated to meet crop requirements. Some have argued that any cost savings derived from substituting sludges for chemical fertilizers may be insignificant (White-Stevens, 1977) and that unless the waste generators offer them payment, the financial incentive for farmers to apply sewage sludge to cropland may be marginal. Others point out that sludge has significant nutrient value, which can range from $100 to $140 per acre (EPA, 1994), and that its effect on soil physical properties can increase crop yield (e.g., Logdson, 1993). Generally, the POTW makes arrangements for hauling and spreading sewage sludge on farmland.

Ecological Linkages Between Urban and Agricultural Systems

The land application of sewage sludge can ecologically link nutrient usage within urban and rural landscapes (Millner, 1994). If nutrients and organic matter are returned to agricultural soil via land application of sludges, the need to supplement the agroecosystem in terms of nutrients will diminish. In this sense, cropland recycling of sewage sludge close to its urban source can conserve energy as does the recycling of crop residues and farm animal manures.

In natural ecosystems, the external inputs to primary food production are solar energy and water (Figure 2.7). Natural ecosystem productivity is sustained through the recycling of nutrients extracted by primary producers (plants) and made available again in the process of organic matter mineralization. In contrast, conventional crop production is enhanced by external inputs of energy, water, nutrients, and chemical herbicides and pesticides (Figure 2.7). The capacity of modern agroecosystems for natural feedback and regulation has been greatly reduced in order to increase crop yields (Risser, 1985; Barrett et al., 1990). When these external inputs

TABLE 2.9 Amount of Cropland Required to Accommodate In-state Sludge Applications at Agronomic Rates

State	Population[a] (millions)	Sludge Produced[b] (thousands of metric tons)	Cropland Required[c] (thousands of hectares)	Cropland[d] (thousands of hectares)	Percent of State Cropland
New England					
Maine	1.24	24.78	9.91	158	6.3
New Hampshire	1.12	22.38	8.95	43	20.8
Vermont	0.57	11.39	4.56	177	2.6
Massachusetts	6.01	120.10	48.0	79	60.8
Rhode Island	1.00	19.98	7.99	8	100.0
Connecticut	3.27	65.35	26.1	62	42.1
Middle Atlantic					
New York	18.70	363.63	149.4	1,539	9.7
New Jersey	7.87	157.27	62.9	166	37.9
Pennsylvania	12.05	240.80	96.3	1,716	5.6
East North Central					
Ohio	11.10	221.82	88.7	3,921	2.3
Indiana	5.71	114.11	45.6	4,335	1.1
Illinois	11.70	233.81	93.5	8,162	1.1
Michigan	9.47	189.25	75.7	2,591	2.9
Wisconsin	5.04	100.72	40.3	3,339	1.2
West North Central					
Minnesota	4.52	90.33	36.1	7,086	
Iowa	2.81	56.15	22.5	8,359	0.51
Missouri	5.23	104.52	41.8	4,987	0.27
North Dakota	0.63	12.59	5.04	10,305	0.84
South Dakota	0.71	14.19	5.68	6,889	0.05
Nebraska	1.60	31.99	12.8	7,285	0.08
Kansas	2.53	50.58	20.2	10,433	0.18
South Atlantic					
Delaware	0.70	13.99	5.6	202	2.8
Maryland	4.96	99.12	39.6	578	6.9
Dist. of Columbia	0.58	11.59	4.64	0	0.0
Virginia	6.49	129.69	51.9	1,081	4.8
West Virginia	1.82	36.36	14.5	274	5.3
North Carolina	6.94	138.69	55.5	1,647	3.4
South Carolina	3.64	72.74	29.1	786	3.7
Georgia	6.92	138.29	55.3	1,516	3.6
Florida	13.68	273.38	109.4	931	11.8

State	Population[a] (millions)	Sludge Produced[b] (thousands of metric tons)	Cropland Required[c] (thousands of hectares)	Cropland[d] (thousands of hectares)	Percent of State Cropland
East South Central					
Kentucky	3.79	75.74	30.3	1,923	1.6
Tennessee	5.10	101.92	40.8	1,731	2.4
Alabama	4.19	83.73	33.5	959	3.5
Mississippi	2.64	52.76	21.1	1,635	1.3
West South Central					
Arkansas	2.42	48.36	19.3	2,711	0.71
Louisiana	4.29	85.73	34.3	1,612	2.1
Oklahoma	3.23	64.55	25.8	3,871	0.67
Texas	18.03	360.31	144.1	7,911	1.8
Mountain					
Montana	0.84	16.79	6.72	6,200	0.11
Idaho	1.10	21.98	8.79	2,065	0.43
Wyoming	0.47	9.39	3.76	870	0.43
Colorado	3.56	71.14	28.5	3,514	0.81
New Mexico	1.61	32.17	12.9	493	2.6
Arizona	3.93	78.54	31.4	427	7.4
Utah	1.86	37.17	14.9	517	2.9
Nevada	1.39	27.78	11.1	236	4.7
Pacific					
Washington	5.25	104.91	42.5	2,701	1.6
Oregon	3.03	60.55	24.2	1,495	1.6
California	31.21	623.69	249.5	3,516	7.1
Alaska	0.60	11.99	4.8	13	36.9
Hawaii	1.17	23.38	9.35	66	14.2

[a] Estimate of July 1993 population from U.S. Census Bureau.
[b] Sludge production estimates assume 75% of population is sewered and produces .073 kg of sludge per person per day.
[c] State cropland required if all sludge produced in-state were to be applied at agronomic rates using the assumption of 4 percent available nitrogen dry weight and an application rate of 100 kilograms per hectare per year.
[d] 1987 land utilization from U.S. Department of Agriculture, 1992.

exceed the capacity of the agroecosystem to accommodate them, the result is an increase in system outputs of both natural and unnatural byproducts that can cause environmental harm. Society often bears the financial costs required to restore environmental quality and to maintain high crop yields.

Frequently, cropland is removed from crop production and permitted to lie fallow for several years. These fallow fields are often referred to as old-field communities or old-field ecosystems. Various studies on the effects of sludge application to old-field ecosystems have focused on ecological trophic levels, including producers (Maly and Barrett, 1984; Hyder and

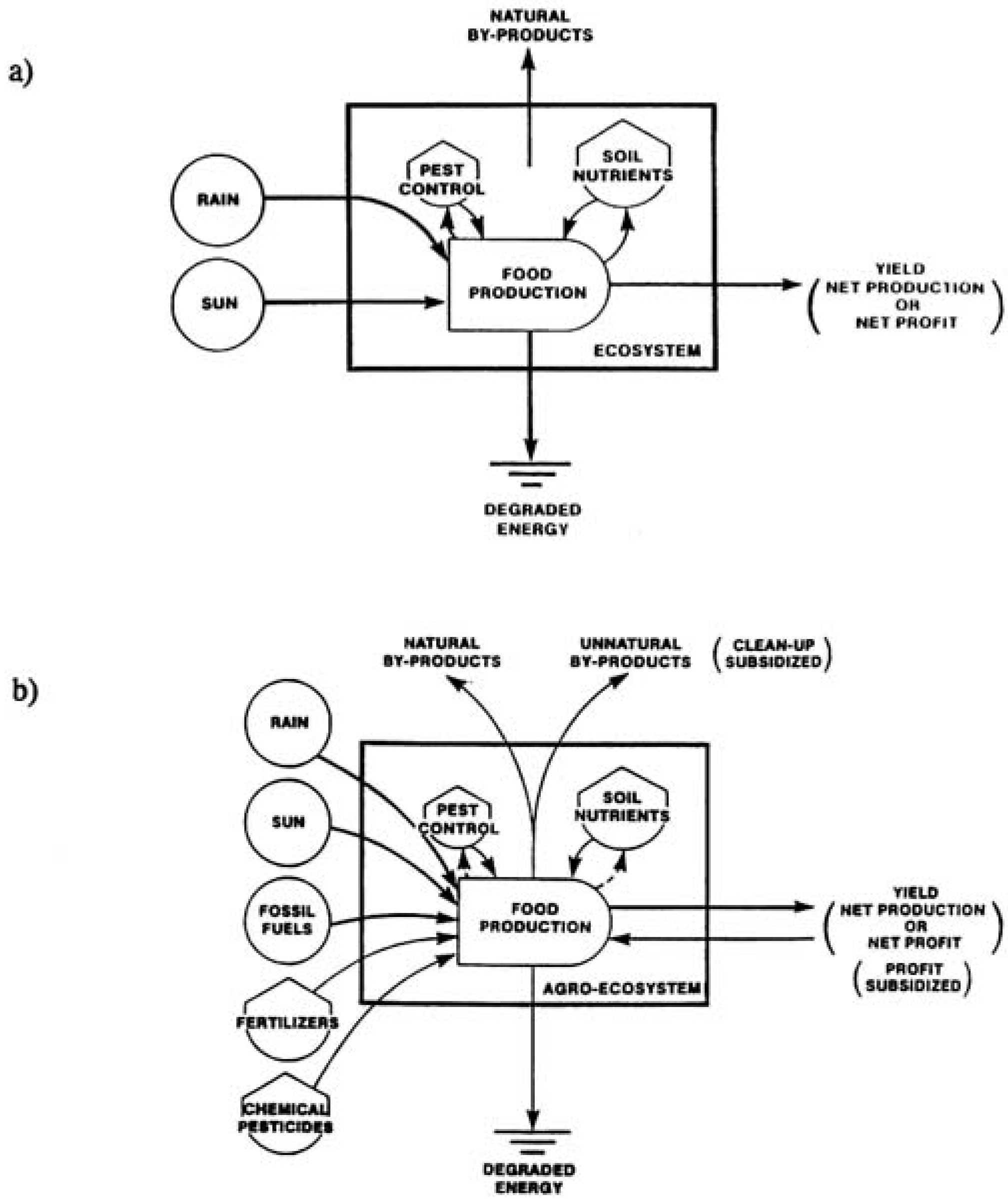

FIGURE 2.7 Diagrams depicting a) natural, and b) human inputs into agroecosystems.
SOURCE: Adapted from Barrett et al., 1990.

Barrett, 1986), primary consumers (Anderson and Barrett, 1982; Brewer et al., 1994), secondary consumers (Brueske and Barrett, 1991), detritivores (Kruse and Barrett, 1985; Levine et al., 1989) and decomposers (Sutton et al., 1991,; Brewer et al., 1994). Thus far, the research indicates that old-field ecosystems are ecologically safe and economically viable sites for sludge disposal (Maly and Barrett, 1984; Carson and Barrett, 1988; Levine et al., 1989; and Brewer et al., 1994). These old-fields may again revert to cropland usage due to improved productivity and soil conditioning.

SUMMARY

With continuing advancement in wastewater treatment technology and increasingly stringent wastewater discharge requirements, treated wastewater effluents produced by municipal treatment plants in the United States have achieved consistent high water quality and are increasingly being considered for nonpotable reuse. In the semiarid and arid western states, treated wastewater has been used as a new source of water to help alleviate shortages faced by water-deficient communities. More recently, the need to meet local minimum in-stream water quality limits when treated effluents are discharged into surface water bodies has motivated many municipalities to consider effluent irrigation.

The chemical composition of most treated effluents is within the range defined by accepted irrigation water quality criteria and is comparable to that of water commonly used in crop and landscaping irrigation. At present, treated municipal wastewater probably accounts for much less than one percent of national irrigation water requirements, and it is likely that the level of agricultural use will not significantly increase. Effective barriers to increased use include the limited availability of irrigated agricultural land near municipal centers, and the competition with more cost-effective, higher-value urban uses for reclaimed water.

Much of the wastewater in the United States is produced in regions where agricultural irrigation is not needed or is only occasionally needed. Judging from the acreage of irrigated cropland compared to the availability of reclaimed wastewater and the current pattern of reclaimed water use, only a very small fraction of the food crops in the United States would ever be exposed to reclaimed wastewater.

Treated sewage sludge is an end product of municipal wastewater treatment and contains many of the pollutants that are removed from the influent wastewater during treatment. The nutrients and organic matter in treated sludge resembles those in other organic waste-based soil amendments such as animal manure and organic composts. The use of sludge as a soil conditioner serves to improve soil physical properties in a manner similar to other organic-based soil amendments. While sewage sludge has been land applied since it was first produced, most of the early operations were carried out with little regard for possible adverse impacts to soil, crops, or ground water. In the past two decades, more emphasis has been placed on applying treated sludges to cropland at agronomic rates.

The financial incentive for farmers to use sewage sludge in crop production is debatable. Fertilizers presently account for a relatively small percentage of total crop production costs, and sewage sludge may be more difficult to use than commercial fertilizer. However, the nutrient value of sludge is promoted as a benefit, and the POTW often provides for transport and application of sludge for free or at a nominal cost.

Community-wide source control and industrial wastewater pretreatment programs have resulted in significant reduction of toxic pollutants in wastewater and thus in sewage sludge. Still, land application of treated effluents and treated sludge will increase the level of toxic chemicals and pathogens in the soil. The public is concerned about pollutants and pathogens that may contaminate food crops or be transported elsewhere in the environment.

If the total amount of municipal sludge produced in the United States were applied to cropland at agronomic rates, less than 2 percent of the nation's cropland would be necessary to accept it. However, there are some regions where limited cropland acreage may constrain sludge management options. A lack of available disposal options near densely populated urban centers has forced many municipalities to seek distant disposal and land application sites at considerable costs. Given these economic and geographic constraints, it is not likely that all of the sewage sludge will be applied to cropland in the foreseeable future, and thus only a very small percentage of the food crops grown in the United States would ever be exposed to sewage sludge.

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3

Municipal Wastewater and Sludge Treatment

At municipal wastewater treatment plants in the United States, raw municipal wastewater undergoes preliminary, primary, secondary, and in some cases, additional treatment to yield treated effluent and a concentrated stream of solids in liquid, called sludge. The sludge is treated as required for utilization or disposal, and additional treatment of effluent may be needed to accommodate specific water reuse opportunities.

The practice of municipal wastewater treatment evolved primarily to accommodate discharge of treated effluent to surface waters, not to facilitate use of effluent on crops (see Chapter 2). Because municipal wastewater treatment techniques are well established in the United States and because effluent from some municipal wastewater treatment facilities is discharged both to surface water and used to irrigate agricultural land, secondary or higher levels of wastewater treatment typically precede wastewater reuse in agriculture in the United States.

The relationship of municipal wastewater and sludge treatment to crop production is shown schematically in Figure 3.1. As illustrated, reuse of wastewater for food crop production or in other reuse applications, such as ground water recharge or urban landscape irrigation, typically occurs after secondary wastewater treatment and may necessitate additional treatment. Treatment to produce reclaimed water often adds coagulation, filtration, and disinfection to secondary treatment. Figure 3.1 also illustrates the origin and treatment of municipal wastewater sludges applied to cropland. Following treatment, sludges may be disposed of (for example, in a landfill) or used for food crop production or in other applications (such as silviculture and nonfood crop agriculture).

This chapter briefly reviews typical amounts and properties of treated effluent and sludge, then examines processes used in conventional wastewater treatment (defined as preliminary, primary, and secondary treatment), processes intended specifically to accommodate wastewater application to crops, and typical sludge treatment processes.

QUANTITY AND QUALITY OF MUNICIPAL WASTEWATER EFFLUENT AND SLUDGE

Municipal wastewater represents the spent water supply of communities. In 1990, average

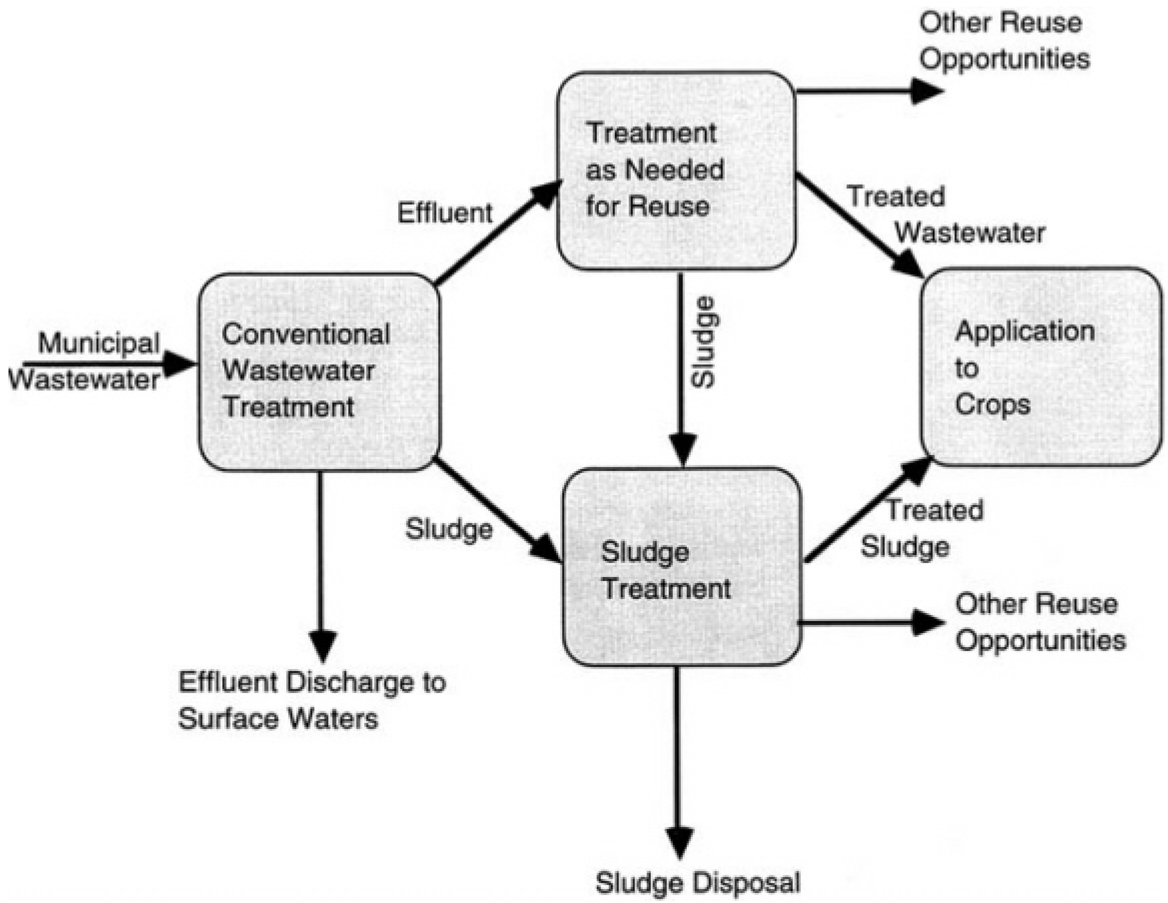

FIGURE 3.1 Following conventional wastewater treatment (preliminary, primary, and secondary), municipal wastewater is discharged to surface waters or reused, or before discharge to surface waters (not illustrated). Additional treatment may be needed before reuse. Sludge from wastewater treatment processes are treated and then disposed or reused in crop production or other applications.

per capita usage from public water supply systems in the United States was 184 gallons (700 liters) per day (Solley et al., 1993). In arid areas, municipal wastewater production is typically less than the amount withdrawn for water supply, but in some areas, wastewater flow exceeds the water supply because of infiltration and inflow (e.g. stormwater) into wastewater collection systems. Using 85 percent of water use as an estimate of typical wastewater production (Henry and Heinke, 1989), a city of 200,000 people would produce an average of about 31,000,000 gal/day (about 117,000 m3/day) of raw wastewater. The amount of treated wastewater effluent extracted is not appreciably diminished from the original quantity of raw wastewater particularly if sludge is dewatered, as is common.

The quality of treated effluent from secondary wastewater treatment plants in the United

States must comply with the federal regulation of a monthly average of 30 milligrams per liter of biochemical oxygen demand or BOD (a measure of the amount of biodegradable organic material remaining in the treated wastewater) and 30 mg/liter of suspended solids (particles removable by filtration). Typical concentrations of other constituents in wastewater treatment plant effluent are summarized in Chapter 2 . More detailed information on typical effluent quality is presented in sections of this report where potential effects of individual constituents are considered. For example, Chapter 5 includes information on the types and quantities of pathogens typically found in various wastewater treatment plant effluents.

The volume of municipal wastewater sludge produced by wastewater treatment facilities is an elusive quantity because it varies as a result of typical sludge treatment (see "Volume Reduction Processes" later in this chapter). Since the mass of dry solids is conserved during most treatment processes, dry weight is a more useful basis for expressing the amount of sludge from municipal wastewater treatment. Typical primary and secondary wastewater treatment produces a total of about 1.95 lbs (0.94 kg) of dry solids per 1,000 gal (3.78 m3) of wastewater treated (Metcalf and Eddy, 1991). Chemical addition to sludges during conditioning and stabilization processes (see later sections of this chapter) can appreciably increase the mass of solids in sludges. Biological stabilization acts to reduce the mass of suspended solids through oxidation of some of the volatile organic solids in sludges. For example, if sludge contains 80 percent volatile suspended solids and 50 percent of them are destroyed through oxidation, the stabilized mass of sludge solids would be reduced to 60 percent of the initial mass.

Typical solids contents of sludges at various stages of treatment are summarized in this chapter. Typical ranges of other common constituents in sludges are summarized in Chapter 2. As with wastewater effluents, more detailed information about specific sludge constituents is found in sections of the report where the potential effects of those constituents are discussed.

CONVENTIONAL WASTEWATER TREATMENT PROCESSES

Municipal wastewater treatment typically comprises preliminary treatment, primary treatment, and secondary treatment. Secondary treatment is the United States national standard for effluent discharged to surface waters. A higher degree of treatment, termed here "advanced" or "tertiary" treatment, may be required at specific locations to protect health or environmental quality. In this report, conventional municipal wastewater treatment is considered to include screening, grit removal, primary sedimentation, and biological treatment because it is the most common method (Figure 3.2). Elaboration on these terse descriptions may be found in sources such as Henry and Heinke (1989) and Metcalf and Eddy (1991).

Preliminary Wastewater Treatment

Preliminary wastewater treatment ordinarily includes screening and grit removal. Wastewater screening removes coarse solids such as rags that would interfere with mechanical equipment. Grit removal separates heavy, inorganic, sandlike solids that would settle in channels and interfere with treatment processes.

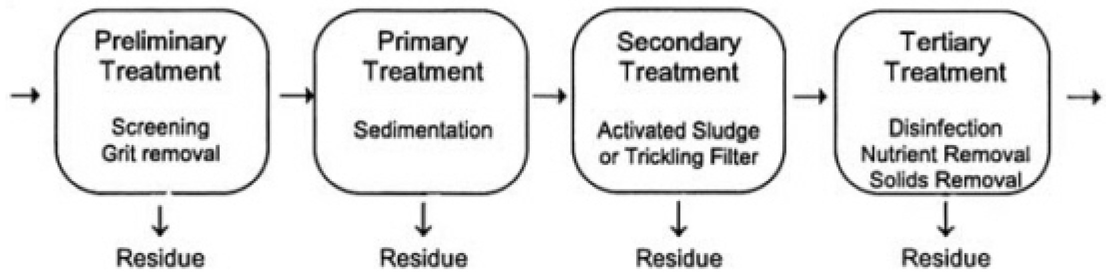

FIGURE 3.2 Municipal wastewater is conventionally subjected to preliminary, primary, and secondary treatment in the United States. Additional tertiary or advanced treatment may be justified by local conditions. Processes typically involved in each stage of treatment are shown. Preliminary treatment effects minimal change in wastewater quality. Primary treatment typically removes about one-third of the BOD and one-half of the suspended solids in domestic wastewaters. Combined primary and secondary treatment is required to achieve 85 percent reduction in both BOD and suspended solids concentration to meet the regulatory definition of secondary treatment.

Preliminary treatment serves to prepare wastewater for subsequent treatment, but it effects little change in wastewater quality. The residues from preliminary wastewater treatment, screenings and grit, are not ordinarily incorporated with sludges, and they are not considered further in this report.

Primary Wastewater Treatment

Primary wastewater treatment usually involves gravity sedimentation of screened, degritted wastewater to remove settleable solids; slightly more than one-half of the suspended solids ordinarily are removed. BOD in the form of solids removable by sedimentation (typically about one-third of total BOD) is also removed. At one time during the evolution of domestic wastewater treatment in the United States, facilities only practiced primary wastewater treatment and the primary effluent was commonly discharged to surface waters offering appreciable dilution. Now, primary treatment is used as an economical means for removing some contaminants prior to secondary treatment. The residue from primary treatment is a concentrated suspension of particles in water called "primary sludge."

Although the goal of primary wastewater treatment is to separate readily-removable suspended solids and BOD, wastewater constituents that exist as settleable solids or are sorbed to settleable wastewater solids may also be removed. Thus, primary treatment effects some reduction in the effluent concentration of nutrients, pathogenic organisms, trace elements, and potentially toxic organic compounds. The constituents that are removed are contained in primary sludge.

Secondary Wastewater Treatment

Secondary municipal wastewater treatment is almost always accomplished by using a biological treatment process. Microorganisms in suspension (in the "activated sludge" process), attached to media (in a "trickling filter" or one of its variations), or in ponds or other processes are used to remove biodegradable organic material. Part of the organic material is oxidized by the microorganisms to produce carbon dioxide and other end products, and the remainder provides the energy and materials needed to support the microorganism community. The microorganisms biologically flocculate to form settleable particles, and, following biological treatment, this excess biomass is separated in sedimentation tanks as a concentrated suspension called "secondary sludge" (also known as "biological sludge," "waste activated sludge," or "trickling filter humus").

Wastewater constituents can become associated with secondary sludge as a result of microbial assimilation, by sorption onto settleable solids, or by incorporation into agglomerate particles formed as a result of bioflocculation. Some of the wastewater constituents that are incidentally associated with the biomass from secondary treatment processes include pathogens, trace elements, and organic compounds.

Tertiary or Advanced Wastewater Treatment

Tertiary treatment is used at municipal wastewater treatment plants when receiving water conditions or other uses require higher quality effluent than that produced by secondary wastewater treatment. Disinfection for control of pathogenic microorganisms and viruses is the most common type of tertiary treatment. The concentrations of suspended solids and associated BOD in treated effluent can be reduced by filtration, sometimes with the aid of a coagulant. Adsorption, ordinarily on activated carbon, can be used to remove some persistent organic compounds and trace elements. The concentration of ammonia in secondary effluent can be reduced by nitrification. Tertiary treatment to remove nitrogen and phosphorus, so as to minimize nutrient enrichment of surface waters, is common; nitrogen is usually removed by nitrification followed by denitrification, and phosphorus is removed by microbial uptake or chemical precipitation. Not all tertiary treatment processes follow secondary treatment, as was shown schematically in Figure 3.1; nutrient removal, for example, can be achieved by design and operational variations to primary and secondary treatment processes. The residues from tertiary treatment typically become incorporated with sludges from primary and secondary treatment.

There are many variations to these treatment practices. For instance, secondary treatment is rarely achieved using physical and chemical processes rather than biological treatment. Primary treatment is sometimes eliminated. Long-term retention in lagoons is sometimes substituted for both primary and secondary treatment.

TREATMENT TO FACILITATE CROP IRRIGATION WITH RECLAIMED WATER

The degree of wastewater treatment required prior to using wastewater effluent for crop production depends on the crop, local conditions, and state regulations. In considering specific applications of reclaimed wastewater for crop production, tradeoffs may exist between degree of wastewater treatment needed and agricultural practices.

Special treatment to allow agricultural use of treated effluents is not always considered necessary by states that regulate the practice (see Chapter 7); effluents from conventional primary and secondary wastewater treatment are used. Indeed, historically, untreated raw wastewater has been used, but the practice is not found in the United States and is not considered herein.

In identifying appropriate wastewater treatment for crop application, it is appropriate to consider protection of health and environmental quality, water quality requirements of crops, and requirements of the irrigation water storage and delivery system (such as avoiding odors and clogging) (EPA, 1981; Water Pollution Control Federation, 1983). As a practical matter, the extent of wastewater treatment required prior to food crop application ordinarily is established by health and environmental quality considerations. Disinfection and suspended solids removal are the processes most frequently used to further improve conventional wastewater treatment plant effluents for use on crops.

Disinfection of treated effluent is most often accomplished by chlorination. Chlorine is an economical disinfectant, but it reacts with organic material in wastewater effluent to form chlorinated organic compounds that are of potential concern with potable reuse of reclaimed wastewater, but not with irrigation (see Chapter 6). Alternatives to chlorine as a wastewater disinfecting agent include ozone and ultraviolet light. The latter two processes do not provide a residual disinfectant as required by some state regulations for applying treated wastewater to food crops (EPA, 1992).

Additionally, suspended solids are sometimes removed from conventional wastewater treatment plant effluent prior to using the effluent in agriculture. Removal of suspended solids aids in control of pathogenic organisms and viruses by making disinfection more effective. Suspended solid removal minimizes deposition of solids on top of soils, and reduces clogging of some irrigation water delivery systems. Further reduction of suspended solids in effluent is typically achieved by adding a coagulating chemical, settling, and filtering through granular media (Faller and Ryder, 1991; Kuo, et al., 1994).

Treatment technology to produce any degree of wastewater quality perceived to be necessary for food crop production is available; however, treatment costs escalate with incremental water quality improvements. Additionally, residue (sludge) management problems accompany some processes (such as those using membranes) that might be used to improve treated wastewater quality beyond the current norms. Situations exist today in which water quality discharge requirements, the crop value and water scarcity justify the higher degrees of wastewater treatment before application to food crops.

SLUDGE TREATMENT PROCESSES

Primary and secondary sludges may be expected to contain settleable materials from raw wastewater and the products of microbial synthesis. Other materials are also removed from wastewaters and incorporated into primary and secondary sludges, however. The large surface area of particles incorporated into sludges provides sites for adsorption of constituents from the liquid phase. Nondegraded organic compounds in solution may partition into the organic fraction of the particles. Bioflocculation may incorporate colloidal particles that otherwise would not be removed by sedimentation into settleable particles. These and other mechanisms result in selective enrichment of wastewater constituents in sludge. Additionally, wastewater sludges are mostly water and, hence, wastewater constituents remaining in the liquid phase also are included in sludges.

Because primary and secondary sludges have different properties, advantage is sometimes sought by treating them separately. As an illustration, secondary sludge thickens better using the dissolved air flotation process (see following section) than by gravity thickening, and it is sometimes thickened separately from primary sludge. The two sludges almost invariably are combined prior to the end of the treatment, and, for purposes of discussing the ultimate utilization of treated sludge, they are not further distinguished.

A wide variety of sludge treatment processes are used to reduce sludge volume and alter sludge properties prior to disposal or use of the treated product. The nature of these processes is summarized in the sections that follow. Additional details may be found in sources such as Dick (1972), Vesilind (1979), and EPA (1977), and Metcalf and Eddy (1991).

Sludge treatment is considered herein to comprise engineered processes for altering sludge quality prior to disposal or reclamation. When sludge is applied to land, inactivation of remaining pathogenic organisms and viruses continues, biological stabilization of residual organic material progresses, and biologically-mediated and abiotic chemical transformations occur.

Volume Reduction Processes

Biological sludge, as produced from secondary wastewater treatment processes, often has a suspended solids content of less than one percent by weight; that is, each kg of activated sludge solids is accompanied by more than 99 kg of water. Primary sludges are more concentrated, but marginally so; typical combined primary and secondary sludge might contain about 3 percent solids by weight. Because of the voluminous nature of sludges, processes categorized here as "thickening," "dewatering," "conditioning," and "drying" (listed in order of decreasing frequency of application) are common in sludge management. Removal of water from sludges improves efficiency of subsequent treatment processes, reduces storage volume, and decreases transportation costs.

Thickening

Sludge thickening produces a concentrated product that essentially retains the properties of a liquid. Gravity thickening, or concentration by simple sedimentation, is the thickening process most commonly applied to municipal sludges. The product of gravity sludge thickening often contains 5 to 6 percent solid material by weight. Alternatives to gravity thickening include flotation thickening (in which a gas is incorporated with sludge solids, causing them to float), as well as the use of gravity drainage belts, perforated rotating drums, and centrifuges.

Dewatering

Sludge dewatering processes produce material with the properties of a solid, even though the dewatered sludge is still mostly water. Dewatered sludge can be transported in a dump truck, whereas a tank truck is required to transport thickened sludge. Dewatering may be accomplished on sand drying beds and, occasionally, in lagoons, where gravity drainage and evaporation removes moisture. More often, larger municipal installations use mechanical means for dewatering sludge. Mechanical sludge dewatering equipment includes filter presses, belt filter presses, vacuum filters, and centrifuges. The solids content of mechanically dewatered sludge typically ranges from 20 to 45 percent solids by weight; most processes produce concentrations of solids at the lower end of that range.

Conditioning

Sludge conditioning processes do not, in and of themselves, reduce the water content of sludge. Conditioning alters the physical properties of sludge solids to facilitate the release of water in dewatering processes. Indeed, the mechanical dewatering techniques discussed in the previous paragraph would not be economical without prior sludge conditioning. Chemical and, less frequently, physical techniques are used to condition sludge. Chemical conditioning most commonly involves adding synthetic organic polyelectrolytes (or "polymers") to sludge prior to dewatering. Inorganic chemicals (most commonly, ferric chloride and lime in the United States) can also be used. Inorganic chemical conditioning dosages are large, and increase the mass of the solid phase of sludge. Physical conditioning techniques include heat treatment and freezethaw treatment.

Drying

If circumstances justify removal of water beyond that achievable by dewatering processes, drying is needed. Thermal drying with direct or indirect dryers is used to achieve near-complete removal of water from sludges. Solar drying is feasible in some locations. Partial drying also results from heat produced in biochemical reactions during composting and from other chemical reactions described in the stabilization processes below.

Stabilization Processes

The purpose of sludge stabilization is to minimize subsequent complications due to biodegradation of organic compounds. Stabilization is usually accomplished by biological or chemical treatment processes, as described below.

The vector attraction reduction provisions of the Part 503 Sludge Rule (EPA, 1993a) concern stabilization processes. Vectors, such as flies, are organisms that might be attracted to unstabilized sludge and are capable of transmitting infectious diseases. Stabilization process performance requirements are specified in the Part 503 Sludge Rule for both biological and chemical stabilization. When sewage sludge is applied to agricultural land, vector attraction reduction requirements can also be satisfied by injecting sludge below the surface or incorporating sludge into the soil.

Stabilization can also be achieved by drying sludge adequately to impede microbial activity. Obviously, sludge combustion, too, accomplishes the stabilization objective. Many stabilization processes can also cause appreciable inactivation of pathogenic organisms and viruses. Inactivation of pathogens in sludges is considered separately in a subsequent section.

Biological Stabilization

In biological stabilization processes, the organic content of sludges is reduced by biological degradation in controlled, engineered processes. Most commonly, domestic wastewater sludge is biologically stabilized as a liquid in anaerobic digesters from which methane gas is a byproduct. Liquid sludge can also be biologically stabilized in aerobic digesters to which oxygen (or air) must be added. Composting is a process that biologically stabilizes dewatered sludge. Composting is ordinarily an aerobic process, and an amendment such as wood chips or sawdust must be added to improve friability in order to promote aeration. Composting takes place at thermophilic temperatures (often, about 55^{1}C) because of heat released by biochemical transformations. Aerobic digesters can be made to operate thermophilically using heat from the same source. Anaerobic digesters can operate at thermophilic temperatures by burning methane produced from the process, but they typically operate at mesophilic temperatures (at about 35^{1}C) in the United States.

Chemical Stabilization

Chemical stabilization of sludges is aimed not at reducing the quantity of biodegradable organic matter, but at creating conditions that inhibit microorganisms in order to retard the degradation of organic materials and prevent odors. The most common chemical stabilization procedure is to raise the pH of sludge using lime or other alkaline material, such as cement kiln dust. Sludge can be chemically stabilized in liquid or dewatered forms. When dewatered sludge is used, the exothermic reaction of lime with water causes heating which helps destroy pathogens and evaporate water.

Inactivation of Pathogenic Organisms and Viruses

Many of the processes for drying and stabilizing sludges can be designed and operated to achieve appreciable inactivation of pathogenic agents, including bacteria, parasites, and viruses. Alternatively, sludge treatment processes specifically intended to control pathogenic organisms and viruses can be used. Processes specifically intended for inactivating pathogens include irradiation and pasteurization; these processes currently are not widely used in the United States.

