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WATER RECLAMATION AND UNRESTRICTED NONPOTABLE REUSE: A New Tool in Urban Water Management

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■ **Abstract** Growing urbanization accompanying growing population is increasing the demand