In the Part 503 Sludge Rule, (EPA, 1993a) the pathogenic quality of sludge is controlled by categorization of sludges as either "Class A" (safe for direct contact) or "Class B" (crop and site restrictions required), according to criteria for the destiny of indicator and pathogenic organisms and by specification of process performance. The Part 503 Sludge Rule identifies specific processes with regard to their capability for pathogen destruction. Processes that can be used to reach the Class B category are identified by EPA as "Processes to Significantly Reduce Pathogens." These including aerobic digestion, air drying, anaerobic digestion, composting, and lime stabilization, or any combination of processes that can reduce fecal coliform less than 2,000,000 colony forming units per gram of total dry solids. EPA identifies more effective processes that can be used to reach the Class A category called "Processes to Further Reduce Pathogens." These Class A processes include composting at higher, controlled temperatures, heat drying, heat treatment, thermophilic aerobic digestion, beta ray irradiation, gamma ray irradiation, and pasteurization as well as high-level alkaline treatment and other processes that can be demonstrated to reduce pathogens to below detectable levels. Human health concerns about pathogenic organisms and viruses in sludge are considered in more detail in Chapter 5, and regulations to control infectious disease transmission from the use of sludge in crop production are discussed in Chapter 7.

Other Sludge Treatment Processes

A wide variety of processes are used to treat sludges. Those briefly discussed in this section ordinarily are less relevant to sludge management schemes directed towards food crop production than are the processes previously discussed.

Solidification/Immobilization

Solidification/immobilization processes involve the conversion of sludge to a solid material with load-bearing capacity and the incorporation of contaminants in the solid phase so as to minimize their migration. The technology for solidifying and immobilizing waste originated in the nuclear waste industry, and although it has been widely applied in attempts to control hazardous waste, it is less commonly applied to municipal sludges.

Metal Stripping and Toxic Organic Destruction

Research has been conducted on selective removal of trace metals from municipal sludges and destruction of toxic organic compounds in sludges. These processes are not commonly used and were not considered in this report. Control of trace elements and toxic organic compounds in sludges is more appropriately managed by the regulation of wastewater at its sources.

Combustion

Combustion destroys organic compounds in municipal sludges and leaves an inorganic dry ash. Rarely, sludge combustion is carried out in the liquid phase under high pressure, producing an ash in liquid suspension.

Because most of the organic material in sludge has beneficial attributes in agricultural systems, the combustion process is inappropriate when sludges are to be applied to cropland. Accordingly, combustion is not considered further in this report.

Ultimate Sludge Utilization or Disposal

Options for ultimate use or disposal of municipal wastewater sludges are quite restricted. The Clean Water Act and the Ocean Dumping Ban Act eliminated all but land-based options for ultimate use or disposal of municipal wastewater treatment sludges. Any attempt to extract and recycle materials from sludges is unrealistic due to the highly heterogeneous nature of municipal wastewater sludge. With the exception of sludge ash used in building materials, municipal wastewater sludges currently are land-applied for beneficial uses or disposed of on the land.

Beneficial uses of treated municipal wastewater sludges on land include agriculture and silviculture uses; application to parks, golf courses, and public lands; use in reclaiming low quality or spoiled lands; and use as landfill cover or fill material. Disposal on land includes landfilling and permanent storage of dewatered sludge or sludge incinerator ash in lagoons or piles.

Integrated Sludge Management Schemes

The large number of alternatives for accomplishing of the many objectives of sludge treatment lead to many variations in municipal sludge management schemes. When sludge is applied to agricultural land, the extent of water removal during its treatment is a major factor influencing cost and process selection. It is not necessary to remove water from sludge prior to land application—indeed, the water may be beneficial to crops. Sludge dewatering is justified when its cost is offset by savings in transportation costs. Optimization of sludge treatment process integration by Dick, et al. (1982) illustrated that lengthy transport may be cheaper than sludge dewatering. Sludge drying, which is more expensive than sludge dewatering, allows further reduction in transport costs, and also enables sludge to be stored and packaged.

Figures 3.3a, b, and c illustrate sludge management schemes for agricultural application of liquid, dewatered, and dried municipal sludges, respectively. Liquid sludge discharge to agricultural land, as illustrated in Figure 3.3a, is the simplest scheme, but substantial liquid storage capacity might be needed if land application sites are unavailable for extended periods. Agricultural application of dewatered sludge, as illustrated in Figure 3.3b, requires more expensive and extensive processing, but could be compatible with other disposal and use options that may be used in addition to agricultural use. Inclusion of drying in the sludge process-flow as diagramed in Figure 3.3c is ordinarily the most costly of the three options. Storage to accommodate agricultural demand is easiest when sludge is dried, and dried sludge can also be adapted to other disposal and use options.

Integration of sludge treatment processes for use on agricultural land also requires consideration of the effects of the treatment processes on sludge quality. For example, dewatering, composting, or alkaline treatment can be expected to reduce the amount of nitrogen in sludge that is available to plants. This would require on increase in the areal rate of sludge solids applied to satisfy the plant nitrogen demand, and would, in turn, increase the rate at which trace metals and toxic organic chemicals associated with the sludge solids were applied to soil.

INDUSTRIAL WASTEWATER PRETREATMENT

Pretreatment of industrial wastewaters is a means to manage toxic contaminants in treated wastewater effluents and sludge residuals. It is defined as "the removal of toxic materials as the industrial plant before the wastewater is released to the municipal sewer" (National Research Council, 1977). Because industrial activity is a substantial source of toxic chemicals in sludge and reclaimed wastewater in populated metropolitan areas, pretreatment programs have been effective in reducing the concentrations of most heavy metals in wastewater (refer back to Tables 2.3, 2.4, 2.5, and 2.6). They are grouped in four Priority Pollutant categories: Section 307 of the Clean Water Act regulates 127 hazardous compounds, (1) 14 heavy metals and cyanide, (2) 28 volatile organic compounds, (3) 58 semi-volatile organic compounds and (4) 25 pesticides and polychlorinated biphenyls (PCBs) (40 CFR 123.21 (1986)).

Fate of Toxic Chemicals During Secondary Wastewater Treatment

As will be discussed below, most of the priority pollutants in wastewater accumulate in sludge during the wastewater treatment process (Lue-Hing et al., 1992).

Heavy Metals

Investigations of heavy metal partitioning in secondary wastewater treatment plants include both surveys of operating POTWs (Mytelka et al., 1973; Oliver and Cosgrove, 1974; EPA, 1982) and more controlled pilot-plant studies (Petrasek and Kugelman, 1983; Patterson and Kodukula, 1984; Hannah et al., 1986). Researchers have focused on seven heavy metals:

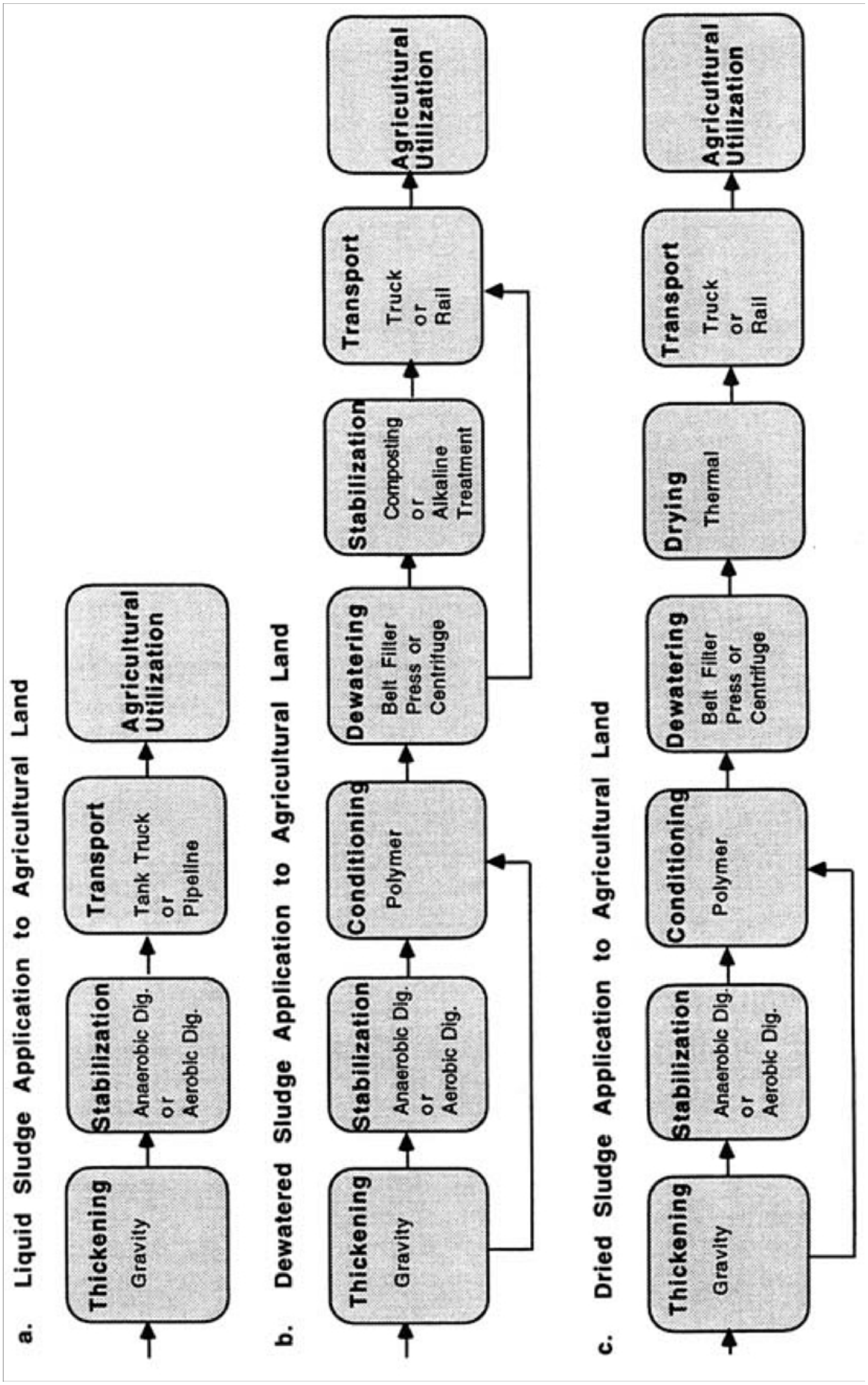

FIGURE 3.3 Sludge Management Schemes

cadmium, chromium, copper, lead, mercury, nickel, and zinc. These heavy metals are partitioned onto sludges both in primary wastewater treatment such as sedimentation, and in biological secondary treatment processes such as like activated sludge. From 5 to 50 percent of these metals were found to have been removed from wastewater and concentrated into primary sludge. Removal of heavy metals in secondary biological sludges was greater: 15 to 80 percent. Combining the findings of a number of studies (Lue-Hing et al., 1992; Cheng et al., 1975; Neufield et al., 1975), the removal of heavy metals from wastewater into secondary sludge is reported to be (in declining order): mercury, copper, lead, chromium, cadmium, zinc, and nickel.

Cyanide

In a study of 40 selected POTWs, removal of cyanide from untreated sewage was found to vary between 7 and 98 percent (Lue-Hing, et al., 1992). This wide removal range is somewhat deceptive. The minimum removal was associated with a very low influent cyanide concentration, 0.003 mg/liter. The maximum reported influent wastewater concentration, 7.58 mg/liter, was associated with higher removals. Many researchers have verified that cyanide is relatively biodegradable by aerobic (Knowles and Bunch, 1986) and anaerobic (Fallon, 1992) metabolic pathways. Richards and Shieh (1989) found that cyanide was removed from wastewater by activated sludge in concentrations of up to 100 mg/liter. It is likely then that small amounts of cyanide from industrial discharge into sewers are destroyed during secondary treatment and are not concentrated into sludge (Lordi et al., 1980).

Toxic Organic Chemicals: Volatile and Semivolatile Organic Compounds, Pesticides and PCBs

There are 111 organic priority pollutants, which constitute the majority percent of the hazardous chemicals regulated in wastewater. Unlike heavy metals, which are concentrated in sludge, many organic priority pollutants are removed from wastewater by a variety of mechanisms: volatilization during secondary treatment aeration, sedimentation and sorption onto both primary and secondary sludges, and biodegradation (Hannah et al., 1986; Petrasek et al., 1983; Kincannon et al., 1983; Tabak et al., 1981). Seven of the organic priority pollutants were found in over 50 percent of samples of treated wastewater effluent from 40 POTWs in the United States: 1,1,1-trichloroethane (52 percent), chloroform (82 percent), methylene chloride (86 percent), bis (2-ethylhexyl) phthalate (84 percent) and di-n-butyl phthalate (52 percent) (EPA, 1982).

Hannah et al. (1986) and Petrasek et al. (1983) conducted activated sludge pilot-plant studies on 21 and 22 organic priority pollutants, respectively. Reported removals ranged from 18 to 99 percent; the investigators found that over 90 percent of the majority of the organic chemicals were removed by the activated sludge process. Volatile organic priority pollutants were not concentrated into either primary or secondary sludge; however, semivolatile organic priority pollutants did accumulate in primary and secondary sludges, with concentration factors ranging from 5 to 200. High concentration factors were associated with higher molecular weight polyaromatic hydrocarbons and phthalate compounds.

Pretreatment

As discussed above, toxic heavy metals and those organic priority pollutants which are not biodegraded or volatilized are concentrated in wastewater sludge. The National Research Council (1977) reported that pretreatment has the potential to alleviate problems of sludge disposal due to heavy metals and toxic organic compounds. In a study of operating POTWs in Chicago, Illinois and in a pilot study at a POTW in Buffalo, New York where significant amounts of industrial wastewater discharge were received, it was found that industrial pretreatment programs reduced toxic heavy metal concentrations by a range of 50 to over 90 percent (Zenz, et al., 1975; EPA, 1977).

Pretreatment Goals

The General Pretreatment Regulations of the Clean Water Act (40 CFR 403 (1978)) establishes limits on industrial discharges of hazardous pollutants to municipal sewers in order to:

- prevent the introduction of pollutants which will interfere with the performance of the POTW treatment processes for wastewater and sludge;
- prevent the pass-through of toxic pollutants into surface waters receiving discharges of treated wastewater effluent; and
- enhance opportunities to recycle treated municipal wastewater and sludge (EPA, 1993b)
-

Pretreatment Implementation

The pretreatment regulations identify strategies for setting numerical standards on industrial dischargers to POTWs. First, 34 categories of industries have been identified as potential sources of priority pollutants in wastewater, and standards have been set for 29 of these categorical dischargers based on the best available technology. Second, discharge standards that prohibit hazardous pollutants enable POTWs to increase the scope of their pretreatment regulation to include all nondomestic users of municipal sewers, in addition to the categorical dischargers. Finally, the local POTW can set more stringent limits based on its specific requirements, and these also are federally enforceable. (Lue-Hing et al., 1992; Outwater, 1994).

More recently, the third goal of pretreatment, to enhance POTWs' ability to beneficially use sludge and reclaim wastewater, has been added to the regulation of industrial wastewater. Because heavy metals and many toxic organic chemicals accumulate in sludge, it is necessary to control not only the end-of-the-pipe concentration of hazardous compounds with standards, but to limit the total mass loading of pollutants that are concentrated in sludge (Outwater, 1994). For example, it has been reported that protection of sludge quality has caused a POTW in Georgia to set heavy metal discharge levels two orders of magnitude below categorical pretreatment limits for these compounds (Ford et al., 1994).

SUMMARY

Conventional municipal wastewater treatment processes were developed to produce effluents suitable for discharge to surface waters. The processes are intended primarily to remove BOD and suspended solids, but wastewater constituents associated with particles are also removed. Thus, substantial removal of trace contaminants may occur in conventional treatment even though the treatment processes were not designed for trace metal or toxic chemical removal.

When required by receiving water conditions or effluent reuse practices, advanced, or tertiary, wastewater treatment processes may be used in addition to conventional municipal wastewater treatment processes. Destruction of pathogenic organisms and increased removal of suspended solids or nutrients are some of the goals of tertiary treatment.

With the exception of compounds biologically degraded or volatilized during wastewater treatment, substances removed from wastewaters are contained in the residues, or sludges, produced. A wide variety of sludge treatment processes are used to prepare municipal wastewater treatment sludges for use or disposal. The objectives of most municipal sludge treatment processes are to reduce the water content of sludges, to avoid complications from decomposition of the biologically degradable fraction of sludges, and to reduce the levels of pathogenic organisms in sludges.

Economically viable technology for selective removal of trace elements and toxic organic compounds from sludges does not exist. Amounts of these constituents in municipal sludges can currently be controlled only by regulating the quality of wastewater entering municipal waste-water collection systems. Industrial wastewater pretreatment programs have been demonstrated to substantially improve the quality of sludge from municipal wastewater treatment. Modification of industrial processes, control of corrosivity of water in water supply systems, and changes in the formulation of disposable consumer products are other measures needed to control wastewater and, hence, sludge quality.

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4

Soil, Crop, and Ground Water Effects

Using treated municipal wastewater effluents and sludge on agricultural land provides an alternative to disposal by utilizing the recyclable constituents in sludge and wastewater in the production of crops. Sewage sludge and wastewater effluents can provide essential plant nutrients and water. Sludge is also rich in organic matter, which, if added in sufficient quantities, will improve the physical condition of the soil and render it a more favorable environment to manage the nutrients and water. However, unlike manufactured fertilizers, whose nutrient properties can be formulated to suit the crop requirements, plant nutrients in sludges and effluents are uncontrolled. For this reason, applying treated sludges and effluents at agronomic rates to satisfy the requirement for one nutrient may cause the levels of other nutrients to be excessive or remain deficient.

Certain source constituents in municipal wastewater and sludge (e.g, salts, cadmium, copper, nickel, and zinc) could be phytotoxic if added to the soil in excess of critical levels. Trace elements and trace organics in sludge are of concern if they are taken up by crops in amounts harmful to consumers or through other pathways (see Chapter 6). The fate and transport of potentially harmful constituents in the environment are also of concern. If the constituents from sludge and effluent application are not immobilized in the surface soil, they may escape the root zone and leach to ground water. This chapter evaluates the possible effects of the agricultural use of treated sludge and effluent on soils, crops, and ground water resources, and includes a brief discussion of landscape-level perspectives.

SLUDGE AS A SOURCE OF PLANT NUTRIENTS

Sewage sludge contains all the elements essential for the growth of higher plants. Because nitrogen and phosphorus are the most abundant major plant nutrients in sludge (Metcalf and Eddy, 1991), its agricultural use is almost exclusively as a supplemental source of nitrogen and/or phosphorus fertilizer.

Nitrogen

Typically, treated sludges include about 1 to 6 percent nitrogen on a dry weight basis (Metcalf and Eddy, 1991; Dean and Smith, 1973). By contrast, nitrogen in commercial fertilizers range from 11 to 82 percent (Lorenz and Maynard, 1988). The nitrogen in treated sludge occurs in both organic and plant-available inorganic forms. The relative proportions of each depend upon the way sludges are processed. In anaerobically digested liquid sludges, microbial oxidation of the organic materials is incomplete, and the nitrogen occurs in both soluble ammoniacal and insoluble organic forms, primarily, in microbial cells (Broadbent, 1973). In aerobically digested sludges, microbial oxidation is greater and there is less residual organic nitrogen than in anaerobically digested sludges. Ammoniacal nitrogen is about 10 percent of the total nitrogen in aerobically digested sludge and about 30 percent of the total nitrogen in anaerobically digested sludge (Linden et al., 1983). In aerobically digested sludge, the ammoniacal nitrogen is further oxidized to nitrate, of which part is lost to wastewater when sludge is dewatered. Likewise, when anaerobically digested sludges are dewatered, part of the ammoniacal nitrogen is lost with the water.

Where sludges are used as a source of nitrogen, the nitrogen application rates should not exceed the agronomic rate (a rate equivalent to the amount of fertilizer nitrogen applied to the soil for the crop grown). As with any fertilizer, nitrogen that leaches beyond the root zone could contaminate ground water. To determine the quantity of sludge needed for the crop's nitrogen requirement, it is important to know the relative proportions of inorganic and organic nitrogen. The inorganic forms of nitrogen (nitrate and ammonium) are immediately available to the crop. Organic forms of nitrogen are not available to the crop and must first be mineralized by microorganisms to inorganic forms. The rate of mineralization depends on a number of factors including sludge type, carbon-to-nitrogen ratio of the soil and/or sludge, climate, soil type, and water content. The rate of mineralization of sludge-borne organic nitrogen in soil ranges from a high of essentially 100 percent per year to a low of a few percent during the initial year of application (Parker and Sommers, 1983). Nitrogen not mineralized during the initial cropping year is mineralized in subsequent years, but usually at a diminishing rate. In general, mineralization rates of organic nitrogen in composted and dry sludges are less than those of liquid sludges and dewatered sludge cake.

A theoretical example is presented in Table 4.1 of a 5-year change in available nitrogen from applying a sludge containing 2 percent organic and 1 percent inorganic nitrogen. In the example, the organic nitrogen mineralization rate is 40 percent the first year, and this rate is reduced by 50 percent each succeeding year (the computation assumes that the only removal of nitrogen from the system is through plant uptake). In this example, the amount of plant-available nitrogen from 5 annual applications of 1 ton of sludge increases from 18 kg/ton to 22 kg/ton, and the amount of sludge required to supply 180 kg available nitrogen per ha decreases from 10 tons to 8.2 tons from year 1 to year 5. The example shows the importance of mineralization of organic nitrogen in succeeding years following the application. If organic nitrogen mineralization is not properly accounted for, overfertilization may occur that will subsequently lead to nitrogen leaching.

TABLE 4.1 Effect of Organic Nitrogen Mineralization on Plant-available Nitrogen (N) from Sludge Applications.a

Year	Available inorganic N (kg/ton)	Available organic N(kg/ton)	Total available N (kg/ton)	Sludge required[b] (tons)
1st	10	8.0	18.0	10.0
2nd	10	10.4	20.4	8.8
3rd	10	11.4	21.4	8.4
4th	10	11.8	21.8	8.3
5th	10	12.0	22.0	8.2

[a] The analysis assumes that sludge contains 1.0 percent inorganic and 2.0 percent organic nitrogen. Mineralization rate is 40 percent the first year, reduced by one-half in each succeeding year (40, 20, 10, 5).
[b] Amount of sludge required to supply 180 kg available nitrogen per hectare.

Phosphorus

Commercial fertilizers typically contain between 8 and 24 percent phosphorus (Lorenz and Maynard, 1988). By contrast, sludges typically contain between 0.8 and 6.1 percent phosphorus (Metcalf and Eddy, 1991; Dean and Smith, 1973). Like nitrogen, the phosphorus in sludges is present in inorganic and organic forms. The proportions of each vary and depend on the source of municipal wastewater and on sludge treatment. Unlike nitrogen, inorganic forms of phosphorus are quite insoluble and phosphorus tends to concentrate in the organic and inorganic solid phases. Almost without exception, the amount of phosphorus applied is more than sufficient to supply the needs of the crop where sludges are applied as a source of nitrogen. For example, a sludge containing 1.5 percent phosphorus, applied at a rate of 10 metric tons per ha, would supply 150 kilograms of phosphorus per ha. At this application rate, available phosphorus may be excessive in many areas, particularly where animal manure is plentiful and where phosphorus is well-above levels needed for maximum crop yields. These high levels could significantly increase the risk of surface water contamination. Based on long-term evaluations of treated sludge use over periods ranging from 9 to 23 years, the Water Environment Research Foundation (1993) has recommended soil phosphorus levels be monitored where sludge applications are used continuously over time, and that sludge application rates may need to be determined by crop phosphorus levels rather than the nitrogen needs of the crop.

Other Essential Plant Nutrients

In addition to nitrogen and phosphorus, treated sludges contain all other nutrients essential for the growth of crops, including calcium, iron, magnesium, manganese, potassium, sodium, and zinc (Linden et al., 1983). Where treated sludges are applied according to agronomic rates for nitrogen, many of these essential nutrients, with the possible exception of potassium, are usually present in amounts adequate to meet the needs of the crop (Chaney, 1990).

TREATED MUNICIPAL WASTEWATER AS A SOURCE OF PLANT NUTRIENTS AND IRRIGATION WATER

Plant Nutrients

Although treated municipal wastewaters are usually applied as a source of irrigation water for crops, they are also a source of plant nutrients, especially nitrogen. The concentration of nutrients in wastewaters depends upon the water supply, the quality of the wastewater, and the type and degree of wastewater treatment. Usually, each stage in the treatment process reduces the concentration of both nitrogen and phosphorus. Typically, conventionally treated municipal wastewaters contain from 10 to 40 mg of nitrogen per liter and from a few to 30 mg of phosphorus per liter (Asano et al. 1985). In the arid southwestern United States, the quantity of irrigation water required to meet the needs of most crops is the equivalent of about 1 meter depth per ha per crop season. This quantity of treated wastewater, containing typical concentrations of nitrogen and phosphorus of 20 and 10 mg/liter respectively, would add 200 kg nitrogen and 100 kg phosphorus per ha. These application rates will meet or, in some cases, exceed the nitrogen and phosphorus fertilizer needs of many crops over the growing season. Further, plants require varying amounts of nutrients and water at different stages in the growth cycle, and the timing of irrigation may not correspond to when plant nutrients are needed. Wastewater applications at times when the plant needs are low can potentially lead to leaching of nitrate-nitrogen and possible contamination of ground water.

When plant nutrient needs are not in phase with irrigation needs, the presence of nutrients in irrigation water may interfere with its use. For example, ill-timed and overfertilization with nitrogen can cause excessive growth, reduce crop yield, and encourage weed growth (Asano and Pettygrove, 1987; Bouwer and Idelovitch, 1987). Yield and crop quality have been harmed by excess nitrogen in many crops, including tomatoes, potatoes, citrus, and grapes (Bouwer and Idelovitch, 1987). To minimize the undesirable effects of excess nutrients, their levels in reclaimed water should be kept within stipulated guidelines, crops should be selected to match nutrient levels, ground water quality should be monitored, and excess water should be diverted elsewhere (Bouwer and Idelovitch, 1987). In the Water Conserv II wastewater reclamation project in Orlando, Florida, excess water not used by citrus growers is diverted into rapid infiltration basins for disposal (Jackson and Cross, 1993). Because the underlying aquifer is a drinking water source, it is closely monitored as part of the Conserv II project.

Irrigation Water Quality Concerns

The feasibility of using treated municipal wastewater as a source of irrigation water depends upon its quality. This in turn depends upon the quality of the municipal water supply, the nature of the constituents added during water use, and the kind and degree of wastewater treatment. Wastewater constituents that can degrade water quality for irrigation include salts, nutrients and trace contaminants. Quality criteria for salinity, permeability, specific ion toxicity, and miscellaneous elements are presented in Table 4.2. The effects of reclaimed water on soil chemical properties, including the accumulation of trace contaminants are discussed in a succeeding

TABLE 4.2 Irrigation Water Quality Criteria

		Degree of restriction on use[a]		
Parameter restricting use	Diagnostic Measurement (units)	None	Slight to Moderate	Severe
Salinity	EC (dS/m)[b]	0.7	0.7–3.0	>3.0
	TDS (mg/1)[c]		450–2000	>2000
Permeability/ infiltration	SAR (mmole/1)1/2[d] and EC (dS/m)			
	EC @ SAR 0–6	>1.2	1.2–0.3	<0.3
	EC @ SAR 12–20	>2.9	2.9–1.3	<1.3
	EC @ SAR 20–40	>5.0	5.0–2.9	<2.9
pH		<8.5	>8.5	
Phytoxicity (mostly tree crops ornamentals)				
With surface irrigation				
Sodium	SAR (mmole/1)1/2	<3	3.9	>9
Chloride	(mg/1)	<140	140–350	>350
Boron	(mg/1)	<0.7	0.7-3.0	>3.0
With sprinkler irrigation				
Sodium	(mg/1)	<70	>70	
Chloride	(mg/1)	<100	>100	
Boron	(mg/1)	<0.7	0.7-3.0	>3.0
With overhead sprinkling only				
Bicarbonate	(mg/1)	<90	90–500	>500
Residual chlorine	(mg/1)	<1	1.0-5.0	>5
Crop quality/ground water protection				
Nitrogen (total N)	mg/1	<5	5–30	>30

[a] Restriction on use but does not indicate that water is unsuitable for use, that there may be a limitation such as crop species or soil type and special management practices may be necessary for full productive capacity.
[b] Electrical conductivity
[c] Total dissolved solids
[d] Sodium Adsorption Ratio
SOURCE: Adapted and condensed from Westcot and Ayers, 1985.

section of the chapter.

EFFECTS OF SLUDGE AND WASTEWATER ON SOIL PHYSICAL PROPERTIES

Organic Matter

Soil organic matter enhances the structural properties of a soil by binding together soil particles into aggregates or lumps and creating large (non-capillary) pores through which air and water more. As land is cropped, soil organic matter is gradually lost, leading to a deterioration of its physical properties. Soils under continuous cultivation are very deficient in organic matter because the rate at which organic matter returns from crop residues is lower than the rate of organic matter decomposition in soils. Where organic matter is lacking, the less stable soil aggregates easily fall apart in the presence of rain or percolating water; in spite of cultivation, the larger soil pores are lost, soil air decreases, water movement is restricted, the soil becomes more closely packed, and the bulk density increases.

Water Retention Properties

Generally, the application of sludge increases the capacity of the soil to retain water. The organic carbon content of sludge may affect water retention either through the direct effect of sludge organic particles themselves or through its indirect effect on other physical properties (such as bulk density, porosity, and pore size distribution). Several researchers have reported an increase in the water retention capacity of soils at field capacity[1] and at the wilting point[1] following sludge application (Chang et al., 1983; Metzger and Yaron, 1987).

Structure and Aggregation

Sludge, like other organic materials, is less dense than the mineral fraction of soil and can improve the structure of soil by reducing bulk density and promoting soil aggregation. However, Chang et al. (1983) cautions that far greater quantities of sludge than normally needed to supply nutrients for crop growth are required to induce significant changes in soil physical properties. Low annual application rates (22.5 and 45 metric tons per ha) of municipal sludge compost improved agronomic performance, but higher amounts (80 metric tons per ha) were required to significantly change soil physical properties (Chang et al., 1983). Nevertheless, even at lower annual rates of sludge application (27 metric tons per ha) the bulk density of soils of various textural classes, including fine-textured soils, are reduced (Hall and Coker, 1983; also see Metzger and Yaron, 1987). As with manures and composts, the organic matter in sludge can increase soil porosity because of improved soil aggregation (Guidi et al., 1983; Pagliai et al., 1981).

The addition of sludge increases the number and size of water-stable aggregates. Increases in aggregate formation, by approximately one-third, were observed by Epstein (1975). This has been substantiated in field experiments on various soil types, in various climates, and with various sludges and composts. Aggregate formation is the result of both chemical and microbial agents.

Aggregate stabilization must occur along with aggregate formation if a permanent increase in soil aggregation is to occur. In a comparative study of four organic materials added

[1] Field capacity is approximately equal to the amount of water that is held at -0.33 bar; the wilting point is when plants begin to show moisture stress, defined as -15 bars.

to soil at 25 metric tons per ha, aggregate stability was increased by 24 percent with sludge, 22 percent with manure, 40 percent with alfalfa, and 59 percent with straw (Martens and Frankenberger, 1992). Anaerobically digested sludges provided the best stabilizing effect compared to other sludge treatment processes (Pagliai et al., 1981).

Water Transmission Properties

Organic matter in sludge and wastewater can impede infiltration and aeration by temporarily plugging the soil surface. However, the net effect of organic matter on soil aggregation, as explained above, is improved soil structure, which enhances water transmission, water infiltration and, in some instances, reduces the soil's susceptibility to erosion.

Under certain conditions, the levels of sodium, calcium, and magnesium in treated effluents can adversely affect soil structure and worsen the soil's infiltration, friability, and tillage characteristics. Sodium, when present in high concentrations relative to calcium and magnesium, can cause dispersion of soil aggregates leading to reduced infiltration and permeability. The degree to which the various concentrations of sodium may affect soil structure is related not only to concentrations of calcium and magnesium but also to the salinity of the effluent. Techniques used to predict the effects of sodium on infiltration and permeability of water are based on the Sodium Adsorption Ratio (SAR), a ratio of the concentration in water of sodium to the square root of the sum of the concentrations of calcium plus magnesium (all concentrations are expressed in millimoles per liter). Waters with high SAR but low salinity disperse the soil, making it less friable, harder to work and less permeable to water. For example (as was shown in Table 4.2), water with a SAR of 12, a total dissolved solids (TDS) level of about 1200 (at an Electrical Conductivity [EC] of about 1.9 deci Siemens per meter [dS/m]) causes no permeability or infiltration problems, while water with a SAR of 3 and a TDS of about 200 (at an EC of about 0.3 dS/m) causes severe permeability problems. The salinity of soil water also affects the growth of crops through its effect on water availability (Bouwer and Idelovitch, 1987). Plants vary in their tolerance of soil salinity (Maas, 1990).

EFFECTS OF SLUDGE AND WASTEWATER ON SOIL CHEMICAL PROPERTIES

Biologically stabilized sewage sludge contains an average of approximately 50 percent organic matter on a dry weight basis. Following addition to soil, the sludge undergoes decomposition to carbon dioxide, water, low molecular weight soluble organic acids, residual organic matter and inorganic constituents. Although most of the organic fraction of the sludge is converted to carbon dioxide and water, some becomes part of the stable soil humus layer (Boyd et al., 1980; Hernandez et al., 1990) and serves to increase the soil's net negative charge and its cation exchange capacity (CEC) (National Research Council, 1977; Thompson et al., 1989). CEC is a measure of the capacity of the soil to retain cations. A high CEC is desirable because it lessens or prevents essential nutrient loss by leaching (Broadbent, 1973; National Research Council, 1977). Collectively, constituents released from sludge following decomposition and present in wastewater may be put into four groupings: 1) the more soluble cations, anions and molecules, 2) trace elements which form sparingly soluble reaction products, 3) potentially harmful inorganic chemicals, and 4) potentially harmful organics.

Soluble Cations, Anions, and Molecules

The soluble cations, anions, and molecules found in effluents and sludge, and which are of concern in agricultural operations, generally include potassium, sodium, calcium, magnesium, chloride, sulfate, nitrate, bicarbonate, selenate, and boron (as boric acid and borate) in lesser concentrations. All of the above are absorbed by plants and those which are essential contribute to the nutrient-supplying power of effluents and sludges. They enter into ion exchange equilibria and those of lesser affinity are leached away by drainage water. Because boric acid is usually uncharged and is weakly adsorbed, it normally is leached to levels safe for most crops where water is applied in excess of evapotranspiration (Keren and Bingham, 1985). Above concentrations of about 0.7 mg/liter in irrigation waters, boron may be toxic to sensitive plants (Maas, 1990). Consequently, precautions must be taken to insure that the boron concentrations in the soil solutions of sludge-amended soils and soils irrigated with municipal wastewater do not exceed this critical level for sensitive crops. Tolerant crops (e.g. cotton) normally withstand irrigation waters containing boron concentrations as high as 10 mg/liter without damage (Maas, 1990).

As with normal irrigation practices, salts in reclaimed wastewater need to be managed to preserve the productivity of the soil. Typical concentrations of salts in treated effluents are within accepted criteria for irrigation water quality (see Table 2.1); however, their concentration can vary widely. Unless salts are removed from the root zone by plants or leaching, they accumulate and eventually reach a level that will prevent the growth of all but the most tolerant plants. Even under the most ideal conditions, plants remove less than 10 percent of the salts applied through irrigation water (Oster and Rhodes, 1985). Therefore, to sustain growth, salts must be leached from the root zone. In temperate and humid regions where irrigation is practiced only during dry periods, precipitation is usually sufficient to leach salts to an acceptable level. However, in semiarid and arid regions, continued irrigation in the absence of leaching will lead to an accumulation of salts in the soil profile to levels that will inhibit the growth of crops. This problem is usually circumvented by adding more water than is used by the crop. The quantity of water in excess of crop requirements is referred to as the leaching requirement. Methods used to manage irrigation waters of varying quality to avoid the accumulation of salinity problems are outlined by Kruse et al. (1990).

Trace Elements

Following organic matter decomposition, trace elements from wastewater and sludge are released and form sparingly soluble reaction products. These trace elements include arsenic, cadmium, copper, cobalt, nickel, lead, selenite-selenium, molybdate-molybdenum, and others. Because of their sparingly soluble nature and their limited uptake by plants, they tend to accumulate in the surface soil and become part of the soil matrix (McGrath et al., 1994). With repeated applications of wastewater, and particularly sludges, these elements could accumulate to levels toxic to plants (Chang et al., 1992) and soil organisms (McGrath et al., 1994). They could also accumulate in crops where they could, in turn, build up to potentially harmful levels in humans, domestic animals, and wildlife that consume the crops (Logan and Chaney, 1983). EPA developed soil concentration limits considered safe for agricultural crops in its Part 503 Sludge Rule (EPA, 1993a) and these limits are presented in Chapter 7.

In general, crops grown on acid soils accumulate higher concentrations of most trace elements in their tissues and are more susceptible to phytotoxicity than are crops grown on neutral or calcareous soils. Because repeated sewage sludge applications lead to accumulations of trace elements in soil, concern has been expressed over possible adverse effects associated with the use of sludge on soils that are acid or that may become acid (McBride, 1995). In an attempt to address this concern, Ryan and Chaney (1994) compared the pH distribution of soils used by EPA in the development of the Part 503 Sludge Rule with pH values of all U.S. soils (as compiled by Holmgren et al. 1993). From this comparison it was evident that acid soils were well represented in EPA's analysis. An additional safeguard arises from a set of conservative assumptions used in EPA's risk assessment. In setting the standards for trace elements, EPA assumed a cumulative application limit of 1000 metric tons of dry sludge per ha. Because sludge application rates used in most of the available research studies were lower than this, EPA used a linear regression technique to extrapolate crop uptake to the limit of 1,000 metric tons. Chaney and Ryan (1992) showed that crop uptake usually reaches a plateau with increasing sludge application and that the actual crop uptake of trace elements should be far lower than predicted by the linear regression values used by EPA. Finally, in normal agricultural practice, crops grown in extremely acid soils with excess zinc, copper, and nickel would show visual phytotoxicity symptoms. In practice, when these symptoms are observed, the soil is limed to correct the problem. In fact, problems associated with soil acidity are normally corrected through routine management operations because, almost without exception, acid soils are limed prior to cropping. This neutralizes acidity to avoid phytotoxicity from naturally occurring aluminum present in the soil (Pearson and Adams, 1967). Therefore, as long as agricultural use of treated sludges and wastewater is in keeping with existing regulations and sound agronomic practices, the possibility that trace elements applied from this practice would adversely affect the yield or wholesomeness of crops is remote.

Concerns have been expressed about what may happen once a site has reached its cumulative limit for metals and sludge application stops (McBride, 1995). The chemical properties of the soil will likely change over time. The availability of certain trace elements may increase and potentially cause phytotoxicity problems and/or cause greater bioaccumulation of trace elements in crops. While there is little published information on this long-term problem, the city of Chicago has accumulated soils and crop data on both reclaimed strip-mined fields and natural soils following termination of sludge applications. Table 4.3 shows an example of some data collected on organic carbon, zinc, cadmium, and copper from seven fields that had received an average of 226 tons per acre of sludge from 1972 through 1984, where monitoring had continued to the present. Additional research is needed in this area, but these preliminary results indicate that trace elements are not necessarily more available for periods of up to 10 years following cessation of sludge applications.

TABLE 4.3 Organic Carbon and Availability of Zinc, Cadmium, and Copper After Cessation of Long-Term Sludge Application

Year	Organic Carbon %	Zinc		Cadmium		Copper	
		soil[a]	corn[b]	soil	corn	soil	corn
1984	4.4	747	26.0	56.5	0.27	295	2.05
1985	4.4	668	33.0	58.3	0.26	321	0.95
1986	4.8	655	26.8	49.8	0.07	261	1.29
1987	4.2	701	25.5	53.5	0.20	295	2.59
1988	4.0	614	35.5	45.9	0.07	240	1.62
1989	3.9	689	33.5	45.5	0.38	255	2.57
1990	4.3	586	33.5	46.2	0.11	232	1.94
1991	4.1	584	33.0	45.8	0.05	242	1.62
1992	4.1	676	33.0	52.1	0.17	289	0.97
1993	3.9	635	20.0	49.6	0.11	275	2.00

[a] Zinc, cadmium, and copper soil measurements are 0.1 M HCl extractable concentrations in mg kg^{-1} for the top six inches of soil as measured annually on samples from each field.
[b] Corn grain concentrations in mg kg^{-1}
Note: Farm fields received an average of 226 tons/acre of sludge from the Metropolitan Water Reclamation District of Greater Chicago from 1972 through 1984. None of the fields have received sludge since 1984. The cumulative loading rate for Zn, Cd and Cu was 1,532, 827 and 127 kg ha^{-1} (1,367, 738, and 113 lb/acre), respectively.
SOURCE: Granato, 1995.

Accumulation of Potentially Harmful Inorganic Chemicals in Soils and Crops

Treated municipal wastewaters rarely contain harmful trace elements at concentrations in excess of criteria established for irrigation water (as was shown earlier in Table 2.1). Therefore, where industrial pretreatment programs are effectively enforced, it would seem reasonable to permit treated municipal wastewaters that meet irrigation water quality criteria to be used for crop irrigation. Assuming this to be the case, municipal wastewater applied at the limits prescribed for irrigation water at the rate of 1.5 m/ha (per growing season) should add relatively minor amounts of trace elements.

The concentrations of trace elements in sewage sludges vary, depending on the contributions from industries and households to the common sewer system and the effectiveness of industrial pretreatment programs (see Chapter 3). Ranges of trace elements based on the EPA 1990 National Sewage Survey (NSSS) are presented in Table 4.4 from Kuchenrither and Carr (1991). Using these data for a typical sludge applied at 10 metric tons per ha, one can compute annual soil loading of trace elements. Data presented in Table 4.5 show annual loading of trace elements with compositions at the 50th, 95th, and 98th percentiles compared to typical soil concentration and the EPA cumulative loading limits from the Part 503 Sludge Rule. Although applications of sludges with compositions at the 95th and 98th percentile add substantially to the

TABLE 4.4 Summary of Results for Regulated Inorganic Pollutants From the EPA 1990 National Sewage Sludge Survey

Pollutant	Number of Times Detected[a]	Mean (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)
Arsenic	194	12.4	0.3	316
Cadmium	194	65.5	0.7	8,220
Chromium	231	258	2.0	3,750
Copper	239	665	6.8	3,120
Lead	213	195	9.4	1,670
Mercury	184	4.1	0.2	47.0
Molybdenum	148	13.1	2.0	67.9
Nickel	201	77.0	2.0	976
Selenium	163	6.2	0.5	70.0
Zinc	239	1,693	37.8	68,000

[a] The values represent the number of times the chemical was detected in samples taken from 209 wastewater treatment plants. Plants were randomly selected from all regions of the U.S. The total number of samples is 239 because of multiple samples taken at some plants.
SOURCE: Adapted from Kuchenrither and Carr, 1991.

background concentrations in soils, additions are well within U.S. EPA limits. In the most limiting cases of copper, lead, and zinc, a sludge with an element concentration equal to the 95th percentile could be applied annually at 10 metric tons per ha for a period of about 75 years before regulatory limits would be reached.

Actual experience at numerous sewage sludge land application sites has indicated that uptake of metals by plants has been minimal. Bray et al. (1985) analyzed three years of silage crop on land amended each year by municipal sludge at moderate to high rates (15–90 metric tons per ha). The silage contained elevated though not excessive levels of cadmium and zinc, but elevated levels were not observed for the other 12 elements tested, including arsenic, chromium, lead, mercury, and selenium.

In developing the Part 503 Sludge Regulations, EPA conducted an extensive review of trace element uptake by crops in relation to amounts added in the form of sewage sludge (EPA, 1993a; 1993b). Table 4.6 lists uptake slopes for different food crops and shows that crops differ substantially in their tendency to bioconcentrate sludge-borne trace elements added to soils. An uptake slope is calculated as the concentration of a chemical in plant tissues in (mg/kg) divided by the amount of chemical added to the soil (in kg/ha). Based upon the geometric mean of uptake slope values, the elements arsenic (As), copper (Cu), lead (Pb), mercury (Hg), and nickel (Ni) consistently show the lowest uptake values across all food groups. The elements cadmium (Cd), selenium (Se), and zinc (Zn) have the highest uptake values in the majority of the food

TABLE 4.5 Annual Loading of Trace Elements for Sludges With Compositions Equal to the 50th, 95th and 98th Percentile From the National Sewage Sludge Survey When Applied at a Rate of 10 m tons/ha Compared to Typical Soil Concentrations and the EPA Loading Limits. All Values are in kg/ha.

Element	Annual Loading at Percentile Compositions			Typical Concentration in Soil	EPA Cumulative Loading Limit
	50th	95th	98th		
Arsenic	0.10	0.40	0.54	12.0	41
Cadmium	0.07	0.15	0.58	0.15	39
Chromium	1.2	5.0	10.0	200.0	3,000
Copper	7.4	21.0	35.0	40.0	1,500
Lead	1.4	4.0	8.0	30.0	300
Mercury	0.05	0.19	0.38	0.06	17
Nickel	0.04	2.0	2.9	80.0	420
Selenium	0.05	0.19	0.27	0.4	100
Zinc	12.0	35.0	60.0	100	2,800

groups, although the uptake slopes are reasonably low in most cases. Molybdenum (Mo) is unique in that its uptake slope is very high for leguminous vegetables. The elements copper, molybdenum, and zinc are essential for the growth of plants, so these data indicate that sludge could correct deficiencies of these elements. The element cadmium, if present in the human diet in sufficient quantities over extended periods of time (decades), is a chronic toxin (Kostial,1986); molybdenum and selenium are toxic to wildlife and domestic animals if consumed above critical levels (Mills and Davis, 1986; Levander, 1986). The public health concerns about exposure to trace elements through the consumption of crops grown on sludge-amended soils are discussed in Chapter 6.

Accumulations of Potentially Harmful Organics in Soils and Crops

Organic chemicals, when added to the soil may volatilize, decompose, or be adsorbed. Consequently, only those that are nonvolatile and are relatively resistant to decomposition will accumulate in soils. Most organic compounds found in treated municipal wastewater occur at concentrations of less than 10 mg/liter, and accumulation in soil from this source is usually so small that it is below the limits detectible by conventional analytical methods (O'Connor et al.,

TABLE 4.6 Uptake Slopes of Trace Elements in Various Food Groups in Relation to Quantity Applied in the Form of Sludge [mg/kg of trace elements in plant tissue] [kg/ha of trace elements applied]-1

	Potatoes		Leafy vegetables		Legumes		Root vegetables		Garden fruit		Grain/Cereal	
Element	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
As	0.002	0.006	0.018	0.340	0.001	0.002	0.004	0.014	0.001	0.003	0.002	0.013
Cd	0.004	0.038	0.182	7.06	0.002	0.027	0.032	0.594	0.045	0.636	0.031	0.173
Cu	0.003	0.007	0.014	0.200	0.004	0.339	0.003	0.024	0.014	0.068	0.002	0.080
Pb	0.001	0.001	0.003	0.039	0.001	0.006	0.001	0.009	0.001	0.011	0.001	0.004
Hg	0.001	0.005	0.005	0.046	0.001	0.001	0.007	0.043	0.005	0.043	0.043	-
Mo	0.011	-	-	-	1.65	4.21	0.012	-	-	-	-	1.48
Ni	0.005	0.024	0.016	7.17	0.031	0.502	0.004	0.067	0.003	0.093	0.033	0.055
Se	0.021	0.048	0.008	0.038	0.012	0.055	0.011	0.048	0.010	0.039	0.003	0.055
Zn	0.012	0.061	0.125	2.24	0.018	0.055	0.022	0.206	0.022	0.197	0.001	0.86

Uptake values are concentrations of trace elements in plant tissue in mg/kg.
[1] Geometric mean.
[2] Designated uptake slope in reference. Value reported as 0.001 are default values to account for data below the limit of detection, and represent either 0.001 or less than 0.001.
SOURCE: EPA, 1993b.

1991, Webber et al., 1994). Based upon the 99th percentile concentration from the NSSS, EPA computed annual loading for 12 reasonably persistent organic chemicals. Available evidence indicates that most trace organics are either not taken up or are taken up in very low amounts by crops (O'Connor et al., 1991, EPA, 1993b). A discussion of possible implications and health consequences of toxic organic compounds in sludges is presented in Chapter 6.

EFFECTS OF SLUDGE ON SOIL MICROORGANISMS

Soil microorganisms include bacteria, actinomycetes, fungi and algae. They are important in the decomposition of organic matter and in the cycling of plant nutrients such as nitrogen, phosphorus, and sulfur. Metal accumulations in soils associated with the long-term applications of sewage sludge have been shown to affect microbial activity and biomass, biological nitrogen fixation, and vesicular-arbuscular mycorrhizae (Giller et al., 1989; McGrath et al., 1988; McGrath et al., 1994; Smith, 1991). Vesicular-arbuscular mycorrihizae refers to the symbiotic association between plants and certain fungi, in which the fungi obtain carbohydrates and the plants obtain nutrients such as phosphorus and zinc for growth.

Microbial Biomass and Activity

The application of sewage sludge will temporally increase microbial populations due to the addition of an exogenous food supply. Depending upon the carbon to nitrogen (C/N) ratio of the added material, the demands of the increased microbial population for nitrogen could reduce the plant-available nitrogen to levels that are deficient for crop growth (Alexander, 1977). This process, referred to as immobilization, occurs when the C/N ratio in the sludge-soil mixture is about 20 or more and microbes convert inorganic nitrogen to organic nitrogen—a form unavailable to crops (Alexander, 1977). However, immobilization of nitrogen is usually temporary. As decomposition proceeds, carbon is volatilized to carbon dioxide, and as the C/N ratio becomes less than about 20, mineralization of the organic nitrogen exceeds immobilization, and excess inorganic nitrogen becomes available to plants.

The accumulation of metals following long-term applications of sewage sludge has been observed to reduce levels of microbial biomass (Brookes et al., 1986b). In a long-term field experiment that compared sludge-amended soils to manure-amended soils, McGrath et al. (1994) reported microbial biomass levels in the high-metal sludge-treated soils to be approximately half those of the manure-treated soils. Similar observations were made by Boyle and Paul (1989) who also reported increased levels of nitrogen in soil biomass following eight years of sludge application. A one time high-rate sludge application has also been reported to decrease soil biomass (Stark and Lee, 1988).

Biological Nitrogen Fixation

The accumulation of metals in soils following long-term applications of sewage sludge has been reported to adversely affect the symbiotic relationship between certain strains of rhizobia (McGrath et al., 1994; Giller et al., 1989). McGrath et al. (1988) observed lesser concentrations of nitrogen and decreased yields of white clover in a soil that had received sludge applications over a period of 20 years. Clover root nodules in the treated group were smaller and ineffective in nitrogen fixation. Clover rhizobia isolated from high metal-contaminated soil were ineffective in nitrogen fixation (Giller et al., 1989). Nitrogen fixation was restored by inoculation of the soil with large numbers of effective rhizobium of the same strain (greater than 10,000 cells per gram of soil) followed by incubation in a moist condition for two months (McGrath et al., 1994). The authors concluded that clover rhizobia were unable to survive in the free-living state outside the protected root nodule in metal-contaminated soils.

The inhibition of rhizobium bacteria following sludge applications is inconclusive, and other studies have shown little or no effect of sludge on nitrogen fixation. Heckman et al. (1987), for example, examined the effects of sludge-amended soil on the symbiotic fixation of nitrogen by soybean. They found no effect of sludge metals on nitrogen fixation at one site but observed a decrease in the amounts of nitrogen fixed where high metal sludges were applied at another site. Kinkle et al. (1987) studied soybean rhizobia in soils that had received sludge 11 years earlier. They observed no long-term detrimental effect of sludge applications on soil rhizobial numbers and no shift in serogroup distribution. Similarly, Angle and Chaney (1989) observed no effect of sludge applications on rhizobia. More recently Ibekwe et al. (1995) reported reduced nodulation and ineffective symbiosis for alfalfa, white clover, and red clover grown in sludge-amended soils (pH equal to or less than 5.2). However, the investigators observed no effect on plant growth, nodulation, and nitrogen fixation when these legumes were grown in sludge-amended soils maintained at pH 6.0 and greater.

Long term applications of sewage sludge resulting in metal accumulations in surface soils have been shown to reduce nitrogen fixation by free-living heterotrophic bacteria (Brookes et al, 1986a; Lorenz et al., 1992; Martensson and Witter, 1990). In an experiment where sludge-treated soils were compared to manure-treated soils, nitrogen-fixing activity by diazotrophs in the sludge-treated soil was decreased to 2 percent of that of the manure-treated soil. Lorenz et al. (1992) also observed reduced nitrogen fixation in plots treated with sludge compared to plots treated with farmyard manure. Nitrogen fixation by cyanobacteria (blue-green algae) has also been reported to be reduced in soils having a history of repeated sludge applications as compared to soils with a long history of farmyard manure applications (Brookes et al., 1986a).

Symbiotic functions between plants and soil microbes are negatively impacted only if the soil microbes affect uptake of nutrients by the associated plants. Studies on vesicular-arbuscular mycorrhizas (VAM)-plant associations in sludge-treated soils are confounded by the rather large amounts of phosphorus added with sludge and the effect of soil pH on VAM, both of which in addition to the effect of metals, could inhibit infection. Available information suggests that sludge applications to soil act to delay rather than suppress mycorrhizal infection (Koomen et al., 1990).

A tractor spreading sewage sludge on a stubble field before the growing season (photo courtesy of Robert Bastian, U.S. Environmental Protection Agency).

EFFECTS ON GROUND WATER

Because municipal wastewater contains only traces of pesticides (O'Connor et al., 1991; Kuchenrither and Carr, 1991), land application of treated wastewater effluents and sludge presents a much smaller hazard of pesticides than does the usual, direct application of pesticides to crops for the control of pests.

Nitrate pollution of ground water is often reported as an effect of excessive application of conventional fertilizers to crops (Hallberg and Keeney, 1993). As described earlier in this chapter, nitrate pollution of groundwater from application of wastewater effluent and sludge can be controlled by the same nutrient management techniques used in traditional agriculture.

The potential for ground water contamination by microorganisms, trace elements and toxic organic compounds from wastewater and sludge is evaluated below. (Chapters 5 and 6 discuss other public health effects of these contaminants.)

Pathogenic Microorganisms

There are three kinds of microorganisms in sewage which are of concern for their effects on human health: bacteria, viruses, and parasites. All have been found in treated secondary effluent and sludges. Wastewater irrigation can potentially transport bacteria and viruses to ground water under certain conditions, as described below. In contrast, because bacteria and viruses in sludge are strongly sorbed to sludge solids, they are not usually desorbed in the soil, and are not likely to be transported to ground water. Helminth cysts and worm eggs are reported to be too large to be transported to ground water (Gerba, 1983).

Viruses are a special concern in wastewater irrigation because virus particles are small, may percolate through soil, and may persist for months in the soil environment (Gerba, 1983). Using traditional methods of virus sampling and assay of water from soil lysimeters at sites irrigated with undisinfected secondary wastewater effluent, Moore et al. (1981), have found coliphage virus particles at a depth of 1.37 meters. Using more sensitive detection methods, several ground water samples were taken 27.5 meters below wastewater soil application sites and were found to be positive for animal viruses. In the same study, the test soil site receiving disinfected wastewater had only one sample which was positive for viruses, significantly less than soils irrigated with undisinfected wastewater effluent (Goyal et al., 1984).

Disinfection appears to be advisable in preventing ground water contamination by viruses from irrigation with treated municipal wastewater. In the context of food crop production, EPA guidelines recommend a minimum of secondary treatment plus disinfection (EPA, 1992). Current state regulations for reclaimed water use on crops vary depending on water quality and process requirements, site restrictions, monitoring, and crop type allowed. Of the 18 states that regulate irrigation of food crops with reclaimed water, only 3 (Arkansas, Nevada, and Michigan) do not have requirements for disinfection or criteria for microbiological water quality; however other restrictions or ground water monitoring may apply (see discussion of state regulations in Chapter 7).

In a summary of virus removal from treated wastewaters, Asano (1992) has estimated that undisinfected effluent has approximately 90 percent of viruses removed (1 log removal) from sewage as a result of primary and secondary wastewater treatment processes. Effluent disinfection accounts for an additional 2 to 5 logs removal, that is, a total of 99.9 to 99.999 percent virus removal. When combined with natural soil sorption processes, virus removal from disinfected effluent applied to soils for the purpose of groundwater recharge has been estimated to be 12.6 to 17 logs of reduction. Using a risk assessment approach, Asano et al. (1992) developed an exposure scenario that uses the nearest well to a ground water recharge site containing 50 percent reclaimed wastewater that has percolated through three meters of soil for six months. The most exposed individual is assumed to consume two liters per day of this wellwater, equivalent to 1 liter per day of reclaimed wastewater. The authors have estimated that the lifetime risk of an individual contracting a single infection from poliovirus or echovirus from drinking ground water recharged with disinfected (tertiary treated) wastewater effluent was very low, in the range of 10^{-6} to 10^{-9}. While not the subject of this report, the use of treated municipal wastewater as a source for ground water recharge has been evaluated by the National Research Council (1994). Its report concludes that where treated municipal wastewater is used to recharge ground water that is a potable water supply, uncertainties remain concerning the transport and fate of viruses in ground water.

Bacteria that are used as indicators of wastewater contamination (fecal coliform and fecal streptococci) have been found in soil water at a depth of 1.37 meters below fields irrigated with treated but undisinfected wastewater effluent. Bacterial counts in lysimeter water ranged from

2 to 370 viable cells per 100 milliliters water for fecal coliform bacteria and from approximately 1 to 77 fecal streptococcus bacteria per 100 milliliters of water (Moore et al., 1981).

In summary, application of treated wastewater effluents to soils may pose some risk of ground water contamination by viruses and bacteria, but that risk is minimized to extremely low levels by disinfection of reclaimed wastewater and by slow infiltration rates (Asano et al., 1992; Gerba, 1983).

Heavy Metals

Through cation exchange, chemical exchange, chemical sorption, precipitation, and complexation reactions, metallic ions are readily removed from wastewater and are concentrated in sludges. Soil particles act to further sequester most heavy metals, and this preference of metals for particulates has been observed often in agricultural soils. (Chang and Page, 1983; Pettygrove and Asano, 1985; Gallier et al., 1993). Therefore heavy metal cations would not be expected to leach out of the unsaturated soil zone into ground water. In fact, of the toxic heavy metals regulated under the Part 503 Sludge Rule, (EPA, 1993b), a scientific peer review panel suggested that the risk of ground water contamination be used only to determine the heavy metal standard for hexavalent chromium (Chaney and Ryan, 1992). Hexavalent chromium is an unstable and rare form of chromium, and is rapidly reduced in most environmental conditions to its trivalent form, which is quite immobile in soils and not expected to leach to ground water.

Heavy metals from sludges may remain in soils for years after application. However, when sludges are applied to soils at rates controlled by agronomic nutrient uptake rates, transport of heavy metals from sludges to ground water is unlikely unless the sludges have unusually high levels of metal ions (Logan and Chaney, 1983).

Toxic Organic Compounds

PCBs and detergents are the only classes of synthetic organic compounds that occur in municipal wastewater sludges and effluents in concentrations higher than those in conventional agricultural irrigation water or soil additives (O'Connor et al., 1991; Brunner et al., 1988; Giger et al., 1987; Furr et al., 1976). In municipal treatment plants, both PCBs and detergents are concentrated into the sludge fraction.

PCBs have been found in sludges from municipal wastewater treatment plants, especially those receiving industrial waste discharges or urban storm drainage. Furr et al. (1976) reported concentrations of PCBs from single sample analyses of sludges from major cities to be in the range of less than 0.01 mg/kg dry weight for San Francisco, California to 23.1 mg/kg for Schenectady, New York. An average PCB concentration in sludges from the 15 cities in this survey was 4.8 mg/kg dry weight, with PCBs detected in 87 percent of the samples. More recently, the NSSS reported that PCB concentration in sludges averaged 3.2 mg/kg dry weight, and PCBs were detected in approximately 10 percent of the samples from about 200 treatment plants (Kuchenrither and Carr, 1991).

PCBs have a strong affinity for particulate material and, under certain circumstances, can be volatilized. They are not very soluble, and it is unlikely that PCB compounds would be transported to ground water from the unsaturated soil zone. Gan and Berthouex (1994) have studied sludge application sites from the Madison (Wisconsin) Metropolitan Sewerage District from 1985 to 1990. They report that there were no measurable PCBs in runoff water from these sites. From their study, it seems that while PCBs may persist in the soil itself and may be taken up by plants, they are not a significant risk for ground water contamination.

Testing for 330 toxic organic compounds in the NSSS found infrequent occurrence in the 209 POTWs sampled. However, one organic compound, bis(2-ethylhexyl) phthalate, was detected in 90 percent of the samples with an average concentration of 108 mg/kg dry weight (Kuchenrither and Carr, 1991). Bis(2-ethylhexyl) phthalate is thought to sorb very strongly to soil, and therefore would not be expected to leach into ground water. Also, the compound is relatively biodegradable with an estimated half-life in soil ranging from 5 to 23 days (Howard et al., 1991). Phthalates are commonly used as plasticizers, such as in polyvinylchloride, and over one million metric tons of phthalates are produced annually worldwide. Because phthalates are so ubiquitous in the environment, laboratory-derived phthalates are reportedly a frequent source of errors in sample analyses (Schwarzenbach et al., 1992).

Detergent compounds, including surfactants like linear alkylbenzene sulfonates and nonylphenol ethoxylates and binders like nitriloacetate, have been found in sludges in relatively high concentrations, in the range of 0.5 to 4 g/kg dry weight (Brunner et al., 1988; Giger et al., 1987). However, in field and laboratory tests, it has been observed that detergents are rapidly removed from the soil-root zone by biodegradation, and are not transported out of the unsaturated soil zone by leaching (Holt et al., 1989).

In summary, a few toxic organic compounds and detergents have been found in sludges; however, because they are either biodegradable in soils or sorb strongly to soil particles, these compounds are not a risk for ground water contamination. Overcash (1983) has stated that leaching of toxic organic constituents to ground water will not occur when application rates for either treated wastewater effluent or sludge to agricultural soils are controlled by crop water and nutrient demands. However, it is cautioned that soils should be allowed to drain after each application and that the ground water table should be more than 0.3 to 1 meter (about 1 to 3 feet) from the soil surface.

LANDSCAPE-LEVEL CONSIDERATIONS

The foregoing discussion is mainly focused on the application of municipal or wastewater sludge on single fields or farms. However, the solution to both pollution problems and the sustainability of agriculture depends on conducting investigations at broader scales, such as communities and watersheds. For example, the impact of agricultural nonpoint pollution on streams and water supplies depends upon the combined effects of all farm practices within a watershed rather than the application of sludge to one field for one year (for example, see Barrett et al., 1990; Barrett and Bohlen, 1991). Indeed, Barrett (1992) noted that a new field of study—agrolandscape ecology—must evolve if society is to develop and manage agriculture in a sustainable and cost-effective manner for future generations. As alternative agricultural (National Research Council, 1989) gains acceptance, the role of sludge at these levels of integration should be evaluated.

SUMMARY

Municipal sewage sludge can be used as a source or supplemental source of nitrogen and phosphorous in the production of crops. Sludge also contains all other essential plant nutrients and, when used as an nitrogen source at agronomic rates, will usually satisfy crop requirements for all essential nutrients, except possibly potassium. The salts, nitrogen, trace elements and trace organics in sludge and wastewater effluents need to be managed properly to avoid damage to the soil, crop, consumer of the crop, and ground water. If the constituents from sludge and wastewater applications are not removed in the harvested crop, volatilized, or degraded, they may escape the root zone and leach to ground water. The accumulation of metals in sludge-amended soils may inhibit the activity of certain strains of clover rhizobia and cyanobacteria, and cause reductions in microbial biomass. This may be of concern to the sustainability of certain native legume species, but should not impact commercial food crop production.

As with the addition to soils of other organic materials, such as hay and animal manures, the addition of organic matter accompanying successive sludge additions improves the physical properties of soils. This, in turn, exerts a positive influence on water penetration, porosity, bulk density, strength, and aggregate stability.

Concentrations of potentially harmful trace elements in sludges are, almost without exception, greater than their concentrations in typical soil. Consequently, sludge applications usually increase the concentrations of trace elements in soils. Because most trace elements are immobile, the added sludge-borne trace elements tend to concentrate in the surface to the depth of incorporation. Where sludge has been applied to soil according to existing guidelines and regulations, there have been no reports of phytotoxicity or accumulation of harmful levels in consumers attributed to the trace elements. Also, as long as agricultural use of treated sludge follows current regulations, no adverse effects on acid soils or potentially acid soils, are anticipated.

A few toxic organic compounds and detergents have been found in sludges; they are either not absorbed or are absorbed by crops through the root systems in such small amounts that they do not present a threat to consumers. Some trace organics may be absorbed by the aerial part of the plant through volatilization of the compounds from the soil surface. However, this pathway does not seem important, particularly where sludges are incorporated into the soil. Because the concentrations of toxic organic compounds in sludge are low and they are either biodegradable in soils or strongly sorb to soil particles, they do not represent a risk to ground water contamination. At application rates of either sludge or treated municipal wastewater to agricultural soils that are controlled by water or nutrient demand by crops, the leaching of organic wastewater constituents to ground water will not occur if soils are allowed to drain after application and the ground water is more than 0.3 to 1 meter from the surface.

Where treated municipal wastewaters are used to irrigate crops, users must take into account nutrients (nitrogen and phosphorous) accompanying the water and adjust fertilizer practices accordingly. Under certain soil-plant systems, it is recommended that soil phosphorus levels be monitored so that the accumulation of soil phosphorus does not exceed crop requirements (usually about 150 kg/ha). As long as treated municipal wastewaters meet irrigation water quality criteria and state regulations governing disease-causing organisms in the water, they should be considered safe for agricultural use.

Treated municipal wastewater effluents and sludge resemble normal irrigation water and manures. Although they may contain some exotic compounds and fertilizer elements in different proportions than an ideal fertilizer, they present no significant hazards to agricultural soils, crops, or the environment if they are applied in quantities commensurate with crop needs.

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5

Public Health Concerns About Infectious Disease Agents

The infectious disease agents associated with municipal wastewater and sludge are those found in the domestic sanitary waste of the population and from industries that process meats, fish, and other food products. These microbial pathogens include a large number of bacteria, viruses, and parasites. Important examples are members of the bacterial genera *Salmonella* and *Shigella*; the infectious hepatitis, Rota and Norwalk viruses; and the parasites associated with giardiasis, cryptosporidiosis, taeniasis, and ascariasis (See Table 5.1 for a more complete list). It is reasonable to assume that any or all of these infectious agents might be present in the water and solids fractions of raw sewage.

INFECTIOUS DISEASE TRANSMISSION

Three conditions are necessary to produce infectious disease in a population: (1) the disease agent must be present, (2) it must be present in sufficient concentration to be infectious, and (3) susceptible individuals must come into contact with the agent in a manner that causes infection and disease. From a public health perspective, it is prudent to presume that raw sewage and sludge contain pathogenic organisms; thus, the first of the above criteria is always met. The concentration of these agents in sewage will be a function of the disease morbidity in the contributing population. An example of the number of pathogenic microorganisms found in raw sewage, treated effluent, and in raw and treated sludge is shown in Table 5.2.

The second of the above criteria—that the infectious agent be present in sufficient concentration—is fraught with uncertainty because available data on human dose response are very limited, particularly at the population level. Usually it takes more than a single organism to produce a detectable disease response in an individual in the exposed population. In many instances a lower dose of pathogens will produce infection but not disease. The limited human dose-response data that have been reported indicate much variation in the severity of sickness among those exposed to known dosages of pathogens (Bryan, 1974). Table 5.3 contains some examples of bacterial pathogen dose response.

TABLE 5.1 Examples of Pathogens Associated With Raw Domestic Sewage and Sewage Solids

Pathogen Class	Examples	Disease
Bacteria	Shigella sp.	Bacillary dysentery
	Salmonella sp.	Salmonellosis (gastroenteritis)
	Salmonella typhi	Typhoid fever
	Vibrio cholerae	Cholera
	Enteropathogenic-*Escherichia coli*	A variety of gastroenteric diseases
	Yersinia sp.	Yersiniosis (gastroenteritis)
	Campylobacter jejuni	Campylobacteriosis (gastroenteritis)
Viruses	Hepatitis A virus	Infectious hepatitis
	Norwalk viruses	Acute gastroenteritis
	Rotaviruses	Acute gastroenteritis
	Polioviruses	Poliomyelitis
	Coxsackie viruses	"flu-like" symptoms
	Echoviruses	"flu-like" symptoms
Protozoa	Entamoeba histolytica	Amebiasis (amoebic dysentery)
	Giardia lamblia	Giardiasis (gastroenteritis)
	Cryptosporidium sp.	Cryptosporidiosis (gastroenteritis)
	Balantidium coli	Balantidiasis (gastroenteritis)
Helminths	Ascaris sp.	Ascariasis (roundworm infection)
	Taenia sp.	Taeniasis (tapeworm infection)
	Necator americanus	Ancylostomiasis (hookworm infection)
	Trichuris trichuria	Trichuriasis (whipworm infection)

The final link in the infectious disease transmission chain is the exposure of the susceptible human population to infectious agents. The primary route of exposure to wastewater-associated pathogens is by ingestion, although other routes, such as respiratory and ocular, can be involved. If reclaimed water and sludges are to be used in the production of human food crops, particularly those that are eaten raw, then there is a chance of exposure through ingestion. Consequently, there is a greater need to reduce pathogen numbers to low levels prior to soil application, or at least prior to crop harvesting or livestock exposure.

Available engineering knowledge and technology can produce reclaimed water of the desired quality for use in such activities as agriculture, landscape irrigation, and ground water recharge. Data in Table 5.2 are illustrative of the effect of tertiary (advanced) treatment of wastewater in the removal of pathogens. The technology has advanced such that, in a number of instances, the use of reclaimed water to augment of water sources for drinking water supplies is either being seriously proposed or is a reality (City of San Diego, 1992; Gunn and Reberger, 1980; James M. Montgomery, Inc., 1983; Lauer and Johns, 1990). Treatment processes are also available to effectively reduce the concentration of pathogens in sewage sludge to levels safe for direct contact. Some examples include lime treatment, heat treatment, drying and composting (EPA, 1992b).

TABLE 5.2 Typical Numbers of Microorganisms Found in Various Stages of Wastewater and Sludge Treatment

	Number Per 100 ml Of Effluent				Numbers Per Gram of Sludge	
Microbe	Raw Sewage	Primary Treatment	Secondary Treatment	Tertiary[a] Treatment	Raw	Digested[b]
Fecal coliform MPN[c]	1,000,000,000	10,000,000	1,000,000	<2	10,000,000	1,000,000
Salmonella MPN	8,000	800	8	<2	1,800	18
Shigella MPN	1,000	100	1	<2	220	3
Enteric virus PFU[d]	50,000	15,000	1,500	0.002	1,400	210
Helminth ova	800	80	0.08	<0.08	30	10
Giardia lamblia cysts	10,000	5,000	2,500	3	140	43

[a] Includes coagulation, sedimentation, filtration and disinfection
[b] Mesophilic anaerobic digestion.
[c] MPN = Most Probable Number
[d] PFU = Plaque-forming units
SOURCES: EPA, 1991 and 1992a; Dean and Smith, 1973; Feachem et al., 1980; Engineering Science, 1987; Gerba, 1983 and Logsdon et al., 1985.

Thus, the technical knowledge is available for the design of processes that can adequately reduce the number of infectious agents present in raw wastewater and solids to safe levels. The important public health concern lies in the ability of these processes to reliably produce an acceptable product. Such reliability must be a critical element in the design and operation of wastewater treatment plants or other facilities producing these materials.

In California, treatment processes specified by the Water Reclamation Criteria (California Water Code, 1994) can achieve a 5 orders of magnitude reduction *in situ* of viruses. This level of reduction produces effluent that is accepted as being "free" of viruses. In the Monterey Wastewater Reclamation Study for Agriculture (Sheikh et al., 1990), tests conducted over a 5-year period of over 80,000 gal of reclaimed water that met Title 22 requirements found no viruses (Engineering Science, 1987). Virus seeding studies were conducted that verified the 5-log reduction in viruses from the treatment process. Additionally, a 99 percent natural die-off rate over 5 days was demonstrated under both field and laboratory conditions for the virus T99.

A rough calculation illustrates the very low level of viruses to be expected after irrigation with reclaimed water of this quality on food crops. In the Monterey study, the median number of viruses detected in the raw wastewater influent was 8 plaque-forming units (pfu) in 67 samples, so that even without treatment, the number of viruses that might remain following irrigation is very small. To illustrate, reclaimed water is typically applied to the crop in an

TABLE 5.3 Dose Required for a 25 to 75 Percent Disease Response in Humans

Number of Bacteria	Bacterial Species
100 – 1,000	*Shigella* sp.
1,000 – 10,000,000	*Salmonella typhi* (Typhoid fever)
100,000 – 1,000,000,000	*Salmonella* sp. (Gastroenteritis)
1,000 – 100,000,000	*Vibrio cholerae* (Cholera)

SOURCE: Bryan, 1974.

"irrigation set" of 2 in. of water. In California, crops cannot be harvested for two weeks following a reclaimed water irrigation set. If a plant occupies 2 square feet, it would receive about 2.4 gal of water. Even if the treatment plant failed completely, and assuming all the viruses in that volume of untreated wastewater stuck to the edible part of the plant, one would expect approximately 10^{-3} pfu per plant. With treatment, the number of viruses remaining on the plant is essentially zero. The study also found that a five-log reduction in viruses occurred in soil after ten days.

While the use of essentially pathogen-free sewage sludge or effluent would be ideal, materials of lesser sanitary quality (less treatment) can be applied in cases where direct human exposure to applied sludge or effluent is minimal. In these instances natural decay processes in the soil would be relied on to reduce the number of pathogenic agents to safe levels. Site restrictions would be required to limit public access and to allow adequate time for pathogen reduction prior to crop planting, harvesting, or domestic animal grazing.

INFECTIOUS DISEASE RISK

Where wastewater or sludge treatment is the primary mechanism to protect the public from infectious disease, acceptable microbiological quality standards must be developed. In the case of treated effluents used for crop irrigation, these values have developed over time and are based upon the use of standard water quality bacterial indicator microorganisms (e.g., coliform group or fecal coliform bacteria). More recently, specific treatment processes have been relied on to effect a significant reduction in the numbers of viruses and parasites (i.e. a process standard rather than a strict microbiological standard). For example, the Water Reclamation Criteria of California, which has been a model of reclaimed water regulations for many states (see Chapter 7), has established process standards for crop irrigation to ensure that the reclaimed water has a concentration of total coliform (or fecal coliform) less than or equal to 2.2 per 100 ml. This criteria is considered safe for human contact, and is based on past experience of health professionals and on a lack of detectable health problems associated with agricultural irrigation with treated effluent that meet this microbiological quality criteria. Thus, the microbiological quality values are not based on a formal risk assessment but rather on experience and the knowledge that accepted treatment processes can effectively reduce pathogen numbers.

There is, in the United States, less public health experience with sludge application than there is with wastewater reuse. EPA has established microbial quality criteria for sewage sludge that is to be applied to land in the Part 503 Sludge Rule (EPA, 1993). As with reclaimed water, the microbiological standards for sludge in the Part 503 Sludge Rule (discussed in more detail in Chapter 7) are also set primarily on the basis of experience, and expected efficiency of treatment processes to reduce pathogens.

There is a desire among regulators, producers, and users to develop and evaluate standards based on a more defined framework for risk assessment. This desire is generating interest in the use of mathematical models to predict the risk of infectious disease among those exposed to domestic waste-associated materials. Mathematical modeling makes assumptions explicit and is useful in organizing data and assumptions into a framework that leads to quantitative predictions. Models should, however, be used with caution. The model itself brings no new data or information to the process, and careful interpretation of modeling results is required; a numerical result of a model has human health significance only in the context of the model's assumptions. The mathematical format and numerical output of these models can lead to overconfidence in their results. There is the danger that inaccurate parameter estimates can lead to unrealistic risk forecasts.

Attempts to provide a quantitative model for the assessment of human health risks associated with the ingestion of waterborne pathogens have generally focused on estimating the probability of an individual infection resulting from a single exposure event. Most models described in the literature are of the same generic form (Fuhs, 1975; Dudley et al., 1976; Hass, 1983; Payment, 1984; Asano and Sakaji, 1990 and Rose and Gerba, 1991). They give a single value estimate of the probability of a particular exposure leading to infection or disease in a single individual and, except for Dudley's work, provide little or no information on the uncertainty or variability in this estimate.

A different approach to infectious disease risk assessment modeling starts from a population perspective and carries the analysis beyond the simple individual risk of infection or disease by estimating the probability distribution of the number of infected or diseased people in the exposed population (Cooper et al., 1986; Olivieri et al., 1986, 1989). This type of dynamic model allows for the evaluation of the sensitivity of the risk distribution to varying the dose and to varying the dose-response assumptions. Ideally the dynamic risk model should include the size of the exposed population, the immune status of the population, and other relevant demographic factors. The strength of this modeling approach is that it overtly acknowledges both uncertainty and variability in parameter values in a structured fashion that helps avoid unrealistic worst-case analysis results. Presently, it would be premature to give too much weight to the results of any of the existing models. It is anticipated that the development of the more sophisticated dynamic models will eventually enable risk managers to better understand the uncertainties involved and more realistically evaluate risk estimates.

MONITORING INFECTIOUS DISEASE POTENTIAL

Many of the variables associated with the transmission of infectious disease from wastewater and sludge are either not well understood or are unpredictable. Thus, it is essential that the dose of infectious agents in these materials be reduced to numbers that minimize the risk of disease transmission. This implies that a treatment process, including site restrictions, be applied that will *reliably* reduce the concentration of pathogens to an acceptable level prior to human or animal contact.

There is a great diversity of pathogenic agents involved in the fecal-oral exposure route, and an equal diversity of dose-response relationships. Monitoring for all of these agents is impractical; therefore, the use of indicator organisms has been the traditional approach to estimating sanitary quality. Coliform bacteria have been the most used in this regard. Their presence in the environment, particularly the fecal coliforms, is an indication of the presence of animal and human fecal matter, and thus the possible presence of many associated pathogens. Intestinal bacterial pathogens will react to environmental phenomena in much the same manner as coliforms, so the rates of removal of coliforms during water reclamation or sludge processing should reflect a similar reduction in pathogenic bacteria. Coliform bacteria determinations, in themselves, may not adequately predict the presence of viruses, protozoa or helminths. Many enteric viruses, for example, have a greater resistance to chemical disinfection and irradiation than do most bacterial indicators.

There are instances in sludge processing, such as composting, in which the coliform levels cannot be satisfactorily reduced even though there is reason to believe that the sanitary quality of the material is otherwise acceptable (EPA, 1992b; Skanavis and Yanko, 1994). In this situation, when the coliform numbers remain high, one should directly monitor for species of *Salmonella* to demonstrate the absence of this common bacterial pathogen.

Many of the parasites of concern exist in the encysted stage outside of the human or animal intestinal track, and are quite resistant to chemical and physical disinfection in this form. Wastewater reclamation practice relies on the treatment process to control these parasites. Parasite ova and cysts concentrate in sewage sludge and thus are of most concern for land application of sludge. Helminth ova are very resistant to those environmental factors that reduce the numbers of bacterial indicators or animal viruses in sludge. Because of its particular resistance, the presence or absence of viable helminth ova is being used as a criterion for monitoring for the presence of helminths in sludge to be applied to land (EPA, 1993).

As previously explained, there in no general agreement on the numerical values used in setting microbiological standards. They vary from region to region, both domestically and internationally. The standards are based on expected performance of wastewater treatment processes and on past experience with land application rather than on predictive science.

Because coliform bacteria are not always reliable indicators of the sanitary quality of reclaimed water or of sludge, there is a continuing search for substitute indicator organisms or for methods for directly measuring pathogens. The bacterium *Clostridium perfringens* is an example. Because of its presence in large numbers in wastewater, ease and speed of detection and the resistance of its spores to disinfection, this bacterium is considered by some to be a good indicator of how effective a treatment process has been. The evaluation of such potential process monitoring indicators should be encouraged.

Applications of immunological and molecular biological methods to environmental microbiology are evolving and offer the possibility for low levels of pathogenic microbes to be detected directly from environmental materials such as water and soil. Fluorescent antibody

(FA) methods are available that are both qualitative and quantitative for specific microbial pathogens such as *Giardia* and *Cryptosporidium* . Gene probes have equal or greater specificity for species of microorganisms as FA, but at the present time are less suitable for rapid quantification. The application of polymerase chain reaction (PCR) methodology has the potential to detect very low levels of specific pathogen nucleic acid and, by inference, the presence of pathogenic microbes. While the application of these sensitive detection methods could result in more definitive monitoring, questions remain about the viability of the microbes detected and about the public health significance detecting very low numbers of these agents in water and sludge that are applied to land.

PUBLIC HEALTH EXPERIENCE WITH THE USE OF RECLAIMED WATER AND SLUDGE

There is an extensive literature on the public health (infectious disease) experience with wastewater reclamation and reuse (EPA, 1992a). This is not the case for the application of treated sludge onto land. There have been no reported outbreaks of infectious disease associated with a population's exposure—either directly or through food consumption pathways—to adequately treated and properly distributed reclaimed water or sludge applied to agricultural land.

Reports of the occurrence of infectious disease transmission linked to the irrigation of food crops with wastewater are associated with *untreated* sewage or treated wastewater of questionable quality. A recent epidemiological review of disease transmission from irrigation with reclaimed water (Shuval, 1990) also concludes that only untreated wastewater has been implicated in the transmission of infectious disease. Except for the use of raw sewage or primary effluent on sewage farms in the late 19th century, there have not been any documented cases of infectious disease resulting from reclaimed water use in the United States (EPA, 1992a, Water Pollution Control Federation, 1989).

In California, as a result of the Monterey study and others (Sheikh et al., 1990), a treatment process for reclaimed water has been approved by the state for any nonpotable purpose, including application to crops eaten raw. State health officials are convinced that specific treatment processes can be used to reduce the levels of pathogens such that treated wastewater is "safe to use." California standards for reclaimed water tend to lead the way in the United States, and are compatible with those developed by EPA in their *Guidelines for Water Reuse* (EPA, 1992a). See Chapter 7 for a discussion of the regulations governing pathogen control in reclaimed water and sludge.

The most extensive literature on human exposure to wastewater is concerned with the infectious disease risk to wastewater treatment plant operators and maintenance personnel. A review of the literature indicates that the occurrence of clinical disease associated with occupational exposure among these workers is rarely reported (Cooper, 1991a,b). From these observations it is not unreasonable to assume that exposure of agricultural workers to reclaimed water used in irrigation would result in an even lower risk of infectious disease than that to sewage plant operators.

Because of the intense public concern over AIDS, sewage treatment plant operators and others who come in close contact with wastewater and sludges have questioned their risk of infection with the HIV virus. All evidence indicates that there is no cause for alarm since the HIV virus does not survive in water; its transmission requires intimate contact with infected blood or body fluids (Moore, 1993; Riggs, 1989).

There have been a limited number of reports concerning an allergic response in sewage treatment plant workers exposed to species of *Aspergillus* fungi in the dust associated with the composting of sewage sludge (Clark et al., 1984; Epstein, 1994). In this instance the fungi source is not wastewater but growth of this common fungi as part of the composting process.

The potential effects of aerosols generated by wastewater treatment plants on the surrounding community have been the subject of much speculation. To date, the information collected by multiple investigators indicates that no health problems have been demonstrated to be associated with these aerosols. This issue was thoroughly documented in the proceedings of an EPA symposium on wastewater aerosols and disease (Pharen, 1979). From these observations, one could assume that the risk of contracting infectious disease from exposure to aerosols of reclaimed irrigation water is also negligible. No adverse health effects have ever been reported from the irrigation of median strips, parks, or private residences irrigated with properly treated reclaimed wastewater.

The limited number of epidemiological studies that have been conducted in the United States on treatment plant workers exposed to municipal wastewater or sludge or populations exposed to reclaimed water or treated sludge land application projects indicate that exposure to these materials was not a significant risk factor. However, the value of prospective epidemiological studies on reclaimed water or sludge use is limited because of a number of factors, including a low illness rate—if any—documented as resulting from these reuse practices, insufficient sensitivity of current epidemiological techniques to detect low-level disease transmission, population mobility, and difficulty in assessing actual levels of exposure.

Infectious diseases of the types that could be associated with municipal wastewater are under-reported and exposures are scattered, so that effects may well go unrecorded. From a public health point of view, the major microbiological considerations for evaluating any reuse management scheme are the ability to effectively monitor for treatment efficacy and the reliability of the process used to effect pathogen reduction.

One must keep in mind that there are a great many sources of these infectious disease agents other than reuse of wastewater or sludge, such as prepared food and person-to-person contact. Therefore, the potential added increment of pathogen exposure from the proper reuse of reclaimed water or sludge is minuscule compared to our everyday exposure to pathogens from other sources.

SUMMARY

Pathogenic microbes are inherent to domestic sewage and sewage solids. Because of the potential for the transmission of these infectious disease agents to humans and animals, use of these effluents on crops and grazing land must employ management strategies that protect the public's health. The main thrust of any management strategy is reduction of concentrations of pathogens to acceptable levels. This reduction can be achieved by treatment prior to land application or, as an alternative scheme in the case of sludge and reclaimed water of lower sanitary quality, crop restrictions and management of the application site to restrict human and grazing animal contact during the time required for pathogens to decay to acceptable levels. Two prime considerations in evaluating any management scheme are the ability to effectively monitor for treatment efficacy and the reliability of the process used to effect pathogen reduction.

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6

Public Health Concerns About Chemical Constituents in Treated Wastewater and Sludge

There are many chemical constituents that enter the municipal waste stream that are of potential concern for human health. These substances include organic chemicals, inorganic trace elements (such as cadmium and lead), and nitrogen. Conventional agricultural practices, such as the use of commercial fertilizers, also have the potential to introduce additional chemical constituents to soil. However, this report is not attempting a comparison between public health effects of conventional agricultural inputs and those derived from municipal wastewater or sludge. The degree to which constituents from municipal wastewater present a risk to human health depend on their concentration in reclaimed water and treated sludge and the fate and transfer of these chemicals from the wastewater/sludge sources to human receptors via various exposure pathways. The chemical composition of sewage and the degree to which chemical concentrations are reduced in effluent and sludge by secondary and advanced treatment were discussed in Chapter 2 and 3. The degree to which chemical concentrations of these contaminants in reclaimed wastewater and sludge are further reduced through natural processes in the environment and their availability to food plants were the subjects of Chapter 4. Transmission of toxic contaminants to humans from agricultural use of reclaimed wastewater and sludge is covered in this chapter.

The U.S. Environmental Protection Agency (EPA) identified Priority Pollutants in regulations that deal with municipal and industrial wastewater (EPA, 1984) due to their toxicity to humans and the aquatic environment. These Priority Pollutants are divided into four classes: (1) heavy metals (oftentimes referred to as trace elements or trace metals) and cyanide, (2) volatile organic compounds, (3) semivolatile organic compounds, and (4) pesticides and polychlorinated biphenyls (PCBs). In addition, nontoxic organic compounds in wastewater can be transformed into potentially toxic chlorinated organic compounds, such as trihalomethanes, when chlorine is used for disinfection purposes (National Research Council, 1980).

For the purpose of this review, non-metallic trace elements, such as selenium, are grouped together with the heavy metals under the more general designation of "trace elements." The following discussion first considers the fate of organic compounds from sludge and wastewater applications to soil. The uptake of these chemicals into plants and animals that go into the human food chain is then examined. Finally, the potential for adverse health effects from trace elements in sludge and wastewater via these same pathways is evaluated.

FATE OF AND EXPOSURE TO ORGANIC CHEMICALS

Principal pathways of human exposure to sludge- and effluent-borne toxic organic compounds from land application to cropland include (Dean and Suess, 1985):

- Uptake by plant roots, transfer to edible portions of plants, and consumption by humans.
  Direct contact of edible plant parts with sludge or reclaimed water applied by spraying, and consequent consumption by humans.
- Direct contact by children who play on sludge/wastewater-treated soil and inadvertently ingest small amounts of soil.
- Uptake by plants used as animal feed, animal ingestion causing transfer to animal food products, and consumption of the animal food products by humans.
- Direct ingestion of soil and/or sludge by grazing animals, transfer to animal food products, and consumption of animal food products by humans.

Human exposure to toxic organic chemicals through incidental ingestion of sludge, effluents, or treated soil (pathways 2 and 3 above) is not considered in detail in this report. Chapter 7 discusses EPA's risk analysis, which evaluated all exposure pathways.

Behavior of Toxic Organics in the Soil

It has been suggested that most toxic organic compounds are present in sludge at concentrations less than 10.0 mg/kg (Jacobs et al., 1987). Therefore, when sludges are applied to soil at agronomic rates and mixed with the surface, concentrations of toxic organics within the top 15 cm of soil normally will not exceed 0.10 mg/kg. In one survey, the level of toxic organics in sludge-amended soils was considered to be similar to or lower than background pesticide soil concentrations of 0.01 to 1.0 mg/kg (Naylor and Loehr 1982). They are further reduced by microbial decomposition.

In theory, there are a number of environmental processes that, when added to the soil, can interrupt the entry of toxic organic chemicals into the food chain. Organic chemicals from wastewater or sewage sludge may be destroyed directly after land application by biodegradation and chemical- and photo-oxidation. Organic compounds may also be volatilized, immobilized onto solid particles by sorption processes, or transported (leached) unaltered through the soil column to reach the ground water. In more complex mechanisms, sorbed organics may subsequently be chemically or photochemically degraded, microbially decomposed, or desorbed.

A considerable body of research has been performed on the behavior of organic pesticides in soil. Both laboratory and field experiments suggest that during land treatment, most pesticide residues are adsorbed by soil particles and remain sorbed on surface soils until degraded by microorganisms or volatized (Cork and Krueger, 1991). The relative degree of intrinsic biodegradability of toxic organics on the EPA Priority Pollutants list was illustrated by Tabak et al. (1981) in laboratory studies. They collected data on biodegradability and microbial acclimation of 96 compounds using bacterial inoculum from domestic wastewater and synthetic bacterial growth medium. Their overall results are summarized in Table 6.1. Significant biodegradation was found for phenolic compounds, phthalate esters, naphthalenes, and nitrogenous organics; variable results were found for monocyclic and polycyclic aromatic compounds, PCBs, halogenated ethers, and halogenated aliphatics; and no significant biodegradation was found for organochlorine pesticides.

Extrapolation of laboratory findings like these to predicting behavior in the field has two important constraints: (1) the rate of biodegradation in soil is probably less than that in laboratory medium and (2) the low concentration of the organics in reclaimed wastewater applied to crops may not support the level of microbial activity necessary for biodegradation in the soil environment.

Literature on the microbial decomposition of toxic organics in soil is diverse (Alexander, 1994). The degradation of petroleum hydrocarbons (a mixture of aliphatic, aromatic, and asphaltic compounds) in soils has been reviewed by Atlas (1981). Factors which appear to be important in encouraging high decomposition rates of petroleum hydrocarbons are temperature, concentrations, adequate supply of essential nutrients, and availability of oxygen. There is little evidence for significant leaching of petroleum organic compounds from the upper soil layers. Experiments with the high-rate application of sludge containing high levels of petroleum hydrocarbons onto land have shown a 77 percent degradation rate near the surface after one year, with most of the degraded compounds being n-alkanes (Lin, 1980). It was concluded that sludge land disposal would not result in petroleum hydrocarbon buildup in the soil. Also, in studies of other organic substances in wastewaters used for irrigation, Dodolina et al. (1976) found that acetaldehyde, crotonaldehyde, benzaldehyde, cyclohexanone, cyclohexanol, and dichloroethane disappeared from soil within ten days.

The behavior of PCBs in soil has been comprehensively reviewed by Griffin and Chian (1980), who concluded that PCBs are strongly adsorbed by soil particulates. Influential factors affecting adsorption are the nature of the soil surface, the soil organic matter content, and the chlorine content and/or hydrophobicity of the individual PCB isomers. Adsorption increases with increasing organic matter content of the soil, with increasing chlorine content, and with increasing hydrophobicity of the PCB molecules. One study that examined percolation of PCB-containing solution through soil columns showed that less than 0.05 percent of one isomer was leached in the worst case. Fairbanks and O'Connor (1984) have shown that PCBs remain tightly adsorbed to sludge-amended soil, with minimal transport by soil water.

Studies involving land treatment of municipal wastewater provide some insight into the fate of toxic organic compounds from wastewater in soils. Land treatment of wastewater is considered to be an alternative form of secondary treatment, and is not performed for crop irrigation purposes. Generally, land treatment systems apply settled wastewater (primary effluent) to vegetated slopes using sprinklers or perforated pipes. The water flows over the sloped surface to collection ditches at the bottom of the slope where the effluent is discharged to a surface water. Biodegradable organic compounds, such as organic nitrogen and ammonia, are oxidized by soil bacteria. Percolation into the soil is negligible. Overland flow treatment slopes are selected for their relative impermeability; also, particulate material tends to seal the soil rapidly. Some water evaporates, but most of the wastewater is collected as surface runoff (Metcalf and Eddy, 1991). Wastewater flows in a very thin sheet across the vegetated slope. The U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory in New

TABLE 6.1 Biodegradability of Priority Pollutant Organic Compounds

Test Compound Class	Number of compounds tested	Percent Degradation[a]
Phenols	11	82 D
Phthalate Esters	6	67 D
Naphthalenes	4	100 D
Monocyclic Aromatics	12	42 D, 50 T
Polycyclic Aromatics	7	50 A, 50 N
Polychlorinated Biphenyls (PCBs)	7	71 N
Halogenated Ethers	6	50 N, 50 D
Nitrogenous Organics	6	67 D, 33 N
Halogenated Aliphatics	23	26 D, 57 A or B, 17 C or N
Organochlorine Pesticides	17	100 N

[a] D-Significant degradation with rapid adaptation; A-significant degradation with gradual adaptation; T-significant degradation with gradual adaptation followed by a deadaptive process (toxicity); B-slow to moderate biodegradative activity, concomitant with significant rate of volatilization; C-very slow biodegradative activity, with long adaptation period needed; N-not significantly degraded under the conditions of test method.
SOURCE: Condensed from Tabak et al., 1981.

Hampshire operated a prototype overland flow wastewater land treatment system and found greater than 94 percent removal of each of 13 trace organics by volatilization and adsorption processes (Jenkins et al. 1983), with removal efficiencies decreasing as application rates increased and temperature decreased. With the possible exception of PCBs, biodegradation prevented contaminant buildup in the surface soil.

Uptake of Toxic Organics by Plants

The following discussion summarizes information presented by O'Connor et al. (1991) from a recent review of the literature dealing with plant uptake of toxic organics. The results reported in the O'Connor et al. review are a mixture of laboratory and field data on plant uptake of organic compounds, both from sludge and from additions of pure chemical.

Phthalate Esters

Phthalate esters, which are the most common toxic organic compounds in sludges, present little risk because plants serve as effective detoxifying barriers to these chemicals and prevent their accumulation in the food chain (Aranda et al. 1989). Also, phthalates added to soils do not persist and are rapidly removed by volatilization and microbial decomposition (Dorney et al., 1985).

Polynuclear Aromatic Hydrocarbons (PAHs),

PAHs (also called "polycyclic aromatics") are produced by incomplete combustion. They are among the most common toxic organics in sludges (EPA, 1990). In the National Sewage Sludge Survey (NSSS), the PAH benzo (a)pyrene was found just at detection levels in 3 percent of the sludges analyzed from 209 municipal treatment plants. An earlier sludge survey of 40 municipal treatment plants conducted in the late 1970s by the EPA (EPA, 1982) found benzo(a)pyrene in 21 percent of the sludges with a mean level of 0.1 mg/kg (Kuchenrither and Carr, 1991). Some PAHs, particularly higher molecular weight species, are long-lived in soils (Bossert and Bartha, 1986). However, in long-term field studies (20-30 yrs), no evidence was found of elevated PAH concentrations in the above-ground portions of several crop species grown in PAH-contaminated soils. Air-borne sources of PAHs were regarded as the main origin of plant contamination in sludge-amended and control treatments alike (Witte et al., 1988; Kampe 1989; Wild et al., 1990). Overall, O'Connor et al. (1991) concluded that minimal PAH contamination occurred when sludge was used prudently for agriculture. The transfer of PAHs from soil was minimal for root crops, and essentially zero for above-ground crops.

Polychlorinated Biphenyls (PCBs).

Two studies found the median total PCB content in municipal sludges to be less than 0.5 mg/kg total PCBs (Jacobs et al. 1987; Mumma et al. 1988). The NSSS confirms this finding (EPA, 1990); it was found in the survey that the median concentration was 0.2 mg/kg. More highly chlorinated PCB cogeners, which dominate in municipal sludges, tend to be more persistent, more strongly sorbed, less volatile and less bioavailable than the less chlorinated PCB species. O'Connor et al. (1990) conducted field studies and greenhouse pot studies using sludge-borne PCBs and found that the PCB levels in crops were below Limits of Detection (LOD), typically 0.20 μg/kg; bioconcentration factors were usually less than 0.02 based on dry weights of soil and crop and LOD. There was no statistically significant evidence of PCB uptake from sludge-borne PCBs in soils by aboveground parts of plants. Carrots were the only crop to contain detectable residues of PCBs, mostly in the carrot peel, which the authors noted can be easily removed with normal culinary practices of washing and peeling. No PCB vapor contamination of crops grown in soils amended with sludge-borne PCBs was detected.

Surface incorporation of PCB-contaminated sludges reduces PCB volatilization (Strek et al. 1981). Low inputs of PCBs to soil-plant systems, combined with low bioavailability, suggest negligible impact on plants grown in sludge-amended soils (Webber et al., 1994; O'Connor et al., 1991; Chaney, 1993). Witte et al. (1988) reported that repeated applications of municipal sludge over a period of 30 years and totaling 130 metric tons per ha, resulted in slight increases in soil PCB concentration, but no detectable (LOD=0.05 μg/kg dry weight) PCB residue in a variety of crops, including carrot. In another study, trace levels of PCBs from municipal sludge that was applied at a rate of about 2 metric tons/ha for two years to an old field resulted in no detectable PCBs in plant samples (Davis et al. 1981).

Adding PCBs (Arochlor 1254) to soils to produce concentrations from 50-100 mg PCBs/kg dry soil resulted in substantial uptake by carrot root with very little translocation to the aboveground plant parts (Iwata, et al., 1974). Computations from the data presented showed PCB concentrations in carrot root ranging from 2.7 to 15.3 mg/kg with concentrations decreasing as the degree of PCB chlorination increased. Ninety-seven percent of the PCBs in the carrot root were in the peel. Although the above study showed substantial uptake by carrot root, it is unlikely that concentrations of this order of magnitude would ever occur in sludge-amended soils because regulations prohibit concentrations of PCBs in sludge greater than 50 mg/kg (EPA 1993a). Applying a sludge containing 50 mg PCBs/kg to a typical soil at a rate of 10 tons/ha would produce a concentration of 0.25 mg PCB/kg soil.

The less-chlorinated PCBs have greater potential to be taken up by the plant, but these are also much more volatile and biodegradable, and thus are less common in sludge. The more highly chlorinated PCBs are absorbed less by plants (Fries and Marrow 1981). Lee et al. (1980) were unable to detect PCBs in carrots grown in soil containing 0.23 mg PCB/kg of soil derived from an application of 224 metric tons/ha of sludge containing 0.93 mg PCB/kg of sludge. Naylor and Mondy (1984) have obtained similar results with potatoes. Over 1,400 samples of soil and crop tissue were analyzed in a greenhouse and field study for the Madison Metropolitan Sewage District (Gan and Berthoex, 1994). No PCB translocation into either corn grain or corn stover samples occurred. It was concluded that little, if any, PCB will be translocated from contaminated soil to plant tops. Apparently, PCB exposure via the plant/soil pathway is minimal.

Webber et al. (1994) determined concentrations of PCBs in corn, cabbage and carrots grown on coal refuse amended with sewage sludge at rates of 785; 1,570; and 3,360 tons per ha. Concentrations of PCBs in the treated coal refuse ranged from 1.3 to 3.7 mg/kg and were not related to treatment. The PCB concentrations in all tissues were less than 0.3 mg/kg; concentrations in carrot peels were greatest, followed in decreasing order by carrot tops; cabbage wrapper, inner leaves, and carrot core; corn ear leaf, stover, and corn grain. In general, the concentrations of PCBs in the plant tissues were independent of the PCB concentration in soil. Webber et al. (1994), Witte et al. (1988), and O'Connor et al. (1991), conclude that PCBs in municipal sludges represent no significant risk to crops or crop consumers.

Although most reports show PCB uptake by crops grown on sludge-amended soil to be negligible, Baker et al. (1980) found that PCB concentration in vegetables grown on garden soils were significantly higher than that of the control soil. However, concentrations of PCBs in the sludge used for that study averaged 479 mg/kg and would be banned from land application by present-day federal regulations.

Chlorinated Pesticides

Some important chlorinated pesticides include aldrin, chlordane, DDD, DDE, DDT, endrin, dieldrin, heptachlor, lindane, and toxaphene. While the use of these pesticides are banned, there are many other approved pesticides that are applied to food crops in the course of normal agricultural operations. The use of approved pesticides is regulated by governmental agencies, and pesticide residues are closely monitored by food processors to prevent contamination of processed food products. Although no longer used in the United States, many of the banned pesticides persist in the environment. Their presence in treated sludge or reclaimed wastewater that is applied to agricultural land used for food crop production may be viewed by food processors as an additional uncontrollable pesticide burden, and they have expressed concern about their product quality being compromised when treated sludge and wastewater are used in food crop production (National Food Processors Association, 1992). Residues of aldrin and dieldrin were detected in 3 and 4 percent, respectively, of the 209 sludges surveyed in the NSSS, at concentrations of 0.002 mg/kg and at LOD, respectively (Kuchenrither and Carr, 1991). Studies in the late 1980s reported median concentrations in sludges for the pesticide compounds listed above to be very much less than 1 mg/kg dry weight and, frequently, below detection limits (0.05 mg/kg) (EPA, 1990). Application rates of sludges with such median concentrations would result in concentrations in plant growth media of less than 0.01 mg/kg. Pot and field studies (Baxter et al., 1983; Kampe, 1989; Singh, 1983; Witte et al., 1988), some of which spanned 30 years, found that sludge additions failed to measurably increase the level of chlorinated pesticides and hydrocarbons above background soil levels. In a study involving the application of municipal sludge to coal refuse at a rate of 3360 tons/ha, Webber et al. (1994) observed sludge concentrations of organochlorine pesticides ranging from less than 0.015 mg/kg (heptachlor, aldrin, pp'-DDT, lindane, hexachlorobutadiene, and hexachlorobenzene) to 0.217 mg/kg (pp'-DDE). Other pesticides and their concentrations (in mg/kg) include alpha and gamma chlordane (0.08 and 0.125), dieldrin (0.042), and pp'-DDD (0.091). Levels of the pesticides in corn, cabbage, and carrot tissues grown on the sludge-treated coal refuse were less than the method's detection limit of 0.1 mg/kg dry weight. Based on the information presented, it seems reasonable to conclude that it is highly unlikely that pesticides in sludge applied to land will harm crops or their consumers.

Disinfection Products

In United States, the treatment and discharge of municipal wastewater are governed by regulations derived from federal legislative mandates in P.L. 92-500 as well as state statutes. The current regulations consider disinfection as an important element of wastewater treatment when necessary to protect public health. While several options are available, chlorination is by far the most commonly used disinfection process for wastewater effluents.

Rook (1976) discovered that chlorine used in disinfection reacts with naturally occurring humic substances in the water to form trihalomathanes (THMs), the most prevalent species among them are chloroform, bromodichloromethane, dibromochlorimethane, and bromoform. Subsequent surveys of municipal water supplies in the United States found that THMs were log-normally distributed with median concentrations less than 30 µg/1. Bellar et al. (1974) found that chloroform also formed during the chlorination of wastewater effluents. Jolley (1975), Glaze and Henderson (1975), and Glaze et al. (1978) evaluated other chlorine-containing compounds that also form, including chlorophenols, chlorbenzoic and chlorphenylacetic acids, and chlorinated purines and pyrimidines.

Byproducts of water and wastewater chlorination are subjects of continuous investigations worldwide (Johnson and Jensen, 1986; Badaway, 1992). Based on their concentrations in chlorinated wastewater effluents and their fate and transport characteristics, it seems unlikely that they will persist in the receiving soil or become bioaccumulated to any great extent (Jolley, 1978; Howard, 1989). Although actual data on the persistence of these byproducts on food crops are lacking, their presence should not limit the use of reclaimed water for crop irrigation.

Acid-Extractable Organic Compounds

Phenols, including pentachlorophenol (PCP) and 2,4-dinitrophenol (DNP), are important acid-extractable organic compounds. Their toxicity to plants is pH-dependent. Toxicity and soil sorption are greatest in acid soils, and their degradability and mobility in soil are greatest in near neutral to alkaline conditions. Studies of PCP and DNP in high pH soils found soil degradation to be rapid. O'Connor et al. (1991) concluded that when soils amended with sludges containing median concentrations of phenols (from NSSS, EPA 1993b) are managed according to sound agronomic practices of pH control, neither DNP or PCP will persist in soils long enough to impact plants, and little plant contamination is expected.

Chlorinated Dibenzo-p-dioxins (CDDs) and Dibenzofurans (CDFs).

Like PAHs, dioxins are generally formed by combustion of organic solids, and they have been reported in sludge quality surveys. In a literature review of studies of plants exposed to dioxin-contaminated soils, Kew et al. (1989) found that root uptake and translocation of tetrachlorodibenzodioxin (TCDD) was minimal, but that significant contamination may occur by volatilization of TCDD from soil and absorption by foliage. Facchetti et al. (1986) concluded that volatilization would be the dominant process of transfer from soil to plant, if it were to occur. Nevertheless, O'Connor et al. (1991) concluded that contamination of plants with either CDDs or CDFs would be unlikely due to their very low bioavailability. Even if present at high initial concentrations, dioxins in sludge would be diluted at least 100-fold at agronomic sludge application rates, and the organic matter with the sludge would increase soil sorption capacity and likely reduce volatilization.

Volatile Aromatic Compounds (VOC)

Although volatile aromatic compounds (e.g., toluene, benzene, xylene) in municipal wastewater are largely lost by volatilization in the sewer or at the treatment plant, they have been detected in sludges (Jacobs et al., 1987). Benzene was detected in 93 percent of the municipal sludge samples analyzed in the 40 Cities Survey (EPA, 1982) with a mean concentration of 1.8 mg/kg; however, some fraction of these sludges were untreated, and therefore not eligible for land application under current regulations. Benzene was detected in less than 2 percent of the sludges from 209 treatment plants in the NSSS in a range of concentrations from 0.01 to 0.2 mg/kg. When sludges are applied to soils, volatile aromatics are rapidly lost due to volatilization. Jin and O'Connor (1990) and concluded that volatile aromatics do not persist long enough in sludge-treated soils to represent a problem for agriculture under normal aerobic soil conditions. However, anaerobic conditions resulting from both bacterial depletion of oxygen due to high organic carbon content and lack or reaeration due to water-logging can promote temporary volatile aromatic retention in soil (Jin and O'Connor 1990). This source of volatile organics should not pose a problem since crops, except for rice, are not grown in waterlogged soils. Some investigators have reported contamination and bioconcentration of toxic volatile aromatic compounds in plants (Facchetti et al., 1986). O'Connor et al. (1991) suggested that further research was necessary to study possible plant contamination by sorption of chemical vapors from volatile aromatic compounds and other volatile organic compounds (e.g., toxaphene, and TCDD).

Generalizations Regarding Uptake of Organics by Plants

Plant bioconcentration factors for most toxic organics are small and are often not significantly different from zero. Most toxic organics occur in sludge at low concentrations and when the sludge is applied to soil, their concentrations are further diluted. Furthermore, toxic organic compounds that are not destroyed by biodegradation, chemical oxidation, or photolysis are so strongly sorbed to the sludge-soil particulate matrix as to have low bioavailability to plants. Many of the organic compounds are chemically or biologically degraded or volatilized from the soil during the cropping season. Finally, because the fraction of sludge-borne toxic organics that does remain in soil has low bioavailability, absorption by crops is negligible. In some cases, volatile toxic organics may contaminate plant tissue through absorption of volatilized compounds; however, management practices, such as incorporation of sludge with soil and application of sludge before plant sprouting, will substantially reduce any plant exposure to VOCs.

Available data indicate that potentially harmful toxic organic pollutants do not enter edible portions of plants that are irrigated with treated municipal wastewater. Irrigation of vegetables in test plots with wastewaters has shown no accumulation of PAHs, especially benzo(a)pyrene (Il'nitskii et al. 1974). In a study of aldehydes and other organics at agricultural land treatment sites, Dodolina et al. (1976) found no uptake of acetaldehyde, crotonaldehyde, and benzaldehyde in the aboveground portions of potatoes and corn. Cyclohexanone and cyclohexanol could be found in corn plants four days after irrigation, but not later. Dichloroethane was taken up by beets and cereals, but was metabolized and absent within about two weeks after irrigation. Although these compounds are found in crops and soils, they appear to be metabolized at a rate sufficient to prevent their occurrence in the harvested product.

Uptake of Toxic Organics by Animals

Toxic organic compounds present in plant tissues (and soil in the case of pastured animals) may be incorporated into animal tissues. However, the low levels of toxic organic compounds to be expected in the aboveground portions of plants growing at land application sites pose little hazard to animals feeding upon them. Under certain site-specific conditions, however, high concentrations of particular organic compounds in the sludge may cause problems.

In considering the pathways for exposure of humans to toxic organic compounds in sludge, Chaney (1985) suggests that direct ingestion of the sludge-soil mixture by animals is the only reasonable route by which toxic organic chemicals have been traced directly from sludge to animal products. However, the transfer of toxic organic compounds to the human food chain via this pathway is still considered to be negligible.

FATE OF AND EXPOSURE TO TRACE ELEMENTS IN SLUDGE

The availability of inorganic chemicals or trace elements for uptake by plants (and thus entry into the human food chain) or transport to ground water is limited by the extent to which these elements remain free in the soil solution. The binding of chemicals to the soil substrate is controlled by the chemical processes of complexation to organic matter, adsorption, and precipitation. Adsorption occurs on organic matter, hydrous oxides of iron and manganese, clays, and other soil minerals. Precipitation reactions include the formation of sparingly soluble oxides, hydroxides, carbonates, phosphates, and sulfides, etc. Mercury may leave the soil through volatilization. As a result of these processes, only small amounts of the trace elements remain free in the soil solution where they would be available for absorption by plant roots. These processes are strongly affected by soil pH, with cation levels decreasing and anion levels increasing in the soil solution with increasing pH (Logan and Chaney, 1983).

Chaney (1980) introduced the concept of the "soil-plant barrier" for consideration of potential toxicity to the food chain if trace elements are applied to soils. After a trace element enters the root cells, translocation to other plant organs (tubers, shoots, leaves, fruits, seeds), depends on the properties of the specific element and the plant. Important plant processes are membrane surfaces, organic chelators, and cells specialized for pumping materials into the xylem, through which it reaches the shoot. One group of metals are so insoluble or so strongly adsorbed to soil or plant roots that they are not translocated into edible plant parts regardless of quantities present in the soil. Elements like trivalent chromium, mercury, and lead are examples. Lead is so insoluble inside the plant root and mercury is so strongly bound inside the fibrous plant roots that harmful levels of these elements are not found in edible plant parts (Berthet et al., 1984; Naylor and Mondy, 1984). Mercury can be transferred through volatilization from the soil surface to plant foliage, but this route is not very relevant to sludges because they are low in mercury.

Copper and zinc belong to another group of elements that are translocated to vegetative parts of the plant. However, before they reach levels in crops that could be potentially harmful to consumers, crop growth is so severely stunted that they are not harvestable. Phytotoxicity thus prevents excessive plant concentration of contaminants to levels harmful to animals, and the food chain is protected (see Chapter 4).

There are exceptions to protection by the soil-plant barrier. These exceptions have been the focus of intense research in agriculture. Livestock have been injured by forage grown on soils with excessive geochemically-derived selenium (Mayland, 1994) or molybdenum (Mills and Davis, 1987) for centuries. Cadmium is absorbed by crops and can reach levels that are dangerous to humans if a high percentage of the consumer's diet is derived from crops grown on cadmium-contaminated soil over an extended time period. Human disease from soil cadmium occurred in Japan where mining wastes polluted paddy rice fields, and farm families consumed the rice grown on these paddies for 40 or more years (Kobayashi, 1978; Nomiyama, 1986). It should be noted that the diets of the Japanese families were low in calcium and zinc. Calcium, iron, and zinc play major roles in interfering with cadmium absorption in the human intestine (Fox, 1988), and when sufficiently present in the human diet, high cadmium foods will not always produce health effects.

Selenium toxicity to humans has been documented in China (Combs and Combs, 1986); however, the source of the selenium was not municipal sewage sludge. Municipal sewage sludges are not high in selenium. Similarly for livestock, soil molybdenum is a potentially toxic element, but no cases have been reported of molybdenum toxicity to animals from consumption of forage grown on sludge-amended soils. In pot studies, where clover was grown on alkaline soils containing up to 16 kg of molybdenum per ha, concentrations in the plant tissue reached levels that could be harmful to animals if the clover were to make up a substantial portion of the diet for an extended period of time (Davis, 1981). Burau et al. (1987) collected five years of field data on the impact of treated municipal wastewater on trace element concentrations in soil and vegetables. They concluded that there was no significant difference in concentration between food crops irrigated with treated domestic wastewater and wellwater. They did observe, however, that commercial fertilizer application did result in increased plant tissue levels of some metals, such as cadmium, zinc, and manganese. Levels in plants, however, were well below those considered harmful.

The uptake of trace elements by plants has been reviewed by Logan and Chaney (1983). Important factors affecting uptake rate include: trace element properties, soil properties, the immediate environment (especially pH) of the roots, plant crop species, and plant crop cultivar (variety or strain). As an example of species effects, leafy vegetables, especially Swiss chard, are much better cadmium accumulators than most other plants. Cultivars of maize (corn) and wheat have been shown to vary in their rates of cadmium accumulation.

Uptake of Trace Elements by Animals

As with toxic organics, animals can be exposed to trace elements through sludge residuals adhering to plants, sludge on the soil surface or mixed into the soil, or trace elements absorbed and translocated by plants. All three routes can operate on grazing land, but only the third is relevant when animals are given feed grown on sludge-amended soils.

At Werribee Farm in Melbourne, Australia, cattle are grazed on wastewater-irrigated pastures and show higher organ levels of cadmium and chromium than farm cattle grazed on nonirrigated pastures, although elevated levels were within the range common to cattle in general (Croxford, 1978). Organ levels of lead, however, did not increase, in spite of lead increases in both soil and pasture plants. Dowdy, et al. (1983) fed silage grown on sludge-amended soils to goats and sheep for a period of three years. The silage contained up to 5.3 mg cadmium/kg, a concentration 10 or more times greater than normal silage. Cadmium and zinc were elevated in the kidney and liver but not in the muscle tissue. Concentrations of copper, nickel, chromium, lead and zinc in organs of animals fed silage from sludge-amended soils did not differ from animals fed a similar diet of forage from lands not receiving sludge. The concentrations of cadmium in the milk of goats that were fed the treated silage did not differ from controls (Dowdy et al., 1983). Telford et al. (1984) also reported that the concentration of cadmium in milk from goats fed silage from sludge-amended soils over a period of 135 days did not differ from the controls. Silage from the sludge-amended soils contained up to 3.8 mg cadmium/kg; control silage contained 0.14 mg cadmium/kg. Concentrations of cadmium in the livers of adult goats fed silage from the sludge-amended soils were significantly greater than the controls.

Studies of the accumulation of trace elements in cattle grazed on sludge-amended pastures have revealed elevated levels in liver and kidney, but not in muscle tissue (Bertrand et al. 1981a, Baxter et al. 1983). Sheep grazing on sludge-amended pasture had no statistically significant increases in tissue levels of cadmium (Hogue et al. 1984). Bertrand et al. (1981b) observed no increases in metal concentration of cattle fed sorghum grown on sludge-amended soil nor did increases occur in tissues of mice or guinea pigs fed lettuce and Swiss chard grown on sludge-amended soil (Chaney et al., 1978a,b). Other studies, however, have shown significant increases of cadmium in kidney and liver, but not in muscle tissue of animals fed sludge-fertilized crops (Hansen and Hinesly, 1979; Lisk et al., 1982; Hinesly et al., 1984; Bray et al., 1985; Hogue et al., 1984). Trace element levels and disease conditions of cattle grazing on land reclaimed using Chicago sludge have been observed by Fitzgerald et al. (1985) for up to eight years; they concluded that little risk to man or animals is associated with land application of anaerobically digested wastewater sludge. All cattle remained healthy and no pathological changes could be attributed to sludge.

Based on these studies, it appears that trace elements either do not accumulate or accumulate in very small quantities in animal muscle tissue. However, cadmium and other metals do accumulate in the liver and kidneys of animals.

The current state of knowledge allows the following generalizations to be made: Elements potentially harmful to consumers which may accumulate in crops include cadmium (humans, animals), molybdenum (animals), and selenium (animals). Cadmium accumulates in the liver and kidney of animals fed crops grown on sludge-amended soils. Although levels of cadmium in foods grown on sludge-amended soil are elevated, there are no documented cases of human or animal poisoning from this source.

NONSPECIFIC HEALTH EFFECTS OF SLUDGE AND WASTEWATER

Although a large number of organic and inorganic constituents of sewage have been identified in the Priority Pollutants list and additions as discussed above, some of the residual fraction that is unidentified may have nonspecific human health effects. Investigations of non-specific or general health effects normally consist of research on non-human organisms as explained below.

Nonspecific toxicological testing of whole reclaimed water using the Ames Salmonella Microsome Mutagen Assay and the Mammalian Cell Transformation Assay have been used to indicate the potential of mutagenic, cytotoxic, and carcinogenic effects on bacterial and mammalian cells (Nellor et al., 1984). Clevinger et al. (1983) performed bioassays on five sludges using the Ames test and found that none had significant mutagenic effects. In another large study where concentrated reclaimed wastewater was given to several species of test animals for two years, no acute or chronic health or developmental effects were found (Lauer, 1993). The latter study is of particular interest because of its thoroughness. The National Research Council (1982) concluded that the "ultimate" evaluation of health effects of reclaimed wastewater used for drinking water purposes must come from studies on whole animals. Furthermore, because of the difficulty of reliable interpretation of results of bioassay studies using single compounds isolated from wastewater, test animals should be exposed to concentrates of the whole reclaimed water.

Accordingly, in a two-year animal effects testing study of reclaimed wastewater for potable reuse, the Denver Water Department compared reclaimed wastewater with Denver municipal drinking water in tests administered to animals as drinking water (Lauer et al., 1990). Matched groups of Fischer 344 rats and $B_6C_3F_1$ mice were used to test for acute and chronic (including carcinogenic) health effects over the 104-week study, and Sprague-Dawley rats were used for a two-generation reproductive toxicity study. The results of chronic toxicity/ carcinogenic studies of both rats and mice showed no significant differences in clinical pathology (hematology, clinical chemistry, and urinalysis) and gross pathology. Similarly, no significant difference were found in the formation of neoplasms between reclaimed water-fed mice and rats and controls fed both treated drinking water and distilled water. Finally, there were no demonstrated effects from the ingestion of reclaimed water on reproductive performance, fetal development, offspring survival or growth during the two-year reproductive study (Lauer, 1993).

A number of studies have been conducted on the effects of feeding sewage sludges to animals either directly or where animals have ingested sewage sludge that was sprayed on forage. Where cattle were fed up to 12 percent of their diet from sludge for 94 days, or 6 percent of their diet for 141 days, no adverse health effects were noted (Keinholz et al., 1979; Bertrand et al., 1981a). No adverse effects were noted when baby pigs were raised on a diet consisting of 5 percent sludge for a period of one month (Firth and Johnson, 1955). Rats and Japanese quail fed diets with 30 percent sludge 2 weeks showed no adverse health effects (Cheeke and Meyer, 1973). Baby chicks consuming a diet consisting of 10 percent sludge for about one month showed no adverse health effects (Firth and Johnson, 1955); where 20 percent of the diet of birds came from sludge, however, body weight gain and liver vitamin A were found to be reduced (Keinholz, 1980). In a four-year study, where 7 percent of the dry matter of the diet of breeding ewes consisted of sludge sterilized by gamma irradiation, Smith et al. (1985) reported no accumulation of hazardous levels of toxic elements and little, if any, evidence of toxicity. Johnson et al. (1981) fed Hereford steers a diet that included 11.5 percent sewage sludge and observed retention of dietary cadmium, mercury and lead to be 0.09 percent, 0.06 percent and 0.3 percent, respectively. Concentrations of these elements in the liver and kidneys of steers were found to increase from 5- to 20-fold following sludge ingestion. The authors' data showed that less than 0.3 percent of the sludge-fed cadmium, mercury, and lead were retained by the cattle. These data indicated that cattle are a moderately effective screen against entry of toxic elements from sludge into the human food chain. Damron et al. (1982) substituted 7 percent sludge in the diet of white Leghorn hens for a period of 84 days and observed no effect on bird performance; egg production was unaffected and no increase in cadmium was found in the eggs.

Keinholz (1980) cited a study of PCBs in cabbage grown on sludge-amended soil that was reportedly linked to degenerative changes in liver and thyroid of sheep (Haschek et al., 1979, cited by Keinholz, 1980). However, the study involved cabbage grown in sludge that contained 17 mg/kg PCBs, an unusually high concentration and about twice the maximum observed in the NSSS. Adding this sludge to soil at an agronomic rate would result in a PCB concentration in soil of less than 0.1 mg/kg in the surface 20 centimeters. Therefore, it is unlikely that sludge containing even this high a concentration of PCBs would be harmful if applied to agricultural land according to present-day regulations and guidelines.

Hansen et al. (1976) studied young swine fed for 56 days on corn grown on sludge-fertilized land. Electroencephalograms, electrocardiograms, clinical chemistry, and histopathology were all normal. However, they did observe elevated levels of hepatic microsomal mixed function oxidase (MFO) activity. This increased MFO activity may have been caused by toxic organics and inorganic trace elements in the sludge, and the authors concluded that further study should be performed before such grain can be recommended as the major dietary component for animals over long periods.

An epidemiologic study on human exposure to pathogens in sludge compared health effects in 164 people living on 47 farms which received 2 to 10 tons of sludge per ha per year for three years to 130 people from 45 farms who formed a control group. Both study groups were from geologically matched areas of rural Ohio. Study participants answered monthly surveys and had annual tuberculin testing and serological tests of quarterly blood samples. In addition, monthly surveys included questions about farm animals' health. It was found that there were no significant differences in the health of those living on farms where sludge was applied compared to the control group with respect to respiratory or digestive illness or other reported physiological symptoms. Similarly, no differences were reported between domestic animals from sludge-amended versus control farms (Brown et al., 1985).

SUMMARY

A review of the literature for toxic organics and for inorganic trace elements in treated municipal wastewater effluents or treated sewage sludge indicates that most of these chemicals are either not transferred from soil to plant tissues or that translocation to edible tissues does not reach levels harmful to consumers under normal agricultural conditions.

With regards to human health concerns about the use of treated sludge on crops, the inorganic chemical considered to be of greatest concern is cadmium. This conclusion is consistent with the policy approach taken to minimize health risks due to chemicals from land application of sewage sludge.

Research on the bioavailability of toxic organic compounds to plants indicates that the risk to humans consuming food crops grown on soils amended with sludge is negligible. Toxic organic compounds are typically present at such low concentrations and/or are largely not bioavailable to plants, that they would accumulate only at very low concentrations, if at all, in edible portions of plants.

Few adverse health effects have been found in studies where treated sludge and treated effluent were fed directly to animals. No adverse human acute or chronic toxicity effects have been reported resulting from ingestion of food plants grown in soils amended by sludges or crops irrigated by reclaimed water.

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7

Regulations Governing Agricultural Use of Municipal Wastewater and Sludge

Government regulations at both the federal and state levels develop within a complex set of circumstances. To fully understand them, regulations must be examined in terms of the regulatory approach taken, the underlying scientific principles that are applied, the objectives of the regulation, and the effectiveness of implementation. The following section begins with a discussion of the regulatory background for agricultural use of municipal wastewater and sludge. Current federal standards for control of pathogens and toxic chemicals in sludge use are then described and evaluated. Finally, state regulations and United States Environmental Protection Agency (EPA) guidelines for agricultural irrigation with treated effluents are discussed.

The implementation of wastewater and sludge reuse programs also involves other regulatory components, including program management, surveillance, and enforcement. Economic considerations, liability issues, and public concerns will likewise play a role. These implementation issues are considered in Chapter 8.

REGULATORY BACKGROUND

Agricultural Irrigation with Wastewater

Irrigation of crops with treated effluent and farmland application of sewage sludge have been conducted without federal regulations for decades in the United States. Early regulations by states addressed infectious disease transmission and the reduction of odor. Wastewater irrigation continues to be regulated at the state level, and those states (such as Arizona, California, Florida, Hawaii, and Texas) that have active water reuse programs have developed comprehensive, numerical water quality criteria for different water uses, including crop irrigation. Pathogen reduction continues to be the major concern, and microbiological limits for treated effluents are based largely on practical experience within the public health community, and on the expected performance of wastewater treatment processes. There have been no reports of infectious disease associated with agricultural reuse projects, and existing criteria are considered to be adequate (see Chapter 5). Most states distinguish between produce (or crops that can be eaten raw) from crops that are commercially processed or cooked prior to consumption, and require more stringent water quality levels for produce crops.

Nevertheless, states differ in the manner in which wastewater irrigation can be implemented. For example, California, with the longest history of regulating reclaimed wastewater for agricultural use, permits high-quality effluents to be used on produce crops. Florida normally restricts the agricultural use of reclaimed water to those food crops that are skinned, cooked, or thermally processed before consumption (EPA, 1992).

Chemical pollutants in treated municipal wastewater have not been targeted by state regulations for reclaimed water. This is because the concentrations of these pollutants in effluents that receive a minimum of secondary treatment are comparable to those in conventional sources of irrigation water, and the reclaimed water generally meets current irrigation water quality criteria (e.g., Wescot and Ayers, 1985) for chemicals that are potentially harmful to crop production or to ground water contamination (see Chapters 2 and 4 for further discussion). Source control of industrial inputs, conventional secondary treatment, and advanced treatment are relied upon to reduce effluent concentrations of chemical pollutants to levels that do not impact the particular end use.

Agricultural Use of Sewage Sludge

Sewage sludges are recognized as potentially harmful because of the chemical pollutants and the disease-causing agents they may contain. Prior to the early 1970s, there was no direct legislative authority for any federal agency to regulate sludge disposal. In 1972, Congress directed EPA to regulate the disposal of sludge entering navigable waters through Section 405(a) of the Federal Water Pollution Control Act. The Resource Conservation and Recovery Act (RCRA) of 1976 (P.L. 95–512) exempts sewage sludge from hazardous waste management regulation in cases where industrial discharges to the publicly owned treatment plant (POTW) are already regulated under EPA-approved pretreatment programs. In 1977, Congress amended section 405 of the Federal Water Pollution Control Act to add a new section, 405(d), that required EPA to develop regulations containing guidelines for the use and disposal of sewage sludge on land as well as in water. These guidelines were to (1) identify alternatives for sludge use and disposal; (2) specify what factors must be accounted for in determining the methods and practices applicable to each of the identified uses; and (3) identify concentrations of pollutants that would interfere with each use. Federal criteria (40 CFR Part 257) identifying "acceptable solid waste disposal practices—including landfill and land application—were issued in 1979 under the joint authority of RCRA (Subtitle D) and the Clean Water Act (Section 405). These criteria specified limits on cadmium in sludge and soil pH levels, limited the soil incorporation of sludges with greater than 10 mg/PCB/kg, and contained criteria for pathogen reduction. However, these criteria for sludge use and disposal were not widely used.

In 1987, Congress once again amended Section 405 to establish a timetable for developing technical standards for sewage sludge use and disposal (Water Quality Act of 1987, P.L. 100-4). Congress directed EPA to identify toxic pollutants that may be present in sewage sludge in concentrations that may affect public health and the environment, and to specify acceptable management practices and numerical limits for sludge that contain these pollutants.

These regulations were to be "adequate to protect the human health and the environment from any reasonably anticipated adverse effect of each pollutant." (Section 405(d)(2)(D)). Section 405 was also amended to specify that technical standards for sludge use and disposal be included in any permit issued to a POTW or other treatment works. The final "Standards for the Use and Disposal of Sewage Sludge" were promulgated in 1993 by the EPA (40 CFR 503, EPA, 1993a) and are referred to as the "Part 503 Sludge Rule" in this report.

FEDERAL STANDARDS FOR THE CONTROL OF PATHOGENS IN SEWAGE SLUDGE

Standards and management practices for the reduction of pathogens to acceptable levels prior to human or animal contact and vector attraction reduction are major aspects of the Part 503 Sludge Rule. Based upon pathogen reduction criteria, the Rule divides sludge into two categories, Class A (safe for direct contact) and Class B (land and crop use restriction supply). Class A sewage sludge can be used in an unrestricted manner. Class A pathogen requirements (shown in Table 7.1) must be met by one of six alternatives and use of either the fecal coliform or salmonella tests as described below.

In Part 503, all Class A sludges must meet either a fecal coliform limit of less than 1,000 fecal coliform/g dry weight of solids or a measure of less than 3 salmonella/4 g dry weight of solids (EPA, 1993a). As discussed in Chapter 5, the threshold of 1,000 fecal coliform/g dry weight appears reasonable given that all evidence points to equal or greater resistance of fecal coliforms in comparison to other common bacterial pathogens such as salmonella. When the numbers of fecal coliforms in raw sludge are in the range of 10,000,000/g, then the reduction to 1,000/g would indicate a similar rate of reduction in bacterial pathogen numbers. For example, the concentration of salmonella in raw sludge is estimated to be 2,000/g of solids; thus, a five log10 reduction would reduce the salmonella level to approximately 2/100 g of solids. In a comparison of the relationship between fecal coliform and salmonella numbers, Yanko (1988) described this same relationship.

Because of the small sample size and interference by large numbers of nonsalmonella bacteria, the method prescribed for salmonella in Part 503 is apt to underestimate the number present in any given sludge sample (also see Yanko et al., 1995). The chances of finding 3 salmonella in 4 g of sludge is much less than those of finding 1,000 fecal coliforms in 1 g. This may be of some concern when the salmonella determination is used in lieu of the fecal coliform assay. As stated in the Rule, to be classified as Class A, all sludges must meet either the fecal coliform or the salmonella requirement. Because standard salmonella determination methods as now practiced are not precise, there may be a temptation to use the salmonella test in lieu of the coliform test, regardless of the regrowth potential in the sludge.

In certain Class A processed sludges, fecal coliform regrowth may occur, in which case the sludge might not meet the fecal coliform requirement, but the sanitary significance of the numbers would be unclear. In this instance the Part 503 Sludge Rule allows for the direct determination of salmonella, and if their concentration is less than 3 salmonella/4 g dry weight of sludge, the Class A classification would hold. Until such time as more accurate salmonella detection methods are developed, it would be expedient to use the salmonella test only after coliform

TABLE 7.1 Summary of Part 503 Sludge Rule Pathogen Limits For Class A Sludge

All Class A sludges must meet:	fecal coliform density of < 1,000 MPN[a]/gram total solids.[b]
	or
	Salmonella sp. density of < 3 MPN/4 grams total solids.
Plus one of 6 alternatives:	
#1	Time and temperature requirements specified, depending on solids content of sludge.
#2	Alkaline and temperature treatment requirements: pH > 12 for at least 72 hours. Temperature > 52^{1}C for at least 12 hours, then air dry sludge to < 50% total solids.
#3	Level of enteric virus and helminth ova prior to pathogen treatment are < 1 PFU[c]/4 grams total solids for virus and < 1 viable ova/4 grams total solids for helminth ova.
	or
	If levels of enteric virus and/or helminth ova prior to pathogen treatment are < 1 PFU or if viable ova are present, then test after treatment. Document process operating parameters to achieve < 1 PFU/4 grams total solids for virus and < 1 viable ova/4 grams total solids for helminth ova.
#4	Levels of enteric virus and helminth ova after treatment and when ready to distribute are < 1 PFU/4 grams total solids for virus and < 1 viable ova/4 grams total solids for helminth ova.
#5	Use of *Process to Further Reduce Pathogens* (PFRP). See requirements for composting, heat drying, heat treatment, thermophilic aerobic digestion, beta ray irradiation, gamma ray irradiation, and pasteurization.
#6	Treat equivalent to PFRP requirements. Determined by the permitting authority.

[a] MPN: Most Probable Number
[b] all weights are dry weights
[c] PFU: Plaque Forming Units
SOURCE: EPA, 1993b

regrowth or regrowth potential has been determined, and not as an alternative to the fecal coliform method for determining pathogen levels in all sludges.

In addition to the fecal coliform or salmonella test, there are six alternative requirements for achieving a Class A sludge status (Table 7.1). These can be summarized as: (1) use of specified application of time and temperature; (2) use of heat and elevated pH; (3) and (4) the demonstration of the absence of viable helminth ova and enteric viruses either before or after some form of treatment; and, (5) and (6) an accepted process to further reduce pathogens (PFRP) or equivalent. The Part 503 Sludge Rule states that all the alternatives are of equal value in that they will meet, as a minimum, the pathogen standard set forth in alternatives (3) and (4).

At the present state of our knowledge, Class A microbial standards or process standards for sludge appear to be adequate for public health protection. However, when relying on the direct measurement of pathogens, one should be aware of the accuracy and precision of the methods that are presently available. The standard may be quite adequate but the method used to determine if the standard has been met can be questionable (Cooper and Riggs, 1994).

Part 503 describes "Class B" as sludge having lesser sanitary quality than Class A at the time of application. This class of sludge is applied to land under a variety of restrictions. There are three alternative requirements that must be met to qualify a sludge as Class B. The first alternative requires a domestic sludge to contain a geometric average fecal coliform level of less than 2,000,000 bacteria most probable number (MPN)/g dry weight based on seven samples. Most wastewater and sludge treatment practices can attain this fecal coliform level. A second alternative for meeting Class B requirements is to use designated sludge treatment processes to significantly reduce pathogens (PSRP). Processes that meet PSRP criteria will, as a minimum, meet the coliform requirement of 2,000,000/g.

In addition to the above quality or process requirements, land use restrictions are also required for the application of Class B sludge. These restrictions are summarized in Table 7.2, and their rational is based on the time required to significantly reduce the number of helminth ova. Helminth ova are among the most environmentally resistant of the infectious agents, and the time required for their reduction would be more than sufficient for the reduction of bacterial and viral pathogens. The Part 503 Sludge Rule requires a 20-month time period to elapse prior to harvesting root crops and a 14-month time period before harvest of other crops that touch the ground. These criteria are based on data developed by the EPA (EPA, 1993b) that indicate a "relatively high rate of die-off of helminth ova on the soil surface" within these time periods. Lawn turf is land with a high potential for human contact, and Feachem et al. (1983) consider a year to be a sufficient waiting period to provide adequate protection to the public from ascaris infection in this context. The 30-day restriction for nonroot or aboveground crops, feed, and fodder was considered to be adequate for the protection of public and animal health.

The analysis for the Part 503 Sludge Rule predicts greater risks to those exposed to runoff water (e.g., from swimming) than for other pathways. Because of this concern, Part 503 urges that drainage be carefully managed. The model also predicted a greater risk to onsite workers during the initial time period of application. The greatest onsite risk calculated was 0.02 infections per 100,000 (EPA, 1993b). It should be kept in mind that the number of individuals exposed onsite is relatively small and thus the occurrence of infection would be limited.

The beef tapeworm, *Taenia sarginata*, and the pork tapeworm, *T. solium* , are the primary human pathogens of concern in the application of Class B sludge to fodder or grazing land. According to Feachem et al., (1983) and the EPA model, 30 days should be a sufficient period of time for destruction of these ova; however, a more recent investigation in Denmark (Ilsole et al., 1991) indicated that a small proportion of the ova remained viable for 5 to 6 months and were nonviable by the end of 8 to 10 months of soil exposure.

The pathogen criteria for the application of Class B sludge to land is based on information from the available literature and, with the exception of the waiting time criteria for fields to be used for fodder and grazing, appear to conform to that literature. Although concern is based only on a single report (Ilsole et al., 1991), it does create a reservation that should be

TABLE 7.2 Class B Sludge Application-Land Use Restrictions

Food crops that touch sludge or soil	Harvest after 14 mos. of sludge application
Root crops	Harvest after 20 mos. if 4 mos. elapse prior to planting
Other food, feed or fodder	Harvest after 30 days of sludge application
Grazing	No grazing prior to 30 days after sludge application
Lawn turf	Harvest after one year of sludge application
Public access to land - high access potential	one year waiting period prior to access
Public access to land - low access potential	30 day waiting period prior to access

addressed. In this country, we depend on consumer cooking of meat to destroy any helminthcysts, including trichina worms in pork. Managing the disposal of human waste to grazing land and meat inspections provide additional controls. Generally, the fewer viableeggs of *Taenia* species allowed on grazing land, the better; however, the actual risk of a too short waiting period may not be measurable.

As stated previously, the reliability of any sludge treatment process in reducing pathogens to acceptable levels is paramount for public health protection. There are many variables, such as pH, moisture, sunlight, temperature, and indigenous microflora, that are involved in the decay of pathogens in the soil environment. Class B applications rely on these natural processes for public health protection. Because of the number of uncontrollable variables, one might assume less reliability in pathogen reduction than in the case of most Class A sludge applications. In this regard the use of Class B solids on fields used to grow for crops for human consumption, particularly those eaten raw, may present a greater risk than does the use of Class A materials. The absolute degree and impact of this increased risk on public health cannot be determined but, at the present state of our knowledge and experience, the difference in infectious disease risk appears to be imperceptible.

A second public health aspect of sewage sludge management is the potential for vector attraction, although this aspect of the Part 503 Sludge Rule has not been evaluated in this study. Vectors are animals involved in the transmission of infectious diseases to humans. In the case of sludge disposal, there is particular concern with insect vectors that might be attracted to the disposal site as a result of management practices. The Part 503 Sludge Rule recognizes this potential and has made provisions for vector attraction and nuisance reduction.

APPROACHES TO TOXIC CHEMICAL REGULATION IN SLUDGE AND WASTEWATER LAND APPLICATION

Philosophically, pollutant inputs to soils through land application of wastewater and sewage sludge may be regulated through two approaches (Chang et al. 1993). One approach is to prevent toxic chemical pollutants from accumulating above natural background levels in the soils. Another approach is to allow pollutants to accumulate so long as the soil capacity for assimilating, attenuating, and detoxifying the pollutants is adequate to minimize the risk to humans, agricultural crops, and the environment.

The part 503 Sludge Rule is based on the second approach, whereas regulations in several European nations, such as Holland and Norway, are based upon the first. McGrath et al. (1994) reviewed regulations controlling pollutant inputs via land application of municipal sludges in the United States and in Western Europe and compared the benefits and disadvantages of each approach. While the scientific principles of these two approaches are both valid, the numerical limits on toxic chemicals derived from each approach may vary by orders of magnitude.

Preventing Toxic Chemical Pollutant Accumulation in Soils

The underlying objective of this approach is to preserve a soil's current condition and to avoid an accumulation of pollutants from long-term applications of sludge and wastewater. This approach aims to prevent an increase in the concentration of pollutants based on the assumption that any increase in pollutants would compromise the soil's ability to support a productive microbial and botanical population and limit its potential use. A land application regulation based on this approach strives to prevent pollutant accumulation in the soil from exceeding levels that exist before sludge or wastewater effluent is applied.

To meet this objective, pollutant input from applications of wastewater or sludge and other sources must be balanced by pollutant output via surface runoff, leaching, atmospheric loss, and plant uptake followed by removal. In soils, pollutant output is typically very low. Consequently, the pollutant loading from all sources including land application of wastewater and sewage sludge must also be very low in order to maintain the balance and prevent any net accumulation. Regulations and guidelines that employ this principle must set very stringent toxic chemical pollutant loading limits for soils that can only be met by preventing all toxic chemical pollutants from entering wastewater collection and treatment systems, or by requiring the use of advanced levels of treatment to physically strip pollutants out of the effluent or sludge prior to land application. Otherwise, the sludges or effluents have to be applied at very low rates to prevent no net change in the pollutant concentration in the soil.

One advantage of this approach is that detailed knowledge about the fate and transport of pollutants, exposure analysis, and dose-response relationships is not necessary. The numerical limits for pollutants may be calculated by simple mass balances (pollutants in sludge and/or wastewater=pollutants transported out of soil system via surface runoff, leaching, atmospheric loss and removal by harvested plants) and this relationship can be applied to any location. However, the disadvantages are twofold: (1) meeting the numerical limits can be very costly, and (2) the allowable application rates are too low to provide any nutrient value.

Allowing Pollutant Accumulation in the Soil

The premise of this approach is that advantage can be taken of the beneficial qualities (moisture, organic matter and nutrients) of sludges and wastewater and of the capacity of soil to attenuate toxic chemical pollutants present in the sludges or wastewater. Soil is a dynamic medium consisting of mineral fragments, organic matter, biota, water, and air. Pollutants introduced into soil are subject to physical, chemical and biological transformations. Consequently, pollutants introduced to soil in low amounts may not have an immediate deleterious effect. Over time, such pollutants will accumulate and when a specific concentration is reached, harmful effects can occur. This knowledge can be used to properly manage cropland application of treated effluents and treated sludge so that the accumulation of chemical pollutants in the soil does not reach levels that harm exposed individuals or the environment. Under this scenario, agronomic benefits of wastewater and sewage sludge may be realized without harming soil quality, public health, and the environment.

This approach entails developing maximum permissible pollutant loading limits and/or maximum permissible pollutant concentration for the soil. It necessitates a more complete understanding of pollutant chemistry, health hazards, pathways to exposure, and sophisticated modeling techniques.

DEVELOPMENT OF U.S. CHEMICAL POLLUTANT STANDARDS FOR AGRICULTURAL USE OF SEWAGE SLUDGE

The part 503 Sludge Rule defines the domain within which sewage sludges may be safely disposed or beneficially used (EPA, 1993a). The sludge management options addressed by this regulation include agricultural land application, nonagricultural land application, sludge-only landfills, surface disposal, and incineration. This report is concerned with agricultural land application of sludge. For this use, the regulation sets numerical limits on cumulative loadings for certain pollutants, defines the sludge- processing requirements necessary to control pathogens and parasites, and outlines an implementation plan. Requirements for nonagricultural land application, including home or horticultural use, are derived from the requirements for agricultural land application.

EPA used a risk assessment approach to develop the standards for chemical pollutant limits in the Part 503 Sludge Rule. In performing the assessment, EPA followed a framework presented by the National Research Council (NRC, 1983). EPA's approach is premised on the condition that chemical pollutants will accumulate in the soil with each application of sludge. The risk assessment considers pollutant transport through various environmental exposure pathways, and has the objective of setting maximum pollutant loading limits and minimum sludge quality requirements for cropland application of sewage sludge. EPA's analysis focused on those chemicals that are resistant to degradation and may be incorporated into food crops, or animal feed, or ingested by grazing animals. EPA also considered human exposure that can occur through direct ingestion of sludge-amended soil. This last pathway was assessed by EPA based on the residential use of packaged sludge-derived material where infants may ingest the dirt, and it is outside the scope of this report. A general description of a risk assessment approach is briefly presented below, after which EPA's specific approach is explained and evaluated.

General Approach to Risk Assessment

The method for performing a risk assessment, as outlined by the NRC (1983), consists of four steps: (1) hazard identification, (2) dose-response evaluation, (3) exposure evaluation, and (4) characterization of risks.

Hazard Identification

The first step in the risk assessment process—hazard identification—is to determine the nature of the effects that may be experienced by a human exposed to an identified pollutant and whether evidence of toxicity exists sufficient to warrant a quantitative risk assessment. Data are gathered on a specific pollutant and qualitatively evaluated based on the type of health effect produced, the conditions of exposure, and the metabolic processes that govern pollutant behavior within the human body or other organism studied. It may also be necessary to characterize the behavior of the pollutant in the environment. Thus, hazard identification helps to determine whether it is scientifically appropriate to infer that effects observed under one set of conditions (e.g., in experimental animals) are likely to occur in other settings (e.g., in human beings), and whether data are adequate to support a quantitative risk assessment. The following two sections discuss how such quantitative assessments are conducted.

Dose-Response Assessment

The second step in the risk assessment process is estimating or evaluating the dose-response relationships—what "dose" of a chemical produces a given "response"—for the pollutant under review. Evaluating dose-response data involves quantitatively characterizing the connection between exposure to a pollutant (measured in terms of quantity and duration) and the extent of toxic injury or disease. Most dose-response relationships estimates are based on animal studies, because even good epidemiological studies rarely have reliable information on human exposure. In this context, two general approaches to dose-response evaluation are used, depending on whether the health effects are based on threshold or nonthreshold characteristics of the pollutant. "Threshold" refers to exposure levels below which no adverse health effects are assumed to occur. Effects that involve altering genetic material (including carcinogenicity and mutagenicity) may take place at very low doses; therefore, they are modeled with no thresholds. For most other biological effects, it is usually, but not always, assumed that threshold levels exist.

Exposure Evaluation

Exposure evaluation estimates environmental concentrations of pollutants. The severity of the exposure is then assessed by evaluating the nature and size of the population exposed to the pollutant, the route of exposure (i.e., oral, inhalation, or dermal), the extent of exposure (concentration times duration), and the circumstances of exposure.

Risk Characterization

In the final phase of a risk assessment, the risk characterization, information on the range of exposures and risks and on all major uncertainties, along with their influence on the assessment, and presented.

EPA's Risk Assessment Approach

Hazard Identification

EPA initially developed environmental profiles and hazard indices on 50 pollutants that were selected by a group of experts convened by EPA in 1984 (EPA, 1993). Of those 50 pollutants, 22 (10 metals and 12 organics) were selected, through a screening process, for regulation in the 1989 proposed rule for land application (Federal Register, 1989). These 22 pollutants are listed in Table 7.3.

After the proposed rule was issued, EPA completed a National Sewage Sludge Survey (NSSS) (EPA, 1990). The NSSS sampled sludge from 209 sewage treatment plants throughout the country to produce national estimates of concentrations of toxic pollutants in sewage sludge.

Using the NSSS data and information from the risk assessment, EPA conducted a further screening analysis to eliminate from regulation any pollutant that was not present in concentrations that posed a significant public health or environmental risk. Based on this screening analysis, 12 organic chemicals were deleted, leaving 10 inorganic chemicals for regulation by the Part 503 Sludge Rule. The criteria used to remove organic pollutants from the rule is discussed below.

Three screening criteria were used to assess the need for regulating the 12 organic pollutants that were part of the original 22 pollutants identified in the proposed rule. If a pollutant satisfied any one of the criteria below, it was exempted from regulation in Part 503. The three criteria were described as follows:

- The pollutant has been banned for use, has restricted use, or is no longer manufactured for use in the United States.
- The pollutant has a low frequency of detection in the sewage sludge (less than 5 percent), based on data from the NSSS.
- The concentration of the pollutant in sewage sludge is already low enough that the estimated annual loading to cropland soil would result in an annual pollutant loading rate within allowable risk-based levels.

Based on these criteria, EPA exempted all of the organic pollutants under consideration. The pollutant loading used for the third criterion is based on the quantity of sewage sludge that would be applied at agronomic rates and using the sludge pollutant concentration equal to the

TABLE 7.3 Pollutants Selected for Initial Hazard Identification Analysis

Inorganic Chemical Pollutants	Organic Chemical Pollutants
Arsenic	Aldrin/Dieldrin
Cadmium	Benzo(a)Pyrene
Chromium	Chlordane
Copper	DDT/DDD/DDE
Lead	Dimethyl nitrosamine
Mercury	Heptachlor
Molybdenum	Hexachlorobenzene
Nickel	Hexachlorobutadiene
Selenium	Lindane
Zinc	Polychlorinated biphenyls (PCBs)
	Toxaphene
	Trichloroethylene

SOURCE: EPA, 1993b.

99th percentile value of the NSSS (EPA, 1993b, Appendix B). Table 7.4 lists the criteria by which each pollutant was screened.

Exposure Assessment

The exposure assessment analyzed 14 pollutant transport pathways (Table 7.5) in agricultural land application of sewage sludge. Of primary relevance to the committee's assessment of human health impacts were the three pathways that involved crop consumption. The other pathways traced effects of digestion of soil on livestock, plants, soil biota, soil biota predators, and human-health. At the end of each pollutant transport pathway, there is an exposed subject who is the receptor of the pollutant. For each pathway, the exposed subject represents the segment of the exposed population that is most susceptible—the "highly exposed individual" (HEI).

The maximum tolerable exposure for the HEI was set equal to the risk reference dose (RfD) corresponding to a risk level of 10^{-4} for known carcinogenic chemicals and equal to the recommended daily allowance (RDA) for non-carcinogenic chemicals. EPA traditionally establishes standards within a range of 1×10^{-7} to 1×10^{-4}, depending on the statute, surrounding issues, uncertainties, and information bases. EPA chose a carcinogenic risk target of 1×10^{-4} for the use of sewage sludge in the production of agricultural crops because EPA's analysis did not indicate a significant aggregate populational carcinogenic risk from this practice, and because of the conservative assumptions built into the HEI approach (EPA, 1993a).

For the purposes of the Part 503 Sludge Rule, models were developed to determine the maximum amount of pollutant that could be added to the soil (otherwise known as a "pollutant loading") that would not cause undue risk. This analysis produced 14 pollutant loadings—one for each pathway—for each of the pollutants evaluated. The smallest value of all pathways was selected as the maximum permissible loading for each pollutant. This value, termed "cumulative

TABLE 7.4 Results of Screening Criteria for Organic Pollutants Considered for Part 503 Sludge Regulations

Pollutants	Pollutant is Banned in United States	Pollutant has < 5% Detection Frequency in the NSSS	Does Not Exceed Risk Assessment Criteria from 99th percentile in NSSS
Aldrin/Dieldrin (total)	x		x
Benzo(a)Pyrene		x	
Chlordane	x	x	x
DDT/DDE/DDD (total)	x	x	x
Heptachlor	x	x	x
Hexachlorobenzene		x	
Hexachlorobutadiene		x	x
Lindane	x	x	x
N-Nitrosodimethylamine	x	x	
PCBs	x		
Toxaphene	x	x	x
Trichloroethylene		x	x

pollutant loading rate," sets the total allowable level of sludge-borne pollutant that can be added to the soil and still maintain an acceptable level of exposure to the HEI from the most sensitive pathway. The analysis treats all pathways as equal so that adverse effects on livestock animals, plants, and soil biota are weighed equally to those on humans. In other words, if a limiting pathway for a pollutant is one in which the HEI is a plant, the numeric limit for the pollutant is more restrictive than necessary to protect a human because the plant is more sensitive than the human. The limiting pathway for each of the 10 pollutants regulated and their corresponding HEIs are listed in Table 7.6. It is important to note that none of the limiting pathways involve the human consumption of crops grown in sludge-amended soils.

TABLE 7.5 Exposure Assessment Pathways

Pathway Numbers	Pathway
1	Sludge-soil-plant-human
2	Sludge-soil-plant-home gardener
3	Sludge-soil-child
4	Sludge-soil-plant-animal-human
5	Sludge-soil-animal-human
6	Sludge-soil-plant-animal
7	Sludge-soil-animal
8	Sludge-soil-plant
9	Sludge-soil-soil biota
10	Sludge-soil-soil biota-predator of soil biota
11	Sludge-soil-airborne dust-human
12	Sludge-soil-surface water-fish-human
13	Sludge-soil-air-human
14	Sludge-soil-ground water-human

Risk Characterization

EPA established cumulative pollutant loading rates for 10 inorganic elements (Table 7.7). These rates represent the maximum amount of a pollutant that can be uniformly applied to a hectare of land and still provide acceptable protection to the HEI.

To provide flexibility in applying sludges and to expedite the use of sewage sludge in nonagricultural land application, several variations in pollutant loading limits were derived from the risk-based cumulative pollutant loading rates. These alternative limits are described below and include pollutant concentration limits, ceiling concentration limits for pollutants, and annual pollutant loading rates. Recordkeeping and management requirements for sludge will vary depending on which set of limits are used (in addition to any requirement based on the pathogen levels as earlier discussed).

TABLE 7.6 Most Limiting Pathway for Pollutants Regulated in CFR Title 40, Parts 503

Pollutant	Highly Exposed Individual (HEI)	Limiting Pathway Number
Arsenic	Sludge eaten by child	3
Cadmium	Sludge eaten by child	3
Chromium	Phytotoxicity	8
Copper	Phytotoxicity	8
Lead	Sludge eaten by child	3
Mercury	Sludge eaten by child	3
Molybdenum	Animal eating feed	6
Nickel	Phytotoxicity	8
Selenium	Sludge eaten by child	3
Zinc	Phytotoxicity	8

Pollutant Concentration Limits To derive pollutant concentration limits, EPA assumes that the life span of a land application site is no more than 100 years and that the annual sludge application rate is less than or equal to 10 metric tons/ha (an agronomic rate for a typical sludge that would provide adequate available nitrogen for a number of crops). In this case, the sludge application rate at a given site will not exceed 1,000 metric tons/ha. The risk-based, cumulative pollutant loading rate (kg of pollutant/ha for the life span of the application site) is then uniformly distributed among 1,000 metric tons of sludge/ha, and a maximum permissible pollutant concentration (in kg of pollutant/ton of sludge or in mg of pollutant/kg of sludge) was calculated. This value was then compared to the 99th percentile concentration value for the pollutant from the NSSS and the more stringent of the two was determined to be the pollutant concentration (EPA, 1993a) as shown in Table 7.8. Given these assumptions, the cumulative pollutant loading rates would not be exceeded in normal agricultural practices and there would be little need for oversight except to assure that the sludge quality meets the criteria prior to distribution or application.

In an effort to encourage the continued reduction of pollutant levels in the municipal wastewater stream, EPA developed the concept of "exceptional quality" sewage sludge. Under this classification, sludges with specified low levels of pollutants, termed "pollutant concentration limits" and Class A pathogen levels, can be applied to agricultural land with a minimum of regulation and oversight.

Ceiling Concentration Limits for Sewage Sludge According to EPA's risk assessment, any sewage sludge may be applied on cropland as long as the cumulative pollutant loading rates are not exceeded. However, some sewage sludges contain unusually high amounts of pollutants that are prone to cause harmful effects when applied on cropland. EPA established ceiling concentrations to prevent such sewage sludges from being applied on cropland. The ceiling concentration of a pollutant is set at the least stringent of: (1) the 99th percentile concentration

TABLE 7.7 Cumulative Pollutant Loading Rates

Pollutant	Cumulative Pollutant Loading Rate (kg/ha)
Arsenic	41
Cadmium	39
Chromium[1]	3,000
Copper	1,500
Lead	300
Mercury	17
Molybdenum[1]	18
Nickel	420
Selenium	100
Zinc	2,800

[1] Above limits have been deleted for chromium (since October 1995) and molybdenum (since February 1994) pending reconsideration by EPA.

Annual pollutant Loading Rates Annual Pollutant Loading Rates (APLR) are used as a management strategy to make sure that sludges sold or given away in bags do not exceed the risk-based cumulative pollutant loading rates. This applies to sewage sludges with concentrations that are less than, or equal to, the ceiling concentrations, but do not meet the pollutant concentrations. The APLR is calculated by assuming the cumulative pollutant loading rates are reached in 20 years of agricultural or residential land applications. These preset annual pollutant loading rates shown in Table 7.8 can not be exceeded.

EVALUATION OF FEDERAL STANDARDS FOR CHEMICAL POLLUTANTS IN SEWAGE SLUDGE

The objectives of the Part 503 Sludge Rule are to protect human health and the environment from reasonably anticipated adverse effect of pollutants in sewage sludge and to encourage the beneficial use of sewage sludge. If the regulation is viewed in this manner, the risk assessment approach used by EPA to establish the numerical limits (cumulative pollutant loading rate) is reasonable. The risk assessment is logical and the exposure analysis is conducted with the best available scientific data. Based on the principles and objectives of the regulation and the approach used for the rule development, the regulation appears to serve its purpose. The limits set on pollutants of concern are sufficient to prevent adverse effects on consumers from food crops or animal products exposed to sludge. This type of regulation provides flexibility for users to develop site-specific land application operations. If the numerical limits on pollutant loadings and associated management practices are followed, cropland application of sewage sludge can be practiced without causing harm to public health and the environment. Sludge generators, appliers, and regulatory agencies must ensure that agronomic rates are followed and that numerical limits are not exceeded.

TABLE 7.8 Ceiling Concentrations, Pollutant Concentration, and Annual Pollutant Loading Rates

Pollutant	Ceiling Concentration Limits (mg/kg)	Pollutant Concentration Limits (mg/kg)	Annual Pollutant Loading Rates (kg/ha/yr)
Arsenic	75	41	2.0
Cadmium	85	39	1.9
Chromium[1]	3,000	1,200	150.0
Copper	4,300	1,500	75.0
Lead	840	300	15.0
Mercury	57	17	0.85
Molybdenum[1]	75	18	0.90
Nickel	420	420	21.0
Selenium[1]	100	36	5.0
Zinc	7,500	2,800	140.0

[1] Above limits for chromium and molybdenum (except for ceiling concentration) have been deleted, and the pollutant concentration limits have been revised for selenium.

In the course of reviewing the rule-making process, the Committee noted some inconsistencies in how the numeric limits were developed. A discussion of these inconsistencies follows. While the inconsistencies do not affect food safety, they point to areas that need attention from EPA in its follow-up assessments to improve confidence in the regulation. EPA is scheduled to update Part 503 in the near future and will be addressing pollutants not currently regulated in "Round Two" of Part 503.

Justification for Exempting Organic Pollutants From Regulation Should be Confirmed

Initially, EPA identified 12 organic pollutants for regulation in 1989. Following a review of public comments on the proposed rule, the Agency undertook a screening exercise to re-evaluate the need to regulate these 12 organic pollutants. The exercise resulted in no organic chemicals being regulated under the final rule promulgated in 1993. The application of the screening criteria, however, leads to concern with certain organic pollutants, whose concentration in sewage sludge may exceed the risk-based limits for these pollutants.

The screening criteria compared the APLR, based upon the NSSS's 99th percentile concentration of each pollutant, to the annual pollutant loading concentration calculated by the Part 503 exposure assessment. If the 99th percentile concentration of a pollutant resulted in an annual pollutant loading rate less than the loading calculated through the risk-based exposure assessment, EPA saw little justification in regulating the pollutant.

However, there are four pollutants (PCBs, benzo(a)pyrene, hexachlorobenzene and N-Nitrosodimethylamine) whose 99th percentile concentrations resulted in calculated APLRs higher than those calculated by the exposure assessment. When calculating the APLR, EPA used 7 metric tons as the annual whole sludge application rate for agricultural land. However, in its development of the APLR for trace elements, 10 metric tons was used. The rationale for using a lower application for calculating trace organic loading rates is based on their decomposition in the soil.

Table 7.9 shows how various percentile concentrations of pollutants from the NSSS compare to the concentrations of pollutants that would have been allowed using the EPA's exposure assessment. This table shows that the 99th percentile concentration of benzo(a)pyrene, hexachlorobenzene, N-Nitrosodimethylamine and PCBs are higher than the concentrations that would have been allowed by the APLR determined through the risk assessment. In other words, should these pollutants be detected in sludges at levels approaching the 99th percentile, they could pose more of a risk than the exposure assessment would have considered acceptable. For the three pollutants other than PCBs, this may be a rare occurrence considering that the NSSS detected these pollutants in less than 5 percent of the sludges sampled. But 19 percent of the sludges had detectable levels of PCBs; thus, those sludges with particularly high concentrations of PCBs may be posing some risk that the risk assessment would consider unacceptable.

However, at the 90th and 50th percentile concentrations of PCBs, few sludges should have total PCB concentrations above the exposure assessment value of 4.6 mg/kg (see Table 7.9). The 90th percentile concentration is 1.2 mg/kg and the 50th percentile concentration is 0.2 mg/kg (the 98th percentile concentration, not shown, is 2.8 mg/kg). Therefore, it is unlikely that most sludges would have levels above 4.6 mg/kg. The concern is then limited to sludges that might have concentrations of total PCBs higher than 4.6 mg/kg; this should be a small percentage of all sludges in the United States.

For N-Nitrosodimethylamine the APLR calculation using the 50th percentile concentration is above the exposure assessment APLR. This pollutant was eliminated because it was detected in less than 5 percent of the samples. However, in those samples where it was detected, the concentrations may be high enough to be of concern.

This entire analysis on organic chemicals depends on the integrity of the NSSS. One criticism of the NSSS was its use of wet weight detection methods and conversion of these to dry weight concentrations. Because of this inconsistency in sampling, the limits of detection may vary by as much as two or more orders of magnitude for the same chemical among sludges from different POTWs. As a result, the frequency of a chemical's detection may be underestimated. When the limit of detection value is used in determining the mean and standard deviation of a chemical's concentration, these measures may become unreliable. This is more of a problem for toxic organic chemicals than for trace elements because many of the toxic organic chemicals occur infrequently and near detection limits in sewage sludge, whereas trace elements are almost always detected. To improve the quality of the data set, EPA plans to repeat the Survey in the near future. A second NSSS is needed to provide more definitive documentation

TABLE 7.9 Comparison of NSSS Percentile Concentrations of Pollutants to Concentrations Using EPAs Risk Assessment for the Part 503 Sludge Rule

Pollutant	Exposure kg/ha/yr[a]	Exposure mg/kg[b]	99th kg/ha/yr[c]	99th mg/kg[d]	90th kg/ha/yr[e]	90th mg/kg[f]	50th kg/ha/yr[g]	50th mg/kg[h]
Aldrin/Dieldrin	0.027	2.7	0.00074	0.074	0.0001	0.01	1.0000E-05	0.001
Benzo(a)pyrene	0.15	15.0	0.43	43.0	0.286	28.6	0.047	4.7
zChlordane	0.86	86.0	0.18	1.8	0.005	0.5	0.0024	0.24
DDT/DDE/DDD	1.2	120.0	0.0014	0.14	0.00041	0.041	0.00009	0.009
Heptachlor	0.074	7.4	0.0014	0.14	0.0003	0.03	0.0001	0.01
Hexachlorobenzene	0.29	29.0	0.43	43.0	0.286	28.6	0.045	4.5
Hexachlorobutadiene	6.0	600.0	0.43	43.0	0.286	28.6	0.045	4.5
Lindane	0.84	84.0	0.0018	0.18	0.0005	0.05	0.0002	0.02
N-Nitrosodimethylamine	0.021	2.1	2.1	210.0	1.43	143.0	0.228	22.8
PCBs	0.046	4.6	0.06	6.0	0.012	1.2	0.002	0.2
Toxaphene	0.1	10.0	0.074	7.4	0.02	2.0	0.0096	0.96
Trichloroethylene	100.0	10,000.0	0.07	7.0	0.02	2.0	0.0035	0.35

[a] The APLR from the 503 Risk Assessment (provided in Table 6, Appendix B) EPA, 1993b

[b] The concentration of pollutants in sludge necessary to meet the APLR from the Part 503 Risk Assessment, EPA, 1993b with an Annual Whole Sludge Application Rate of 10 metric tons/ha/yr.

[c] The APLR derived from using the 99th percentile concentration of the pollutant

[d] The 99th percentile concentration of pollutants in sludge from 1988 NSSS (provided in Table 4, Appendix B, EPA, 1993b, except for PCBs, which is based on weighted nonparametric substitution method stratum estimate, SM-COM. see p. 7–58 EPA, 1992b)

[e] The APLR derived from using the 90th percentile concentration of the pollutant

[f] The 90th percentile concentration of pollutants in sludge from the 1988 NSSS (provided in Table 7–11, EPA, 1992b)

[g] The APLR derived by using the 50th percentile concentration of the pollutant

[h] The 50th percentile concentration of pollutants in sludge from the 1988 NSSS (provided in Table 7–11, EPA, 1992b)

to show whether or not concentrations of organic chemicals are within the range of concentrations that do not pose a risk to human health or the environment. If the NSSS does not support this conclusion, EPA should develop limits for those organics which exceed safe levels.

APLRs May Cause Maximum Permissible Loading Limits to be Exceeded

Sewage sludges that are marketed and distributed in bags are used primarily as soil amendments in landscaping or home gardening. Although "bagged" sludge products are not used routinely for this purpose, the amount of sewage sludge applied each time they are used could be large. In the rule-making process, EPA justified allowing sludges that exceeded the "exceptional quality" criteria of the lowest pollutant concentration limits (see table 7.8) to qualify for marketing and distribution. EPA argued that this approach is justified because pollutant inputs exceeding the calculated annual pollutant loading rate (APLR), should they ever occur, would result in little additional pollutant uptake by plants (Chaney and Ryan, 1992). While this may be an adequate technical justification for agricultural use, allowing sludge of less than the highest quality to be used by the general public opens the door for exceeding regulatory limits, and may undermine the intent of the Part 503 Sludge Rule and public confidence in the law.

Food Safety is not Likely to be Affected by the Regulations

In the risk assessment conducted by EPA, 14 exposure pathways were employed. Among them, nine pathways involve human HEI (pathways 1, 2, 3, 4, 5, 11, 12, 13, and 14 in Table 7.5), three of which are directly related to production of human food crops on sludge-amended agricultural land. These are "sludge-soil-plant-human" (pathways 1), "sludge-soil-plant-animal-human" (pathway 4), and "sludge-soil-animal-human" (pathway 5). In the Part 503 Sludge Rule, the final numerical limit of a pollutant is the lowest cumulative pollutant loading of all 14 exposure pathways. Because other, nonfood-chain pathways resulted in lower pollutant limits, the final cumulative pollutant loading for 10 chemical pollutants currently being regulated are all significantly lower than any of the limits that would be derived from the human food-chain exposure pathways. Table 7.10 shows the final cumulative pollutant loading rates in kg/ha for the 10 regulated pollutants and what the limits would have been if they were based on the food-chain exposure pathways.

In some cases, the food crop production pathway limits were not determined because the oral reference dose (RfD) or the recommended dietary allowance (RDA) for the pollutant did not exist owing to the fact that uptake of the particular constituent is inconsequential, or because the food exposure pathway is extremely small compared to exposure from other sources. In this comparison, the margin of safety provided by the current regulation ranges from 6 to over 1,700 times greater than the final cumulative pollutant loading adopted by EPA.

Table 7.11 shows a corresponding comparison for organic pollutants that were not regulated. In this case, the results have all been converted to annual pollutant loading rates (kg/ha/yr) rather than the cumulative pollutant loading rates shown in Table 7.10 for trace elements

TABLE 7.10 Final Cumulative Pollutant Loading Rates vs. the Maximum Pollutant Loading Rate Calculated from Food-Chain Exposure Pathways

Pollutant	Cumulative Pollutant Loading Rate (kg/ha)	Maximum Permissible Pollutant Loading Rate (kg/ha)		
Pathway 1	Pathway 4	Pathway 5		
Arsenic	41	6,700	NA*	NA
Cadmium	39	610	1,600	68,000
Chromium	3,000	NA	NA	NA
Copper	1,500	NA	NA	NA
Lead	300	NA	NA	NA
Mercury	17	180	1,500	24,000
Molybdenum	18	NA	NA	NA
Nickel	420	63,000	NA	NA
Selenium	100	14,000	15,000	13,000
Zinc	2,800	16,000	150,000	2,200,000

* NA: not applicable because (1) plant uptake is inconsequential, or (2) food exposure route to humans is extremely small compared to exposure from other sources.
SOURCE: EPA, 1993b

(see footnote, p. 140). Table 7.11 shows that the most limiting, risk-based pollutant rate used by EPA to screen these chemicals was, in most cases, based on the risk of consuming animal products from animals directly grazing on sludge-amended fields (pathway 5). As discussed in Chapter 6, organic pollutants in sludge are not readily absorbed by plants. To be of significance to humans consuming crops grown with sludge, the soil concentrations of organic pollutants would have to be orders of magnitude higher than those for the grazing animal pathways. Consuming the meat of animals grazed on sludge-amended fields is a potential concern because animals may accumulate certain pollutants in the kidneys and liver (as discussed in Chapter 6). As discussed earlier and shown in Table 7.9, four organic pollutants are of potential concern because their 99th percentile concentration in the NSSS exceeded the risk-based limits for the pollutant. Of these four, the grazing animal pathway was used to set the risk-based limit for hexachlorobenzene and PCBs. Hexachlorobenzene occurred at low (less than 5 percent) frequency in the survey, but PCBs had a detection level of 19 percent; however, the concern is limited to sludges that might have total concentrations of PCBs higher than 4.6 mg/kg, which should also be a small percentage of all sludges in the United States. (see Table 7.12 for a listing of the limiting pathways).

REGULATIONS AND GUIDANCE FOR AGRICULTURAL USE OF MUNICIPAL WASTEWATER

In the United States, there is a long history of using municipal wastewater for crop irrigation.

TABLE 7.11 Maximum Permissible Organic Pollutant Loading Rates Calculated from Food-Chain Exposure Pathways

Pollutant	Most Limiting Pollutant Rate (kg/ha/yr)	Maximum Permissible Pollutant Loading Rate (kg/ha/yr)		
Pathway 1	Pathway 4	Pathway 5[b]		
Aldrin/Dieldrin	0.03 (5)	2.8[a]	0.2[a]	0.03
Benzo(a)Pyrene	0.15 (3)	23	NA[c]	NA
Chlorodane	0.9 (3)	34	360[a]	23
DDT/DDD/DDE	1.2 (12)	560	48	1.5
Dimethylnitrosoamine	0.02 (3)	87	NA	NA
Heptachlor	0.7 (5)	990	110	0.07
Hexachlorobenzene	0.3 (5)	320	48	0.3
Hexachlorobutadiene	6 (3)	43,300	NA	6
Lindane	0.8 (3)	2,300	1,500	1.4
PCBs	0.05 (5)	37	4.3	0.05
Toxaphene	0.10 (5)	2,800	120	0.1
Trichloroethylene	100 (3)	220,000	NA	NA

[a] Values shown for the Most Limiting Pollutant Rate are obtained from EPA, 1993b in Table 5.4–5.6, pp. 5–436, of the Technical Support Document of the Part 503 Regulation. These values represent the smallest of the reference annual pollutant application rates (or "RPa" measured in kg/ha/yr) for the organic pollutant. Where an RPa was not directly available, it was derived from the reference cumulative application rates (or "RPc" measured in kg/ha, which are used in Table 7-10) by assuming a life span of the application site of 100 years. Therefore, the RPa would be 1/100th of RPc. Alternately, an RPa was derived from the reference concentration of a pollutant in sewage sludge (or "RSC" measured in µg/g) by assuming an annual sewage sludge application rate of 10 metric tons/ha. The number in parenthesis indicates the pathway from which the most limiting pollutant rate is derived.

[b] All values converted from concentration of pollutant in sewage sludge (mg/kg) with the assumption of sewage sludge application rate at 10 metric tons/ha/yr.

[c] NA: not applicable because (1) plant uptake is inconsequential, or (2) food exposure route to humans is extremely small compared to exposure from other sources.

SOURCE: EPA, 1993b

Although the practice has not been extensive, reclaiming municipal wastewater for crop irrigation is well-established in some parts of the country. Over the years, federal agencies have not exercised direct regulatory authority over either wastewater irrigation or other type of effluent reuse, except through provisions in the National Pollutant Discharge Elimination System permit system which regulates the discharge of treated wastewater effluents. In practice, wastewater irrigation is normally treated as a community-wide environmental sanitation and public work improvement project that should undergo rigorous facility planning and engineering evaluation (EPA, 1981). The technical merit, market feasibility, and public health risks of each potential project should be carefully reviewed by many agencies before it is implemented. This

TABLE 7.12 Limiting Pathways for Organic Chemical Pollutants Evaluated in the Development of The Part 503 Sludge Rule

Pollutant	Highly Exposed Individual (HEI)	Limiting Pathway Number
Aldrin	Eating animal fat/milk	5
Dieldrin	Eating animal fat/milk	5
Benzo(a)Pyrene	Sludge eaten by child	3
Chlordane	Sludge eaten by child	3
DDT/DDD/DDE	Eating fish	12
Dimethylnitrosamine	Sludge eaten by child	3
Heptachlor	Eating animal fat/milk	5
Hexachlorobenzene	Eating animal fat/milk	5
Hexachlorobutadiene	Eating animal fat/milk	5
Lindane	Sludge eaten by child	3
PCBs	Eating animal fat/milk	5
Toxaphene	Eating animal fat/milk	5
Trichlororethylene	Sludge eaten by child	3

is usually done and there have been no reported incidents in the United States of food contamination and/or water pollution caused by applying treated wastewater effluents to cropland.

The public health is protected by adequate and reliable treatment of the reclaimed water as well as site restrictions associated with the degree of treatment. In the United States, both the level of wastewater treatment and the microbiological requirements for agricultural reuse vary from state to state. By 1992, at least 19 States had set regulations or guidelines for the use of reclaimed water on food crops.

Recently the EPA published guidelines for the reuse of wastewater in a number of applications, including use in agriculture (EPA, 1992a). Those recommended criteria that are pertinent to infectious disease transmission through agricultural application are summarized in Table 7.13. Reclaimed water applied to most food crops, particularly those that can be eaten uncooked, should be processed at least through secondary treatment followed by filtration and adequate disinfection.

Evolution of Regulations Governing Irrigation with Treated Municipal Wastewater

In many respects, California has been a pioneer in reclaiming and reuse of municipal wastewater. The wastewater irrigation-related regulations in California can therefore be used as a model for examining regulatory development. The California Water Code (State of California, 1987) declares that "the people of the state have a primary interest in the development of facilities to reclaim water containing waste to supplement existing surface and underground water supplies and to assist in meeting the future water requirement of the state" (Cal. Water Code, Section 13510). The statute further declares that "the use of potable domestic water for nonpotable uses, including, but not limited to, cemeteries, golf courses, parks, highway land-scaped

TABLE 7.13 Summary of EPA Guidelines for Reclaimed Water Reuse in Agriculture

Type of reuse	Treatment Required	Water quality
Food crops not commercially processed	Secondary Filtration Disinfection	<2.2 fecal Coliform/100mL 1mg/L Cl_2 residual after 30 min. contact time (minimum) Turbidity ` 2NTU ` 10mg/L BOD
Food crops commercially processed including orchards and vineyards	Secondary Disinfection	`200 fecal coliform/100mL 1mg/L $Cl_2$ residual after 30 min. contact time (minimum) ` 30mg/L BOD ` 30mg/L SS
Nonfood crops pasture, fodder, fiber and seed	Secondary Disinfection	` 200 fecal coliform/100mL 1mg/L $Cl_2$ residual after 30 min. contact time (minimum) ` 30mg/L BOD ` 30mg/L SS

areas, and industrial and irrigation uses, is a waste or an unreasonable use of the water with in the meaning of … the California Constitution if reclaimed water is available.…" (Cal. Water Code, Section 13550). These policy declarations culminated in a mandate that "the State Department of Health Services shall establish statewide reclamation criteria for each type of use of reclaimed water where such use involves the protection of public health" (Cal. Water Code, Section 13521). In California, wastewater reclamation and reuse is an integral part of the water resource management plan. The provisions of Reclamation Criteria of California (Department of Health Services, 1993) reflect the legislative intent. They are conducive to water reuse and are enacted to protect public health when reclaimed water is used.

Long before the statutes were official, domestic wastewater was used in crop irrigation (Ward and Ongerth, 1970). In 1910, at least 35 communities in California operated sewage farms to dispose of raw sewage or septic tank effluents. In 1918, the California Board of Health adopted regulations governing the use of sewage for irrigation purposes. It prohibited the use of raw sewage, septic tank effluents, and other similar wastewater for irrigation of vegetables that would be consumed uncooked by people. The regulation permitted the use of untreated wastewater for irrigating crops that would be cooked before consumption, provided that a 30-day or longer waiting period was observed prior to harvest. It also permitted the use of reclaimed water for fruit and nut trees and melon crops if the products did not come into direct contact with the wastewater. For the next 75 years, the regulations continued to evolve in response to new experience in wastewater use, new wastewater treatment technology, and as the demand for reclaimed wastewater rose.

In 1933, the regulation was revised to allow the use of well-oxidized, nonputrescible, and reliably disinfected or filtered effluents for irrigation of vegetable crops for raw consumption.

Requirements were established for the finished water's coliform counts and the treatment plant operations. Subsequently, a more comprehensive regulation for the use of reclaimed water for irrigation and recreational impoundments was adopted in 1968 to accommodate the increasing population and volume of reclaimed water available for reuse. The new standards specified levels of wastewater treatment required and coliform density of finished water for various type of uses. The need to insure wastewater treatment reliability and to limit public access to the application site was documented based on the data of several field investigations. In 1975, regulatory provisions were added to guarantee wastewater treatment reliability and to limit public access to the application site. Since it inception, the Reclamation Criteria (California Department of Health Services, 1993) has been revised several times. However, the technical requirements for crop irrigation remained the same as written in 1975.

General Description of the State Regulations

As the demand for reclaimed wastewater for crop irrigation spread across the nation, many states enacted regulations or developed guidelines to govern its use. Recently, EPA (1992a) published guidelines for water reuse including the use of reclaimed water in agriculture in the United States. The conditions for use of reclaimed water for irrigating food and nonfood crops in 18 and 35 states, respectively were summarized.

The Reclamation Criteria of California (California Department of Public Health Services, 1993) have been a model for reclaimed water regulations for many states. The primary health concerns targeted have been the risk of pathogen and chemical pollutant exposure to workers involved in irrigation projects, to residents near a wastewater irrigation site, and to consumers of food produced from wastewater-irrigated fields. Regulations have focused on infectious disease risks by establishing the following:

- the level of wastewater treatment required (primary treatment, secondary treatment, oxidized, filtered, coagulated, disinfected, etc.);
- the upper limits for selected water quality parameters to insure wastewater treat-ment reliability (maximum BOD, total suspended solids, chlorine residual, turbidity, indicator organisms concentrations permitted, and pH range, etc.), and on-line chlorine residual and turbidity;
- treatment reliability provisions;
- site management practices that prevent workers and residents from being exposed to applied water and contaminated soils at the application site (providing setback distance, limiting public and worker access, posting warning signs, cross-connection prevention, hydraulic loading rate, etc.); and
- water management practices that minimize contamination of crops (specifying method of irrigation and/or types of crops permitted, requiring waiting period for crop harvesting or animal grazing, maximum water application rate, etc.)

Regulations define the conditions necessary to minimize human exposure to pathogens. This is accomplished by specifying the degree of treatment the wastewater receives, by specifying time and environmental conditions to reduce pathogen survival prior to human contact, and by restricting certain food crops depending on the level of reclaimed water quality. There are usually backup technical requirements in these state regulations such as simultaneous specification of wastewater treatment levels to minimize presence of pathogens, provision of setback distance to prevent direct contact with pathogens, and waiting period requirement after irrigation to reduce pathogen survival.

Five of the 18 states that permit reclaimed water for irrigation of produce crops require advanced wastewater treatment (e.g., oxidation, clarification, coagulation, filtration, and disinfection). To ensure the consistency of treatment performance, the total coliform (or fecal coliform) density of finished water is required to be less than or equal to 2.2 per 100 milliliters. Under such a circumstance, the reclaimed water is considered to be essentially free of pathogens for nonpotable reuse purposes. Other requirements such as setback distance, waiting period, and restricted site access are, in this case, not necessary.

At the other end of the spectrum, primary effluents may be permitted to irrigate food crops for processing if requirements are met to protect workers and nearby residents and to prevent water pollution. Human exposure to pathogens is controlled by factors other than pathogen density in the wastewater effluents. The deficiency in one factor may be mitigated by more stringent requirements of other factors. For example, in Utah, food crops may be irrigated by secondary effluents with total coliform density up to 2000/100 ml (30-day average), provided spray irrigation is not used. In this case, the risk of exposure to pathogens is reduced by preventing the water from coming into direct contact with the food crop.

If reclaimed water is used to irrigate nonfood crops or animal food crops, the risk of exposure to pathogens is considerably smaller than with vegetables produced for raw consumption by humans. Therefore, restrictions on wastewater treatment levels and operational reliability usually are more relaxed for nonfood crops than are those required for irrigating human-consumed food crops. Effluents from oxidation ponds, primary treatment, and secondary treatment are all acceptable under various circumstances. But the other requirements such as setback distance and site access usually remained the same or become more stringent for the protection of workers and nearby residents. Many states (15 of the 35 states that permitted reclaimed wastewater for nonfood crop irrigation in 1992) either: (1) ban the used of lower-quality treated wastewater on pasture, (2) require disinfection when irrigating pastures for milking animals, or (3) require an extended waiting period before animals are allowed on fields irrigated with lower-quality wastewater effluents.

So far, trace chemical contaminants in treated municipal wastewater have not been targeted by State regulations or EPA guidelines for reclaimed water because their concentrations in wastewater receiving a minimum of secondary treatment are comparable to conventional sources of irrigation water (see Chapter 4). Source control of industrial inputs, conventional secondary treatment, and advanced treatment are relied on to reduce effluent concentrations of chemical pollutants to levels that meet current irrigation water quality criteria (e.g., Wescot and Ayers, 1985) for chemicals that are potentially harmful to crop production or to ground water contamination. This assumption appears justified if industrial pretreatment programs are rigorously enforced by municipalities and wastewater is properly treated. In such case, it is possible to produce reclaimed wastewater that meets the highest required water quality standard for irrigation of food crops and with trace element and organic chemical concentrations that are lower than the maximum contamination levels of the National Primary Drinking Water Standard (Crook et al., 1990). If the concentrations of chemical pollutants tabulated in Table 7.14 are typical for reclaimed water, the annual pollutant inputs to the soil through reclaimed water irrigation will be small and will be balanced or out-balanced by the output through crop absorption (see Chapter 4 for details). In this manner, toxic chemicals and trace elements are not expected to accumulate in soils irrigated with reclaimed water to levels that are harmful to humans.

Adequacy of Current Regulations for Reclaimed Water

California's Water Code defines the Reclamation Criteria as "levels of constituents of reclaimed water, which will result in reclaimed water safe from the standpoint of public health, for the uses to be made" (Cal. Water Code, Section 13520). Early on, state regulatory agencies recognized that numerous pollutants are present in reclaimed water, and it is impractical, if not impossible, to track all of them. Besides, there is little epidemiological data to define the dose-response relationships. Defining "levels of constituents of reclaimed wastewater" suitable for various uses is difficult if the epidemiological data for quantitative dose-response evaluation are not available. As a result, regulations for reclaimed wastewater irrigation always rely on the capability of wastewater treatment and site management to accomplish the goal of public health protection.

While the public health safety record for reclaimed water irrigation has been excellent, there are little epidemiological data to support or refute the currently regulated levels (Crook, 1978; 1982). For developing countries, recent research in epidemiology indicates that the public health risks resulting from crop irrigation with treated municipal wastewater are overestimated, and that the United States guideline may be "unjustifiably restrictive, particularly with respect of bacterial pathogens" (World Health Organization, 1989).

Are current regulations for reclaimed water adequate to protect human health? The answer to this question does not lie in the regulations alone. Over the past century, the environmental sanitation practice of collecting, treating, and disposing municipal wastewater has been instrumental in improving the public health. Over time, an integrated infrastructure has evolved to regulate, plan, and implement the monumental task of handling municipal wastewater day-in and day-out. This system is vertically integrated with the environmental protection and pollution control authorities at the federal level, water quality and public health authorities at the state level, and the environmental sanitation authorities at the local level. The nation is also horizontally connected across political boundaries by special service agencies that have responsibilities for collecting, treating and disposing wastewater. Within the framework of this infrastructure, policies are made; funds are generated and appropriated, regulations are enacted; and physical plants are planned, built, and maintained. The common objective cutting across the entire infrastructure are to safeguard public health and to prevent environmental pollution.

TABLE 7.14 Concentration of Trace Elements and Toxic Organic Chemicals in Selected Treated Effluents in California

Pollutant	Unit	San Jose Creek	Whittier Narrow	Pomona	NPDWS[a]
Arsenic	mg/l	0.005	0.004	<0.004	0.05
Aluminum	mg/l	<0.06	<00	<0.08	1.0
Barium	mg/l	0.06	0.04	0.04	1.0
Cadmium	mg/l	ND[b]	ND	ND	0.01
Chromium	mg/l	<0.02	<0.03	<0.03	0.05
Lead	mg/l	ND	ND	<0.05	0.05
Manganese	mg/l	<0.02	<0.01	<0.01	0.05
Mercury	mg/l	<0.0003	ND	<0.0001	0.002
Selenium	mg/l	<0.001	0.007	<0.004	0.01
Silver	mg/l	<0.005	ND	<0.005	0.05
Lindane	μg/l	ND	ND	ND	4
Endrin	μg/l	ND	ND	ND	0.2
Toxaphene	μg/l	ND	ND	ND	5
Methoxychlor	μg/l	ND	ND	ND	100
2,4-D	μg/l	ND	ND	ND	100
2,4,5-D	μg/l	<01	ND	ND	10
Turbidity	NTU[b] (silica scale)	1.6	1.6	1.0	2
Total Coliform	No./100 ml	<1	<1	<1	2.2

[a] National Primary drinking water standards
[b] ND denotes the constituent was not detected in the specimen.
SOURCE: Crook et al., 1990.

The interdependency and interlinking of the components provide check-and-balance and technical redundancy to ensure that integrity will not be breached and that the well-being of the public is not threatened by pollutants and pathogens in the wastewater (see additional discussion in Chapter 8 on Other Government Regulations).

When viewed in this manner, the practice of irrigation with reclaimed water is not a monolithic event. Instead, it is merely one component of this integrated wastewater handling, treatment, and disposal infrastructure erected to protect public health and prevent environmental pollution. Whether crop irrigation can be safely administered is therefore interdependent on whether other components of the system are performing up to expectation. The current reclaimed wastewater irrigations regulations take full advantage of the advances in wastewater treatment technology to deliver water of appropriate quality. Again, the record has been a successful one.

If the integrity of the infrastructure is maintained, it is reasonable to assume that reclamation of wastewater for food crop irrigation will continue to be practiced safely. Because of the checks and balances and technical redundancy offered by the system, the likelihood of failure is small and, if failure occurs, it is likely to be promptly detected and corrected. Although the risk from trace chemical contaminants in reclaimed water applied to food crops has not been quantified, it is likely that such use presents little additional risk since the levels of trace chemical contaminants in reclaimed water are normally within accepted guidelines that have been developed for irrigation with conventional sources of irrigation water.

SUMMARY

Pathogen Regulations for Sludge

In the United States, the Part 503 Sludge Rule is the current management strategy for the application of sludge to land. At the present state of our knowledge, this rule appears to be, with one possible exception, adequate for the protection of the public from the transmission of waste associated pathogens. The possible exception is the potential that the prescribed waiting period between the application of Class B sludge and animal grazing may not be adequate to prevent the transmission of tapeworm to grazing cattle.

Toxic Chemicals Regulations for Sludge

The Part 503 Sludge Rule was developed with the intent to encourage beneficial use of sewage sludge. Using risk-assessment-based calculations, the regulation specifies numerical limits for chemical pollutant loading rates within which the sewage sludge may be safely applied on cropland. The regulation has a sound conceptual basis for protecting public health and encouraging beneficial use of sewage sludge.

In terms of trace elements, sewage sludge that is applied according to the pollutant loading rates specified in Part 503 should not affect the safety of the nation's food supply. The pollutant loading rates are set by the maximum permissible loading rates of nonfood-chain pathways, which are 6 to 1,700 times smaller than the maximum permissible pollutant rates according to food-chain related exposure pathways.

No organics are currently regulated by Part 503. Most toxic organic compounds found in municipal sewage sludges exist at concentrations well below those considered to pose a risk to human health or the environment. However, benzo(a)pyrene, hexachlorobenzene, and N-nitrosodimethylamine, detected in less than 5 percent of the sludge samples analyzed in the NSSS, occurred at concentrations above the 99th percentile ceiling concentration used by EPA in setting an acceptable risk. Total PCBs may be of concern because they occurred at a higher frequency of detection (19 percent), but only a small fraction is expected to exceed risk-based limits. Some of the sample preparation and analytical methods used in the NSSS for measuring concentration of toxic organic compounds in sludge were not sufficiently sensitive to show whether or not toxic organic compounds were present sludges at levels that would pose a threat to human and animal health. Therefore, a second survey should be conducted with better sampling methods to determine concentrations of toxic organic compounds, and those which exceed risk-based limits should be regulated.

Sludges allowed for marketing and distribution to the public have the potential to cause maximum permissible pollutant limits to be exceeded. While not a food safety issue, this has the potential to undermine the intent of Part 503.

Regulations for Effluent Irrigation

State regulations governing reclaimed wastewater for crop irrigation rely on wastewater treatment and site management to (1) minimize the presence of pathogens, (2) prevent workers, residents, and consumers from direct contact with wastewater or wastewater-contaminated soils and crops, and (3) minimize the opportunity for pathogen survival after water application. They do not address trace chemical contaminants. The requirements stipulated in these regulations, such as type of wastewater treatment, set-back distance, waiting period, coliform density of finished water, etc., vary considerably. The variation is caused by the many factors that control the risk of exposure. The deficiency in one factor is often offset by more stringent requirements for other factors.

The current requirements of reclaimed wastewater for crop irrigation were not derived by risk-based analysis and are not supported or refuted by actual epidemiological data. They are based on experience in wastewater treatment and reclaimed wastewater crop irrigation operations. The checks and balances and technical redundancies provided by today's wastewater treatment infrastructure seem to provide an ample margin of safety.

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8

Economic, Legal, and Institutional Issues

Earlier chapters have made the case that agricultural use of wastewater effluent and sludge, when appropriately treated (Chapter 3) and applied according to prevailing regulations or guidelines (Chapter 7), can be practiced satisfactorily with respect to public health (Chapters 5 and 6), crop production, and environmental concerns (Chapters 2 and 4). This chapter discusses some of the economic issues, "residual risks", and other regulatory matters facing various interested parties involved in implementation. Residual risks are risks perceived by crop producers, food processors, and the public (such as local nuisance, food consumer safety, and agribusiness liability as examples) that persist despite federal (for sludge) and state (for effluent) regulatory safeguards. This chapter begins with an examination of the economic incentives driving beneficial reuse from the perspectives of society, the municipal wastewater treatment utility (also known as the "publicly-owned treatment works" or POTW), the landowner or farmer, and the food processor. Discussion then turns to key concerns about residual risks for the various groups. The chapter concludes with a review of the regulatory framework for food safety and environmental protection and its capacity to address the residual risks. Thus, the chapter provides an assessment of the adequacy of existing economic, legal, and regulatory mechanisms for addressing these outstanding concerns.

ECONOMIC INCENTIVES FOR LAND APPLICATION OF TREATED MUNICIPAL WASTEWATER AND SLUDGE

Interest in reclaiming treated wastewater effluents is being driven by two major factors. One is the increasing cost of water supplies in many metropolitan areas, especially the arid western United States. For example, the wholesale cost for fresh water in Southern California can exceed $800/acre-foot ($2.45/1000 gal), depending on the treatment requirements and the distance from the source; by comparison, most types of water reclamation cost much less than $750/acre foot (Water Reuse Association of California, 1993). The second factor is the growing volume of wastewater (as shown in Figure 1.1) and the increasing cost of complying with water pollution control regulations governing wastewater discharges into the environment. This is especially apparent where excess nutrients from discharged wastewaters can cause water quality problems. For example, the sensitivity of aquatic habitats in Florida prompted the City of Orlando and Orange County to develop, as an alternative to surface water discharge, the CONSERV II program which combines wastewater irrigation on citrus groves with ground water recharge (D'Angelo et al., 1985). In St. Petersberg, Florida, water reclamation also began based on disposal requirements; however, the reclaimed water now has a greater value as a substitute for scarce potable water drawn from aquifers 50 miles away. Driven by economic and environmental concerns, and encouraged by the similarity of treated wastewater effluents to irrigation water, the use of reclaimed wastewater for agricultural irrigation is potentially competitive with other sources of water and can be a cost-effective alternative to wastewater discharge in selected parts of the country.

Generation of sewage sludge likewise has been steadily increasing in this country as a result of higher treatment levels and greater quantities of wastewater from continued population growth. Municipalities have used various options for the disposal of sewage sludge, including landfill, incineration and ash disposal, ocean dumping, and land application. The public reaction in 1988 to the appearance of medical wastes along New Jersey shores (Spector, 1992) led to the enactment of the Ocean Dumping Act (P.L. 100-68) that included a ban on ocean disposal of sewage sludge. The limited capacity of sanitary landfills is quickly exhausted, and communities are not providing for new landfills. Air quality requirements for incineration plants are increasingly stringent. Because of the these restrictions, the Bureau for Clean Water, which handles waste-water treatment for New York City, must spend approximately $800/ton to ship its sludge out of state (Wagner, 1994). As society has continues to reevaluate and regulate disposal options, agricultural use of sludge is becoming an increasingly attractive option because of its low cost and because of the fertilizer and soil amendment properties of sludge (see Chapter 4).

The following sections describe economic issues relating to the use of both reclaimed treated wastewater effluents and treated sewage sludge from the perspectives of the various parties affected by agricultural use projects. The specific costs and benefits are site specific; thus, no generic assessment of the tradeoffs is possible. The focus of this study is on the use of treated effluents and treated sludge in the production of food crops, and no comparative assessment is made of the economics of other use or disposal alternatives for sludge and wastewater.

POTW Economic Perspectives

The alternatives available to POTWs for treatment and ultimate release of wastewater and sludge into the environment are circumscribed by the Clean Water Act and by state and federal regulations for solid waste disposal. Thus, POTWs face the problem of deciding which of the available options for treatment and disposal of the sludge and wastewater are most appropriate and cost effective for their particular circumstances.

Cost-effectiveness analysis (Baumol and Oates, 1988) is an analytic tool commonly used by POTWs in choosing among available options for wastewater management. The major cost components of conventional wastewater systems include collection, treatment, wastewater discharge, and disposal of sludge (Milliken, 1990). Direct cost factors include the characteristics of the wastewater, type of treatment, size of facility, location, and type of sludge treatment, and ultimate disposal or reuse method. The costs of performing these functions include capital costs for building the facility, and annual operation and maintenance costs. The capital costs are generally amortized over the life of the facility in order to arrive at an annualized capital cost.

Most POTWs in the United States are required to perform a minimum of secondary treatment (see Chapter 3), and this can be considered as a baseline for POTWs in considering a change in their function from providing wastewater disposal to reclamation. Only the additional level of treatment and other costs associated with changing to water reclamation options need to be considered. However, in some areas (e.g., Florida), land application of wastewater may allow for lower levels and costs of treatment compared to surface water disposal due to the advance treatment that would be required to remove nutrients from effluents prior to discharge into sensitive surface waters.

The Florida Department of Environmental Regulation (1991) issued guidelines for the economic evaluation of implementing water reuse projects. The feasibility guidelines require the comparison of the net present values of alternatives (including the current practice) over a 20-year period. Capital construction costs are to include the cost of wastewater collection and treatment, and reclaimed water transmission to the point of delivery for the end user, plus reasonable levels of related costs such as engineering, legal service, and administration. Annual operation and maintenance costs must also be calculated for each alternative. Effluent irrigation alternatives generally require additional costs for effluent collection, advanced treatment, transportation to reuse sites, irrigation management, and water storage.

State requirements for wastewater effluent quality vary depending on the type of crop and irrigation method. The U.S. Environmental Protection Agency suggested guidelines (EPA, 1992) for water reuse include secondary treatment plus disinfection for nonfood crops, commercially processed food crops, and surface irrigation of orchards and vineyards. Secondary treatment plus filtration and disinfection is suggested for irrigation of food crops that are not commercially processed and that could be eaten raw.

An analysis of the cost of supplying reclaimed water to agriculture was recently completed in the Tampa, Florida area (Hazen and Sawyer, 1994). Treatment included filtration and chlorination of secondary treated effluent. Additional costs included 2.5 million gal of storage for every 10 million gal/day of capacity and transmission costs of $.35/1000 gal. Total costs of supplying reclaimed water to agriculture were estimated to range from $.70 to $.90 per 1,000 gal (approximately $225 to $300 per acre-foot). For comparison purposes, farmers typically pump water directly from the aquifer at a cost of approximately $.10 to $.15 per 1,000 gal. Water obtained from the water utility service is at the same order of magnitude at $.82 to $1.06 per 1000 gal. The cost to the farmer will depend on whether reclaimed water is used to comply with water quality regulations, which is the case in Orlando and Tallahassee, or whether reclaimed water is used to offset short supplies of water, as in Tampa. Incentives to the farmers will not be needed in water-short areas, but may be needed in other areas where water quality concerns drive the reclamation effort.

There are a variety of economic approaches and market alternatives that POTWs may use to offset current and future costs of supplying reclaimed water. If water reclamation results in a reduction in the demand for current potable water—i.e., if agriculture is drawing on an existing or potential potable water supply—the reduction should be valued at the average rate charged for potable water in order to determine the benefits of the reclaimed water. If the reclaimed water is sold, then revenue from the sale of reclaimed water may be available to offset reclamation costs. Finally, the POTW may decide to own and manage agricultural land for land disposal of wastewater effluent. In this case, revenue from the sale of commodities produced may be available to help offset reclamation costs. For example, the city of Tallahassee, Florida owns a 1,720 acre agricultural operation that accommodates an average of 12 to 18 million gal/day of effluent (Roberts and Bidak, 1994).

The implementation of any wastewater reclamation plan may allow the community to avoid or delay the cost of expanding potable water supply systems, and potential cost savings should be included in the economic analysis of water reclamation alternatives. A study by the Irvine Ranch Water District in California showed that, while the 1987 wholesale cost of treated fresh water (at $230/acre-foot) was less that the cost for water reclamation (at $303/acre-foot), it was projected that wholesale water costs would rise to $449/acre-foot (calculated in 1987 dollars) by the year 2000 because of rising demand and system expansion (Young et al., 1987). Water reclamation would allow the community to avoid the need for water supply expansion and thus save $146/acre-foot.

Sludge handling is an important aspect of POTW operations. Evans and Filman (1988) indicate that sludge handling costs accounted for an average of 47 percent of the total treatment plant costs for four large treatment plants in Ontario, Canada. Some of the processes that are used include thickening, dewatering, drying, conditioning and transportation (as described in Chapter 3). The EPA handbook, *Estimating Sludge Management Costs* (EPA, 1985) describes a number of different unit processes that can be used to achieve each of these various steps and provides generic comparative cost curves as well as specific algorithms for calculating unit costs for each process. However, the large number of processes that can variously be combined into any particular sludge management train, and the site-specific nature of the costs of implementing many of these processes, prevents meaningful generic cost comparisons. For example, the Evans and Filman (1988) study compared sludge handling costs for four treatment plants with different sludge handling processes, but all subject to identical effluent disposal requirements. Total sludge processing costs ranged from $266/ton to $925/ton depending upon the specific unit processes employed for sludge treatment.

Treatment procedures and quality criteria to be met for various types of end uses or disposal of sludge are specified in the *Standards for the Use and Disposal of Sewage Sludge* (or "Part 503 Sludge Rule", EPA, 1993). Effective pollutant source control and industrial pretreatment programs will be required to meet EPA requirements for high-quality pollutant concentration limits. Specific processes are necessary to meet the Class A pathogen reduction levels. The advantage of meeting these higher-quality sludge requirements is that the sludge can be applied to agricultural land with lower costs for regulatory compliance.

Sludge transportation can be a significant cost of land application. Transportation costs depend primarily on the quantity of water in the sludge and the distance transported. As described in Chapter 3, sludge volume can be reduced by thickening, dewatering, conditioning, and drying. Dick and Hasit (1981) discuss the tradeoff between additional treatment costs to reduce sludge volume and the savings in transportation costs. This tradeoff depends upon the distance the sludge is to be transported, the mode of transportation, and the cost of reducing sludge volume. The Madison, Wisconsin Metrogro Program determined that agricultural use of liquid sludge was the least expensive alternative since they had access to over 30,000 acres of farmland within a 20 mi radius of the POTW (Taylor and Northouse, 1992).

Comparisons of sludge management alternatives, should include the potential, if any, of revenue from beneficial land applications. Sludge contains nutrients and organic matter that can substitute in part or whole for commercial fertilizers or soil amendments (e.g, see Table 2.2). The Madison Metrogro program charges farmers $7.50/acre of sludge applied (Taylor and Northouse, 1992). Their application rates are determined by the most limiting factor, either crop nitrogen requirements or regulatory levels for metals. However, income generated from this fee covers only 1–2 percent of total program cost. The fee charged to farmers exists primarily to reinforce the concept that sludge is a beneficial product rather than a waste. Since 1979, Metrogro has recycled 139,000 tons of dry solids, with a total fertilizer value of over $2 million. Farmers' demand to participate in the program far exceeds the District's ability to supply sludge and is indicative of the local value of sludge as a soil amendment product.

Farm Economics of Treated Wastewater and Sludge Use

A farmer considering the use of reclaimed wastewater or sludge will initially have several concerns, including the potential health risks to family and employees, potential toxic effects on the plants, long-term detrimental changes in physical or chemical properties of the soil that may affect crop production, the potential liability associated with the sale or consumption of crops grown using wastewater and sludges, and the fear of liability for contamination of the land with hazardous wastes. Sewage sludge is not listed as a hazardous waste under the Resource Conservation and Recovery Act (RCRA) unless it exhibits characteristics that make it a hazardous waste and prevent its beneficial use (EPA, 1993). This last issue has been of concern to farm bank lenders who have a financial interest in the value of the land. These concerns, which are reviewed in the next section under "Managing Residual Risks," will have to be addressed before growers will even consider whether using wastewater or sludge is profitable or not.

Only after these concerns are adequately addressed will farm economics come into play. Treated wastewater and sludge provide inputs (water and nutrients) to agriculture. The demand for these inputs will depend on their relative contribution to production—also known as "marginal productivity"—and the price of the crop. The cost and availability of substitute sources of fertilizer or irrigation water provide ceilings to the price the farmer will pay for the nutrients and water in the treated effluent. In general, the greater the marginal productivity and the higher the price of the product, the higher will be the marginal value of the crop and the willingness-to-pay for water or nutrients. The agricultural marginal value for irrigation water is quite variable. In the early 1980s, the congressional Office of Technology Assessment (1983) estimated that the values of water for irrigated agriculture ranged from $9/acre-foot for pasture to $103/acre-foot for vegetables (these 1983 estimates would be about 50 percent larger in 1995 dollars.) Boggess et al. (1993) provide a comprehensive discussion of the economics of water use in agriculture. Moore, et al. (1985) provide a detailed assessment of the on-farm economics of reclaimed wastewater irrigation in California (also see the discussion of irrigation water value in Chapter 2).

The value of the nutrients will depend primarily on the relative levels of the various nutrients in the water and the nutrient requirements of the crop. Estimates for the CONSERV II project in Florida place the total value of nutrients in the reclaimed water at $100 to $250 per acre per year (D'Angelo et al. 1985), which is equal to or exceeds current farm fertilizer costs of approximately $100–$120 per acre (Muraro et al., 1994). Because fertilizer costs generally do not exceed 10 percent of total farm costs, and because its application through irrigation is not as easily controlled as through conventional fertilizers, it is not likely that farmers will place much value on the fertilizer benefits of reclaimed water. Additionally, nutrients in wastewater effluent may present a problem for some crops at certain stages of growth as discussed in Chapter 4.

Whether or not reclaimed wastewater can be marketed to agriculture also depends on the cost and availability of reclaimed water relative to other sources of irrigation water. Supply considerations include seasonality and storage as well as the on-site delivered cost of reclaimed water. Florida, for example, receives an average of 50 in. of rain per year, but irrigation is critical for the production of high-value crops. This is due to the low water-holding capacity of the soils, the high evapotranspiration rates, and irregular timing of rainfall events. Estimates for the CONSERV II project indicate that growers save from $75 to $150/acre/year in irrigation costs (D'Angelo et al. 1985). However, this estimate is based on the total amount of water sent to the growers in the CONSERV II program, which is in excess of what they would normally use. Typical irrigation costs for growers pumping ground water in the areas are estimated at $30–$70 per acre (Muraro et al., 1994). Nevertheless, growers in the CONSERV II project have not been required to pay for the new water supply because water sources in the area (from ground water) are inexpensive and easily accessible, and more importantly, because the CONSERV II project was initiated by the county and city to avoid the higher cost of complying with the water quality requirements for discharge, not because water is a scarce resource.

Where effluent irrigation projects are motivated by disposal, farmers may resist applying water to oblige the utility. In addition, farmers will be concerned about whether sufficient water will be available during periods of peak need, or whether or not they will be required to take water in excess of their needs. These concerns were worked out in the CONSERV II project in Florida (D'Angelo et al. 1985). The citrus grower participants in the project have agreements that require them to take a total of approximately 50 in. of water per year even though typical irrigation rates are only 12 to 24 in. per year. The contract allows the grower to refuse delivery of scheduled quantities of water for a limited number of periods each year. In addition, the City of Orlando and Orange County agreed to provide additional wells to the farmers to insure adequate water to protect crops from freezing, since the supply of treated effluents would be inadequate during these peak use events. In accommodating the seasonal nature of water demand, the POTW developed a series of rapid infiltration basins for ground water recharge. This option allows the POTW to divert excess effluent to the recharge basins when crop irrigation needs are low.

Sewage sludge has value to the farmer for its nutrient content and as a soil conditioner. The market demand for sludge will depend on the marginal productivity of sludge, the cost of alternative sources of nutrients or soil amendments, and regulatory and permitting costs. The marginal productivity of sludge varies with the soil and type of crop. Crop yields will show greater responses to sludge applications on those soils which are poor in nutrients and organic matter (see Chapter 4). Likewise, certain crops require greater quantities of nutrients. Thus, from a strictly economic perspective, the willingness-to-pay for sludge should be positively related to the crop's nutrient requirements and inversely related to the inherent fertility of the soil.

The availability of low-cost commercial fertilizers will generally be a limiting factor on farmers' willingness-to-pay for sludge. The nitrogen content of sludge usually ranges between 1 and 4 percent, which would be worth roughly $6–$24 per dry ton, given 1994 prices for commercial bulk nitrogen fertilizers. Other nutrients in sludge, such as phosphorus, may also contribute to its value (EPA, 1994). Metrogro, the sewage sludge agricultural use program in Wisconsin, estimates an average fertilizer value of $15/dry ton of sludge (Taylor and Northouse, 1992). Farmers will also be concerned about the mix of nutrients in the sludge relative to the crop's needs. While sewage sludge can supply all crop nutrients if applied according to nitrogen requirements, fertilizer application rates are not as easily controlled as with commercial products and supplemental fertilizer may be needed in some instances to meet the crop's requirements (see Chapter 4).

Other economic considerations for the farmer include the cost of applying sludge and the additional monitoring, recordkeeping, and management required by federal, state, and local regulations. However, some or all of these costs are typically incurred by the contractor and/or POTW. Conversely, the POTW may choose a higher level of sludge treatment and thus reduce other regulatory requirements. Treatment and regulatory costs incurred by the POTW, may be passed on to the public in the form of higher rates. Regulatory and some monitoring costs are generally incurred by public agencies, and thus, taxpayers. Other management and monitoring costs are borne directly by sludge handlers and users.

In some cases, the costs associated with monitoring, handling, and recordkeeping requirements may equal or exceed the direct economic benefits of land application, even though land application may be the environmentally preferable and the most cost-effective alternative from society's point of view (i.e. when all direct, indirect and social costs and benefits are considered). In these cases, it may be necessary and appropriate for the POTW to subsidize private sludge handlers and users in order to offset these costs. However, care should be taken to insure that the subsidy payments are properly structured and don't create incentives for "dumping" or application of sludge at rates exceeding appropriate agronomic levels. Subsidies also can obscure beneficial value and create the illusion that sludge is a waste product that farmers have to be paid to accept. As earlier mentioned, the Madison Metrogro program solved this problem by having the POTW incur the costs for transporting the sludge to the farm site, injecting it into the ground, and perform the monitoring recordkeeping. Farmers pay $7.50/acre, which pays only a small portion of program costs, but helps to reinforce the notion that sludge is beneficial product.

Benefits of crop productivity and cost savings have been documented in individual cases. In western Washington state, the Wegner farm has been applying sludge from Spokane since 1988 at 4.5 dry tons/acre/year (Logsdon, 1993). The sludge, in the form of wet cake, is incorporated into the soil before the growing season. Wegner reports 35 percent increases in yields (and increased protein content) of barley and wheat and a fertilizer savings of $12 to $25 per acre.

Food Processor Perspectives

To survive financially, food processors and retailers must have a demand for their food products and fill it economically. Thus, anything that may affect the demand for their products of their cost of production is of concern. The use of wastewater and sludge may reduce the cost to the buyers of raw food products if growers are able to reduce their costs, increase productivity, and sell their crops at a more competitive price. However, the impact of using treated effluents and sludge on the cost of producing food crops is likely to be quite small for two reasons. First, as discussed in Chapter 2, the extent of wastewater irrigation in agriculture represents much less than one percent of irrigated crops and is not likely to increase, due to the limited availability of cropland close to wastewater treatment plants, and the competing (mostly urban) uses for reclaimed water in those areas where reclaimed water has value. For sludge, even if all of the sewage sludge produced in the United States were land-applied to agriculture, these inputs would provide nutrients for less than 2 percent of cropland. Secondly, the value of sludge and wastewater as fertilizer will be no more than 10 percent of the total costs of farm production. As a result of these scale effects, land application is not likely to have significant impact on the average cost of growing food. Finally, from a farmer's perspective, the potential problems associated with sludge and wastewater could quickly outweigh the benefits. These factors will limit any cost savings that could be passed on to food processors as an incentive to purchase from farms that apply wastewater and sludge.

The potential liabilities or costs associated with the use of treated effluents and sludge for food processors stem from the public perception that adverse health effects could result (for example, the concern over Alar pesticide in apples, bovine growth hormones in milk, or conversely, the popularity of foods labeled as "organic"). Nevertheless, public perception does not necessarily depend on objective, scientific evidence. As discussed in Chapter 7, negative human health effects from the consumption of food crops are unlikely under the Part 503 Sludge Rule or under state regulations for effluent irrigation of crops. Still, food processors and retailers are particularly concerned about potential liability for health risks attributed to the consumption of food grown with the use of treated wastewater effluents or treated sludge. They require evidence to convince them that all aspects of the process are being carefully managed according to the regulations and guidelines, and that there is adequate oversight and enforcement.

MANAGING RESIDUAL RISKS

It is important to consider management and program oversight before embarking on reuse alternatives for both wastewater and sludge. Acceptance of the practice by the local community and farmers, and the public's confidence and trust in the public utility is a prerequisite to program success. As discussed in the following sections, concerns over public health, food safety, neighborhood nuisances, community land values, marketability of crops, sustainability of farmland, and the reliability of safe farming practices are important implementation issues. These all need to be adequately addressed, and will impose new burdens on agencies and the private parties involved. The capacity of the POTW to undertake an agricultural-use project in this context is an important threshold consideration. Florida, for example, limits water reuse projects to larger POTWs because smaller facilities may lack the staff and finances to do an adequate job (Ferraro, 1994).

Residual Risks

The purpose of EPA's Part 503 Sludge Rule and state regulations on wastewater irrigation are to assure safe use of sludge and wastewater in agriculture. In addition, numerous other regulatory programs are designed to protect the environment from agricultural contamination and protect consumers from adulterated foods (as discussed later in the chapter).

Nevertheless, many concerns have been raised about the "residual risks" of using sludge and wastewater in agriculture—those risks that may persist despite the regulatory safeguards. These concerns include potential risks to:

- the health of persons and livestock who consume foods produced with treated sludge and treated wastewater effluents;
  the health of agricultural workers and other persons on agricultural sites where sludge and wastewater are used;
- the health of persons who consume ground water, surface water, or fish or shellfish from areas where sludge and wastewater are used;
- the quality of life and value of property of nearby residents; and
- the quality of natural resources, such as agricultural soil, rivers, wetlands, ground water, flora, and fauna.

While only the first concern—that of health effects from food crops—is the main focus of this report, the implementation of agricultural use programs for wastewater effluents and sewage sludge will ultimately depend on the degree to which all of these concerns are addressed. Business risks and burdens also arise from these concerns about residual risks, making farmers and food processors reluctant to produce and process foods grown with the aid of sludge and wastewater, and making retailers reluctant to sell these foods. The business risks may outweigh any benefits that farmers gain by using these materials. For example, community concerns can lead to enactment of local or state regulations that prohibit agricultural use of sludge or wastewater in certain regions, or impose new and costly technical safeguards and monitoring duties. On a national scale, consumer concerns about the safety of crops grown with sludge or wastewater can stimulate consumer and retailer boycotts of certain products, new labeling requirements (which tend to stigmatize such products), and new food inspection and reporting procedures.

In addition, several banks that finance farmers in the northeast have been concerned about whether repeated applications of sludge containing toxic substances (such as cadmium and lead), even at the levels set by EPA's Part 503 Sludge Rule, could potentially put a farm at risk of becoming a hazardous waste site and create cleanup liabilities. These lenders have an interest in protecting the value of the farmland that secures their loans, and are concerned about whether they would be designated as "responsible parties" liable for the cleanup costs. After studying the issue, the Farm Credit Institutions of the Northeast (an organization of farm credit banks) determined that assurances may be needed to cover the economic risk. They proposed that farmers seeking their loans through mortgage financing should make sure that the POTW that provides them with sludge will indemnify them in the event of hazardous waste liabilities that result from application of the sludge (Benbrook and Allbee, 1994).

Other business risks pervade the sensitive markets for food products. Farmers and food processors are affected when a court or agency finds that its food product is contaminated and has caused, or is likely to cause, personal injury to consumers or livestock. Such determinations can rapidly lead to economic losses in the form of agency impoundment and destruction of the products, regulatory penalties, tort liability in the form of compensatory and punitive damages for personal injuries, and contract liability for breach of product warranties.

But the major business risk for farmers and food processors in such instances is stigmatization of the product and its source. This leads to loss of customer confidence, choice of competing products, and loss of market share on regional and even national scales. Even if contamination or injury causation is unproved, these consequences may occur because widespread media coverage, speculations, or allegations may be enough to make retailers and consumers reject the product.

Thus, public concerns about residual risks create business risks and militate against agricultural use of sludge and reclaimed water despite the regulatory safeguards provided by federal and state agencies. Proponents of sludge and wastewater use must, therefore, address the sources of such public concerns if they are to achieve their goals.

Public Concerns to be Addressed

Public concerns fall into several categories. One category consists of "nuisance" risks to community quality of life and property values, such as odors, traffic, and the attraction of vermin to sludge application sites. Another category of concern has to do with protection of nearby natural resources of high value, such as wellwater, other water supplies, and fish. It is common experience that such resources are highly vulnerable to agricultural contamination (e.g., from pesticides). Consequently, local opposition to specific projects and general public concern are not uncommon, especially where there has been a limited history of relatively safe use (see Zimmerman et al., 1991; Gigliotti, 1991; Business Publishers, Inc., 1993). Some states may limit the ability of local authority to place restrictions on practices that are allowed by the state. Small community governments have a limited capacity to deal with all the issues that are raised, and local residents may feel threatened. For example, the residents of New Harmony, New Jersey have been plagued by odors from an adjacent farm, which appears to be a dumping ground for both municipal sludge and food processor wastes (Markle, 1994). Also concerned about environmental impacts, the New Harmony residents have been repeatedly frustrated in their attempts to bring their concerns to the attention of state regulators who permit the farm for application of in-state and out-of-state sludge.

Elsewhere, these types of public concerns have already led to enactment of local ordinances banning or restricting sludge application, as in Merced County, California (Sludge Newsletter, 1993). Such ordinances have survived legal challenges where they are not preempted by federal law and are within the broad scope of the "police power" possessed by state and local governments. For example, a federal district court ruled that a Virginia county ordinance completely banning the land application of sewage sludge as a method of disposal is not preempted by federal law and does not interfere with interstate commerce (Welch v. Rappahannock County Board of Supervisors, DC WSVA, No. 94-002-C, May 24, 1995).

The POTW and cognizant officials must provide the public with assurances that meet such concerns. Studies have shown the importance of bringing the public into the decision-making process at an early stage for this purpose, and the importance of informing the public of the results. Necessary assurances may include a demonstration of stringent self-regulation and monitoring by state and local agencies; reliable management and reporting by the POTW, contractors, and farmers; and vigilant enforcement by regulatory agencies. In particular, there must be assurance that the beneficial use program has credible means of preventing nuisance risks and harm to the nearby resources of high value. Visible demonstrations have been shown to be effective in making people aware and comfortable with reuse projects. Moreover, it is unlikely that insurance, liability, indemnification, or other compensation for harms would be sufficient to offset such public concerns.

In Chapter 7, questions were raised about EPA's approach to screening toxic organic pollutants and their exemption from regulation. While the committee concluded that these organic pollutants in sludge were not likely to present a risk to consumers of food crops, public concerns have been raised by the fact that even a small percent of sludges have concentrations of certain pollutants (e.g., PCBs) that exceed a risk-based limit of acceptability. In addition, it is difficult for the public to understand that the application of sludge on cropland is safe when ocean dumping of sludge is prohibited even though the major reason for prohibiting ocean disposal of sewage sludge had to do with excess nutrient loads on marine ecosystems rather than toxic pollutants or beach safety concerns. Other questions have been raised about the safety of wastewater effluents and sludge. A recent report by the General Accounting Office (1994) dealt with the presence of radioactive material entering sewage treatment plants and the lack of regulatory action on this issue. This committee has not delved into that particular issue or other issues involving the quality of municipal wastewater, but it is possible that such concerns will arise when a POTW elects to recycle wastewater or sludge on cropland. Addressing such concerns about sludge requires convincing scientific analysis showing that adequate safeguards are being applied.

Finally, some of the concerns about the use of sludge in agriculture are based on a lack of confidence in the ability of federal and state government to adequately enforce regulations that have been enacted to safeguard health and the environment. In addition, farm management is not regulated by the Part 503 Sludge Rule. As with other fertilizers or soil amendments, farmers are expected to use good farming practices that prevent the nutrients in sludge from causing water quality problems. When using sludge of lower sanitary quality ("Class B" sludge), the Part 503 Sludge Rule requires a statement by farmers that they understand and have complied with restrictions on the type of crops used and necessary waiting times prior to harvest. The public health impact of using Class B sludge on farms is protected if the farmer follows these restrictions and guidelines (see discussion in Chapter 7). However, the Part 503 Sludge Rule does not regulate potential water-quality impacts that are broadly covered by the Clean Water Act (EPA, 1993, and see discussion later in this Chapter), and farm management is not easily enforced. These public concerns must also be addressed by state and local authorities.

Risk Management: Private Sector

Private sector forces have the potential to deter inappropriate behavior by the parties involved in the production, treatment, and use of sludge and wastewater. These include: (1) common law liability, (2) market forces, and (3) voluntary self regulation. Taken together, the private sector forces and regulatory programs have the potential to minimize the residual risks and possibly to dispel public concerns.

Common Law Liability

As with many products, liabilities for personal injury and property damage can arise at various stages in the life cycles of treated sludge and treated effluents, such as when the product is put to use, when it becomes a component of other products (crops and derivative foods), when the subsequent products are consumed as foods by consumers, and when the product wastes are disposed. In the event that the primary or derivative products or their wastes are found to cause harm to consumer health, property, or resources during any part of the life cycle, it is likely that liability, in the form of compensatory and punitive damages, will be imposed by the courts in accordance with the tort and product liability doctrines of state common law. In the case of environmental problems, regulatory penalties and cleanup costs may also be imposed.

For example, if harm befalls a consumer of a product that was produced with sludge or wastewater, the farmer or food processor may incur liability for negligence if it is shown that they failed to meet the prevailing standard of care in their field of activity. Parties who produce or sell food products are held to a particularly high standard of care and are thereby especially vulnerable to negligence actions. They are even more vulnerable in those states that hold that failure to meet a regulatory requirement constitutes negligence per se, obviating the need for the victim to prove negligent conduct.

Personal injury claims by food consumers may also be brought against farmers or food processors under a state's strict product liability doctrine for selling a "defective product." According to this doctrine, a defective product is one that is unreasonably dangerous due to faulty design or manufacture (e.g. due to a breakdown in POTW treatment, in farm management practice, or in food processor quality control) or due to inadequate warnings of latent risks of the product or inadequate instructions for its safe use. In such cases, farmers, food processors, and even POTWs are particularly vulnerable to liability because the victim need establish only that the product was defective and that the defect caused the injury, and is not required to prove negligent conduct, a more difficult task.

Liability may also arise from nuisance claims by owners of neighboring property, such as when sludge or wastewater contaminates or otherwise impairs (e.g. via odors) their use and enjoyment of their property. Liability can arise from claims of breach of contract warranty (express or implied warranty) regarding the fitness of the product for use in the production of food or as a constituent part of a processed food for human or animal consumption.

Finally, claims of inverse condemnation may be brought against POTWs by farmers whose land is contaminated by improperly treated sludge or wastewater provided by the POTW. Such a claim could be based on the constitutional doctrine that prohibits governmental "taking" of private property without just compensation. An inverse condemnation action would be a possible means of securing compensation for property damage from a governmental organization (such as a POTW) despite laws in many states which establish governmental immunity from tort claims.

As a result, farmers and food processors face potential liability for compensatory and punitive damages under the common law for a broad range of harms that might occur throughout the life cycles of treated sludge and wastewater. Liability should make these parties act responsibly when engaging in agricultural and food production practices that use sludge and wastewater. Insurance and indemnification agreements are helpful and may cover or shift liability to other parties; however, these devices are incapable of reducing the stigma and loss of customers that usually follows from liability claims. The economic consequences of high-profile accusations can be more severe than the liability itself.

Thus far, the risk of common law liability has been too high for some food processors and some farmers, and has contributed to their reluctance to use sludge and wastewater as part of food crop production for processing. A longer term view is that liability potential will induce care, and in the case at hand, will not be viewed as a deterrent to sludge or wastewater use when the parties have sufficient confidence that their practices will not incur liability. Development of such practices is aided by regulatory requirements. It is also aided by voluntary self-regulation, as discussed below.

Market Forces

When treated wastewater is reclaimed to meet water supply demand in regions where natural water supply is inadequate, the treated effluent has economic value. This value should support investment by the POTW seller in reliable treatment systems, and other expenditures to minimize risks, such as proper application and use, by the farmer who purchases it. Accordingly, risks in this "strong market" scenario are likely to be adequately controlled.

A different scenario arises when agricultural use of wastewater or sludge is being promoted by the POTW in order to facilitate disposal and reduce disposal costs, as in cases where environmental constraints limit other disposal options and there is no local demand for the wastewater. In such cases, the wastewater is without economic value and its subsequent disposal by means of agricultural use may have negative economic value because of the expenditures that will still be required for its treatment and safe use. If POTW cost avoidance is the rationale, farmers, community residents and others may be concerned about the POTW's responsibilities and require special assurances.

Once sludge or wastewater has been used to grow crops, market forces arise that may act to reassure consumers about the safety of food products. As discussed earlier, farmers and food processors operate in safety-conscious markets. Thus, once a farmer has accepted sludge or wastewater, the market forces should act to assure that appropriate farm management practices are followed, and that effective quality control methods will be used by food processors, since both parties have so much at stake. Experience of the marketability of crops grown with reclaimed water in California with food brokers and buyers for food chains show no reason for separate labeling, low business risk, and a good track record with no incidents (The Marketing Aim, 1983). However, in other cases, this market force has been perceived as both a cost burden and business risk, which many farmers and food processors are unwilling to assume. Voluntary self-regulation of sludge application by farmers and food processors, in the form of codes of conduct and self-imposed management practices, could help to mitigate negative market force effects, as discussed below.

Voluntary Self-Regulation

Self-regulatory programs are being developed in many business sectors to help companies comply with regulations, avoid liability, and to help customers use products safely. Although company conformance to such guidance is voluntary, failure to conform marks a company as one that does not meet the prevailing industry standard of care or its state of the art for managing risks. Conformance to the standard is promoted by the potential of adverse economic consequences of nonconformance (e.g, loss of customer confidence, heightened potential for negligence liability, and regulatory action in the event of an injurious outcome).

Food processors currently protect themselves by having an official position of not purchasing food from farms that use sludge or wastewater (National Food Processors Association, 1993). However, food processors and farmers have the opportunity, through their various associations, to develop new guidance for quality control and farm management practices that can reduce the residual risks of using treated sludge and wastewater. Such guidance, if followed, could have the further effects of mitigating public concerns about regulatory inadequacies, and mitigating business concerns about liability.

Successful self-regulatory programs are available as models. They include private sector training and certification programs, self-auditing, independent third party evaluation of performance, and specific practices for risk management.

Although such self-regulation and codes of conduct are developed within the private sector, government agencies such as EPA and U.S. Food and Drug Administration could provide encouragement and generic guidance to assure their proper design. The agencies could also provide various incentives for such self-regulation, such as cooperative agreements, which lessen regulatory actions, inspection, and enforcement in accordance with the effectiveness of self-regulation.

OTHER, RELATED GOVERNMENT REGULATIONS

The part 503 Sludge Rule and state regulations for agricultural irrigation with treated effluent work within a much larger framework of regulations. To assure that adequate institutional controls address residual risk, it is important to understand the relationships between the various regulatory programs other than those that deal strictly with agricultural use of municipal wastewater and sludge. In this regard it is important to keep in mind two concepts.

First, all of society's wastes eventually become reassimilated within our environment, and therefore possess a potential for adverse impact to humans. Second, existing institutional programs and other factors, such as liability, have thus far mitigated most risks from the use of treated wastewater and sewage sludge, and, in the case of sludge, these programs are now being supplemented by beneficial use management options in the Part 503 Sludge Rule.

This section of the report illustrates the relationship between federal programs to show how the seemingly unrelated programs combine to achieve a protective strategy that mitigates potential residual risks associated with municipal wastewater and sludge management.

Toxic Waste Segregation, Waste Collection, and Treatment

Figure 8.1 illustrates some of the processes in the wastewater and sludge life cycle generally addressed by federal and state environmental regulations. Management of municipal wastewater begins before treatment through source control and pollution prevention programs. Residential sources are managed through separation of storm water from sanitary wastewaters and by public education that promotes responsible behavior towards hazardous material disposal. Pollution from industrial wastewater sources is regulated through limits on certain toxic substances entering the municipal wastewater (40 CFR 129), and specific industrial effluent quality standards assigned to particular types of industries (40 CFR 400–471). Many industries also employ voluntary programs to recycle or recover materials in industrial processes that would otherwise pollute the waste stream. Additional protection is indirectly provided by the Toxic Substances Control Act (40 CFR 700–799), which describes specific use requirements for many chemical substances. Wastewaters from residential and industrial sources are conducted through the common, public sewers. Discharge of the wastewater into surface waters is regulated by state permits under the National Pollution Discharge Elimination System (NPDES) program (40 CFR 122–125).

Solid waste collected from residential, commercial and institutional sources is separated from other wastes (40 CFR 256–259) and is subject to treatment, storage, and volume reduction (40 CFR 264), or materials recovery (40 CFR 245). Solid waste classified as hazardous material are identified, transported, and processed under more stringent criteria (40 CFR 260–280).

Control over these various forms of municipal wastes has been instrumental in improving the quality of effluent discharged from municipal wastewater treatment systems and in meeting the performance criteria established by NPDES. These various controls also create conditions that can improve the quality of sewage sludge, and increase the likelihood of meeting the standards required by the Part 503 Sludge Rule. If it were not for this regulatory framework and investment by industry, beneficial use of sludge would not be a viable option.

If the quality of sludge does not meet beneficial use criteria, it must be disposed as required under the Part 503 Sludge Rule or, if mixed with non-hazardous solid waste, managed under existing state solid waste plans (40 CFR 256 and 258). Sewage sludge is now regulated under the solid waste rules only if it is mixed with municipal solid waste and disposed of by means not covered under the Part 503 Sludge Rule, which otherwise covers all land application of sewage sludge. In this regard, the credibility of sludge beneficial use programs may be improved if EPA and states assign authority to local government solid waste regulators for

FIGURE 8.1 Some of the processes in the wastewater and sludge life cycle generally addressed by federal and state environmental regulations.

responding to any reports of inappropriate activities related to beneficial reuse of sludge, such as excessive application, odor, or illegal dumping. Some of the negative public reaction to land application of sludge may be due to an erroneous public belief that prohibited materials may now be land applied.

Treated Effluent and Sludge Discharge Management Options

In the regulatory framework diagram illustrated by figure 8.1, treated municipal wastewater effluent can be managed through two options: disposal to a surface water discharge point assigned by the NPDES permit (40 CFR 122–125), or by meeting state standards for land treatment, land disposal, or wastewater reuse. Usually, additional pathogen attenuation and/or crop selection and harvest restrictions are imposed if the effluent will be applied to crops intended for human consumption.

Treated sewage sludge can be managed for either disposal or beneficial use. Sludge can be disposed under established solid waste programs (40 CFR 240–299) if disposed into solid waste disposal facilities controlled by these programs, or it can be disposed or beneficially used under the requirements of the Part 503 Sludge Rule (EPA, 1993). As described in Chapter 3, the sludge may be applied to agricultural land for beneficial use if the trace element pollutant concentrations are low enough and if pathogen and vector attraction reduction methods are employed.

Surface and Ground Water Protection

Figure 8.2 shows the processes in food production and solid waste management generally addressed by federal and state regulations and by guidelines related to surface and ground water protection, especially those used for drinking water. Many programs have been established to mitigate adverse impacts from nonpoint sources. The U.S. Department of Agriculture (USDA) through the Natural Resource Conservation Service (NRCS), provides technical assistance and controls to mitigate adverse environmental impact related to agriculture. Most of these programs are established through the NRCS (7 CFR 600–611) and they support activities such as environmental

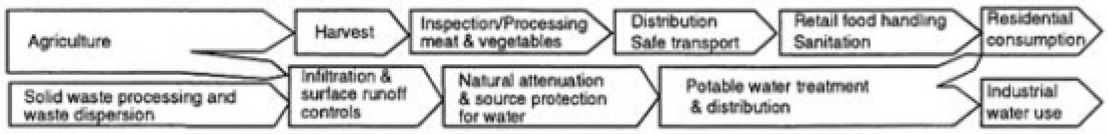

FIGURE 8.2 The processes in food production and solid waste management generally addressed by federal and state regulations and guidelines related to surface and ground water protection.

services, conservation, and watershed protection (7 CFR 650–658). Many of these programs are specifically designed to minimize erosion and contaminant runoff from agricultural land (7 CFR 799, 7 CFR 3100, 7 CFR 3407). Erosion control programs can minimize the amount of soil loss (along with any surface-applied sludge) that may occur from land application sites.

Crop selection and nutrient application advice by state and local extension agents help farmers to minimize ground water contamination from nitrate leaching. As discussed in Chapters 4 and 6, unsaturated soil is capable of attenuating many contaminants in sludge and wastewater if they are applied according to crop requirements. The contaminants in sewage sludge tend to be immobile and not available for leaching to ground waters. In this context, the use of wastewater and sludge is no different than other agronomic inputs that should be considered in watershed management and in the protection of ground water resources. When drinking water is drawn from surface or ground waters, it is subjected to maximum contaminant and treatment performance criteria under the National Primary and Secondary Drinking Water Standards (40 CFR 141–143). If public drinking water does not meet mandatory requirements, suppliers must provide notice to customers (40 CFR 135).

Public Health Protection for Harvested Crops

When EPA first promulgated criteria for land application of sewage sludge to cropland in 1979, some food processors raised a series of questions about the perceived safety and legality of food crops grown on sludge-amended soils, and the adequacy of procedures to properly manage the application of sewage sludge to land used to grow fruits and vegetables. The principal federal agencies involved—EPA, the FDA, and the USDA—developed a joint statement of federal policy and guidance on the use of sewage sludge in the production of fruits and vegetables in 1981 (EPA, 1981) to provide assurances to the food industry that the high quality of food would not be compromised by the use of treated municipal sludges with adherence to proper management practices. However, the food processors were not convinced (National Food Processors Association, 1993) as earlier discussed.

Neither USDA nor FDA have specific regulations for the use of sludge or reclaimed water in food crop production, but rely on existing regulatory programs involved with the consumption of animal products and foods that are commercially processed or receive cooking in commercial establishments (illustrated by Figure 8.3). Food processors and retailers normally operate under the assumption that all raw meat has pathogens and handle it accordingly. The principal regulatory protection for meat that is cooked at home is the USDA meat inspection program (9 CFR 301–391). The USDA requires mandatory inspection for all meats and meat products under 9 CFR 301–335, and has the enforcement capability to act on criminal offenses. However, since meat is a perishable commodity, improper preparation or handling of meat can encourage the growth of pathogens and toxic substance even after inspection. Therefore, consumers need to be educated as to the hazards involved in meat preparation and cook meat thoroughly. The food industry and health regulators educate the public to raise awareness of the food-borne illness risk associated with any improper food handling practices. No regulatory program can be expected to eliminate this risk, and vigilant cooking practices are necessary for health protection regardless of whether a beneficial sludge or wastewater program is in effect.

Standards for inspection and certification of fresh fruits, vegetables and other processed food products are provided under 7 CFR 51–75. Standards related to the condition of containers and their inspection are established under 7 CFR 42. FDA is directly involved with regulatory controls over food processing practices for harvested foods under 21 CFR 100–199. These regulations address issues of specific food labeling, standards for quality, unavoidable contaminants in food for human consumption (21 CFR 109) and help assure that "Good Manufacturing Practices" are applied during manufacturing, packing or holding human food (21 CFR 110). The Good Manufacturing Practices (21 CFR 110) are an extremely effective self-regulatory control mechanism where specific regulations do not exist. They require the use of only wholesome, unadulterated products and the best handling methods possible. If a consumer of a processed food becomes ill and the episode is traced to a problem during food processing, the company will be measured against this standard as part of the basis for assigning liability. Enforcement policies and methods for dealing with criminal violations are covered by 21 CFR 7. These regulations guide production processes and use of additives, and establish lists of direct and indirect food substances that can be considered safe additives (21 CFR 184–186). Substances prohibited from use in human food, or prohibited from indirect addition to human food through food contact surfaces, are also evaluated and listed (21 CFR 186–189).

FDA, acting under the authority of the Public Health Service Act (42 U.S.C. 243 and 311) and the Economy Act (31 U.S.C. 686), developed a Model Food Code. Each edition of the code incorporates the latest and best scientifically based advice available for preventing foodborne illness. The Model Food Code has been adopted by local, state, territorial, tribal, and federal agencies who are responsible for inspecting and enforcing federal, state, and local laws related to safe food handling practices at the retail level. Assistance in implementing the code is provided by the FDA under the Federal Food, Drug and Cosmetic Act (21 U.S.C. 301). This may be the most important protective activity that exists within the regulatory framework because it promotes uniform implementation of national regulatory policy for food at retail establishments throughout the United States.

Uncooked food sold by retail establishments and food consumed at home by the public is not directly protected by the Model Food Code. Vegetables that may be consumed uncooked need to be properly handled, regardless of whether or not beneficial reuse practices are implemented.

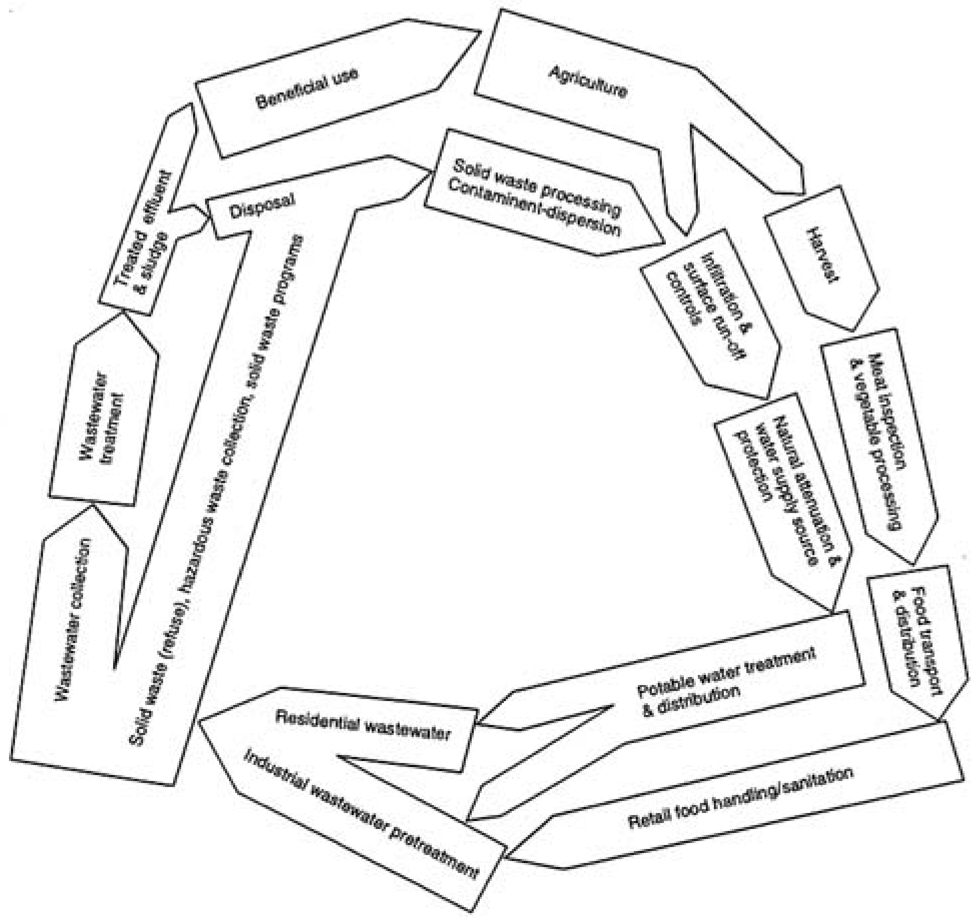

FIGURE 8.3 Some of the Processes in Food Crop Harvest and Food Production that are Addressed by Federal and State Regulations and Guidelines.

In general, fresh produce requires a higher level of protection from pathogenic contamination during harvest, transport and storage than do crops destined for commercial processing. The Part 503 Sludge Rule requires farmers who grow produce crops to adhere to rigid cropping and harvesting practices if Class B municipal sludge is land applied. The federal regulations require a statement by farmers that they have complied with the restrictions on cropping and harvest. However, no training or certification is required for farm workers, nor is any compliance inspection or surveillance included in this program.

Protecting food during transport is another critical aspect of food safety. Food products that are intended for direct human consumption or for indirect consumption, such as feed for grazing animals, may be contaminated from a variety of sources during transport for distribution. If harvested crops were "backloaded" in vessels used to transport Class B sludge, crops could be exposed to pathogens. Congress has provided agencies with the authority to deal with this problem by enacting the Sanitary Food Transportation Act of 1990 (Public Law 101–500). Section 4 of this act requires (1) appropriate recordkeeping, identification, marking and certification or other means to ensure compliance. (2) appropriate decontamination. Section 5 prohibits transportation of food products in cargo tanks, rail cars and tank trucks that are used to transport nonfood products that would make food unsafe to the health of humans or animals. The existence of the this law, properly enforced, should act as a deterrent that would minimize the potential of backhauling harvested food products in vehicles that were previously used to transport sewage sludge to agricultural areas.

Analysis for Regulatory Gaps and Overlap

An evaluation of the framework reveals that many existing regulatory controls are available to protect the environment and public health. Federal regulations governing drinking water are generally considered to be credible. Harvested crops that are cooked and handled by retail operations are also subjected to numerous, specific regulatory controls that have achieved public credibility and trust due to surveillance and enforcement. Agricultural crops irrigated with treated municipal effluents may be even better protected than those irrigated with local surface waters due to stringent regulatory standards imposed by state authorities on the quality and reliability of effluents.

Industrial pretreatment and source control programs have been effective in minimizing trace element contamination of municipal wastewater. These programs have been effective because of a combination of industry self-monitoring efforts, surveillance and enforcement activity by government regulators, and lawsuits by citizen action groups. The Part 503 Sludge Rule has been adopted as a result of the credibility achieved by the control over trace element contaminants in wastewater entering municipal treatment works.

Applying sludge that is not pathogen-free raises the possibility of foodborne illness. Food quality is regulated by a host of specific standards imposed on retail operations (food processors, distributors, and restaurants) by the FDA and state health agencies charged with the responsibility for inspecting and enforcing public health regulations. These stringently enforced, costly controls have been responsible for achieving extremely high expectations of food quality by the American public. Even in cases where specific operation standards do not exist, processors and retailers are still constrained by "Good Manufacturing Practices" that require all possible effort to protect health. If they are charged by a civil or criminal suit, they must be able to prove that "Good Manufacturing Practices" were employed. Failure to do so can be costly for an industry.

The standards assigned to the use of Class B sludge emphasize site restrictions and farm management practices, as opposed to the treatment or microbial quality criteria that defines Class A sludge. Questions have been raised over whether Class B sludge management practices present a credible program for monitoring and enforcement. If the POTW is not actively involved with management aspects, then reliance is placed on contractors and farmers to comply with the necessary site and harvesting restrictions. This is not of immediate concern for crops that undergo processing operations because of the existing food processing safety standards imposed and enforced by FDA. Also, retail establishments are obliged to follow proper cooking procedures according to the "Food Code." However, neither of these regulatory controls will protect the health of those who consume uncooked vegetable crops in retail establishments (e.g. salad at a restaurant) or prepared at home. If management standards for Class B sludge are not followed for fresh produce crops that can be eaten raw, public health could be compromised.

Public confidence in the use of Class B sludge could be improved by more explicit involvement of local or state public health authorities. In matters of infectious disease control, public health agencies can quickly step in with immediate consequences for non-compliance, which can include public notice, fines, immediate cessation of operation, and/or product recall as necessary. In contrast, environmental authorities typically impose fines and may allow offending conduct to continue. Additionally, food safety programs normally require personnel training and certification. If municipal treatment systems wish to introduce a product of value to the agricultural and food community, that product must not be perceived as a risk to consumers. The only means to ensure this is to (1) demonstrate that the applied material is safe to handle and meets high-quality pollutant and pathogen limits so that minimal oversight is necessary after land application, or (2) assure that all personnel associated with transport, application and use of sludge are trained and certified, and maintain accessible records to reassure interested parties that pathogens and chemical pollutants are being managed effectively.

SUMMARY

Economic incentives play an important role in decisions to pursue beneficial land application of reclaimed wastewater and treated sludge. In many cases there are clear economic incentives for society as well as POTWs to pursue beneficial use options, even though revenues from these projects will often be small or nonexistent. With the exception of water-short areas, there are only limited incentives for farmers to apply reclaimed wastewater and sludge, due to the low cost of alternative sources of nutrients and water. Thus, subsidies may be appropriate where regulatory costs associated with reclaimed wastewater and sludge application exceed beneficial use values. However, subsidy programs should be structured to avoid creation of incentives to apply effluent or sludge at rates in excess of crop requirements.

There are only negligible economic incentives for food processors to accept products produced with reclaimed wastewater or sludge. Benefits in terms of lower raw food costs are likely to be minimal, whereas the risks from negative public perception could be substantial. Negative public perception of food crops produced using treated wastewater or sludge could have detrimental impacts on consumer demand and the profit and survival of firms.

Despite the existence of extensive regulations, public perceptions of significant risks associated with beneficial land application persist in some areas. Extensive evidence has shown the importance of public education and early involvement in the design of beneficial land application for successful implementation of reuse programs. In addition, a number of private sector forces deter inappropriate behavior by the various parties involved in beneficial reuse programs. These forces include common law liability, market forces, and voluntary self-regulation (e.g. codes of conduct, worker training and certification, audits).

Sectors of society that are hesitant, or may become hesitant, to endorse the concept of beneficial use of wastewater and sludge in food crop production—the food industry, farmers, product consumers, and adjoining property owners—will need to have evidence of adequate surveillance and enforcement of the existing suite of pollutant criteria, process standards, and management requirements. This is especially important for use of Class B sludge on produce crops. One way to maximize program credibility is to require training and certification for members of the agricultural community who use Class B sludge to grow crops for human consumption.

From a regulatory perspective it is important to remember that the Part 503 Sludge Rule and state regulations governing the agricultural use of reclaimed wastewater merely augment a wide array of existing institutional programs and controls that have responsibly mitigated risks from these practices in the past. Related regulations pertain to toxic waste handling and treatment, surface and groundwater protection, and public health. These regulations and their overlapping authority are complex and need to be adequately explained to both the regulatory community and the interested public to avoid confusion and the perception that beneficial use is a disguise for the dumping of wastes. Although some clarification and streamlining of the Part 503 Sludge Rule would be beneficial, the regulatory framework appears generally adequate to manage risks associated with land application of both treated municipal wastewater and treated sewage sludge.

The suite of existing federal regulations, available avenues for additional state and local regulatory actions, and private sector forces appear adequate to allow, with time and education, the development of safe beneficial reuse of reclaimed wastewater and sludge. In fact, there are many such programs already in operation.

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Appendix

COMMITTEE MEMBER BIOGRAPHICAL INFORMATION

Albert L. Page (Chair) is Professor of Soil Science and Chemistry and Chair of the Department of Soil and Environmental Sciences at the University of California at Riverside. Dr. Page received his B.A. in chemistry from the University of California at Riverside and his Ph.D. in soil science from the University of California at Davis. his current research interest is on the fate of trace elements when applied to soils in the form of environmental wastes. Dr. Page was a member of the National Research Council's Committee on Irrigation Induced Water Quality Problems.

Abateni Ayanaba is Manager of Agricultural Research and Seed Quality Management at Del Monte Corporation. He is responsible for the management of varietal development, plant pathology, soil microbiology, and agricultural research; seed quality programs on crops of interest to Del Monte; and development of biocontrols for pea and bean diseases. Dr. Ayanaba is a Soil Microbiologist with more than 20 years of broad-based domestic and international experience, emphasizing biocontrol, microbial ecology and physiology, and plant-microbe interactions. He earned his B.S. in plant and soil sciences from the University of Massachusetts, and his M.S. and Ph.D. in soil microbiology from Cornell University.

Michael S. Baram is Professor and Director of the Center for Law and Technology at Boston University School of Law, and Professor of Health Law at Boston University School of Public Health. He is also a partner in Bracken and Baram, a Boston law firm specializing in environmental, health, and energy law. Mr. Baram received his B.S. from Tufts University, and his LL.B. from Columbia University Law School. His research interests include corporate risk management (facility accidents, hazardous wastes, product safety, etc.); risk communication law and information policy; biotechnology legal and policy issues; and use of risk assessment and scientific evidence for decision-making in regulatory, judicial, and corporate contexts.

Gary W. Barrett is Odum Professor of Ecology and Director of the Institute of Ecology at the University of Georgia. He received his B.S. in biology from Oakland city College in Indiana, M.S. in biology form Marquette University, and Ph.D. in zoology from the University of Georgia, Athens. Dr. Barrett's research interests include stress effects (e.g., pesticides, fertilizer, sludge, or fire) on ecosystem dynamics; mammalian population dynamics; applied ecology; agroecosystem ecology; integrated pest management; restoration ecology; and landscape ecology. He is a member of the American Institute of Biological Sciences, Association of Ecosystem Research Centers, and the Ecological Society of America, among others.

William G. Boggess is head of the Department of Agricultural and Resources Economics at Oregon State University, Corvallis. He has a B.S. in agricultural business and a Ph.D. in agricultural economics from Iowa State University. His research interests include the interactions between agriculture and the environment with emphasis on water allocation, water pollution and environmental policy. In addition, he is interested in applied decision theory under risk and uncertainty, and stochastic/dynamic simulation and optimization techniques. Dr. Boggess was elected vice president of the Southern Agricultural Economics Association for 1993, and received the society's Distinguished Professional Contribution Award for Research in 1987.

Andrew C. Chang is Professor in the Department of Soil and Environmental Sciences, and Director of the Kearney Foundation for Soil Science at the University of California, Riverside, California. He received his Ph.D in Agricultural Engineering from Purdue University. His areas of research include the land application of municipal wastes, environmental chemistry of phosphorus, physics and chemistry of organic pollutants, and methodology of establishing land disposal criteria. He has conducted a study for the World Health Organization on Human Health-Related Chemical Standards for using Reclaimed Wastewater for Crop Irrigation and Sewage Sludges for Fertilizer. He has served on several state and federal committees for risk assessment of municipal sludge disposal. Dr. Chang received the 1991 U.S. Environmental Protection Agency Sludge Beneficial Use Award for research, and the 1991 U.S. Department of Agriculture Superior Service Award for Natural Resource and Environment.

Robert C. Cooper is Vice President of BioVir Laboratories in Benicia, CA. He received his Ph.D and M.S. in microbiology and public health from Michigan State University and a B.S. in public health from the University of California at Berkeley. He is Professor Emeritus at the Department of Biomedical and Environmental Health Services, School of Public Health at the University of California at Berkeley. Dr. Cooper's research interests include environmental health, wastewater reuse, microbiology, and effects of water quality on human health. Dr. Cooper participated in the National Research Council's Committee to Review the USGS National Water Quality Assessment Pilot Program.

Richard I. Dick is the Joseph P. Ripley Professor of Engineering in the Civil Engineering Department at Cornell University. He received his B.S. in civil engineering from Iowa State University, M.S. in sanitary engineering at State University of Iowa, and Ph.D. in environmental engineering at University of Illinois. Dr. Dick's research interests are sludge treatment, utilization, and disposal. He is a member of the Association of Environmental Engineering Professors, Water Pollution Control Federation, American Water Works Association, and the International Association on Water Quality, among others. Dr. Dick served on the National Research Council's Committee on a Multimedium Approach to Municipal Sludge Management, and was a member of the National Research Council U.S./U.S.S.R. Task Group on External Utility Systems.

Stephen P. Graef is Director of Technical Services for Western Carolina Regional Sewer Authority where he is responsible for collection, treatment, solids reuse and disposal, laboratory, and industrial waste pretreatment and engineering. He received his B.S. in civil engineering from Valparaiso University, M.S. in environmental health engineering from the University of Cincinnati, and Ph.D. in environmental systems engineering from Clemson University. Previously, Dr. Graef was Director of Operation at Milwaukee Metropolitan Sewerage District. He is a member of the Water Environment Federation, American Academy of Environmental Engineers, American Society of Civil Engineers, and the International Association of Water Pollution Research and Control.

Thomas E. Long is a Wastewater Management Specialist for the Washington State Department of Health where he is responsible for community environmental health programs, and for promulgating on-site sewage treatment regulations. He is also a liaison with the Department of Ecology, revising best management practice for agricultural application of biosolids. Mr. Long holds a B.A. in environmental science from the University of West Florida. He is a member of the Australian Water and Wastewater Association, International Association on Water Pollution Research and Control, and the Water Pollution Control Federation.

Catherine St. Hilaire is Director of Regulatory Affairs at Hershey Foods Corporation. She earned her B.S. in science education from West Virginia University, and her Ph.D. in microbiology from the College of Medicine, Pennsylvania State University. Her expertise is in the areas of cancer research, toxicological evaluations, health risk assessments, and regulatory analysis. Prior to joining Hershey Foods in 1990, Dr. St. Hilaire was a Principal of ENVIRON Corporation where she was involved in a number of projects related to the public health risks of environmental chemicals. She served as a Staff Officer for the National Research Council where she worked on a number of reports including Risk Assessment in the Federal Government: Managing the Process. Dr. St. Hilaire is a member of the American Association for the Advancement of Science, Society of Toxicology, Society for Risk Analysis, and the American College of Toxicology.

JoAnn Silverstein is Associate Professor in the Department of Civil, Environmental and Architectural Engineering at the University of Colorado, Boulder. She earned a B.A. in psychology from Stanford University and a Ph.D., M.S., and B.S. in civil engineering from the University of California at Davis. Her research interests include the application of biological processes to water, wastewater, and sludge treatment; kinetic and process modeling of degradation of toxic organic compounds by mixed communities of microorganisms; biological oxidation and reduction of nitrogen; and the use of pH and oxidation-reduction potential sensors to control biological processes. She is a registered professional engineer in the State of Colorado. She is a member of the American Society of Civil Engineers, International Association for Water Pollution Research Control, American Water Works Asso-ciation, Water Pollution Control Federation, American Society for Microbiology, Association of Environmental Engineering Professors, and the Society of Women Engineers.

Sarah Clark Stuart is a program officer with the Pew Charitable Trusts in Philadelphia and is a private environmental consultant. She earned her B.A. in botany with an emphasis on plant ecology from Pomona College and her M.F.S. from the Yale School of Forestry and Environmental Studies with an emphasis in soil and water science. She was Staff Scientist and Co-Program Head for the Environmental Defense Fund's Eastern Water Program where she was involved with research, writing and advocacy on local and national coastal water pollution issues, including sewage sludge management, wastewater treatment, contaminated sediments, and ocean disposal and dredge material.

Paul E. Waggoner is Distinguished Scientist and former Director of the Connecticut Agricultural Experiment Station in New Haven. He earned his S.B. from the University of Chicago, and his M.S. and Ph.D. from Iowa State University. Dr. Waggoner's research interests include agriculture, plant pathology, and the effect of the environment on plants, especially plant diseases. He chaired a Council for Agricultural Science and Technology Task Force on Preparing U.S. Agriculture for Global Climate Change. He has been a member of several National Research Council committees, and chaired a subpanel of the Committee on Policy Implications for Greenhouse Warming. Dr. Waggoner is a member of the National Academy of Sciences, American Meteorology Society, American Society of Agronomy, and American Phytopathological Society.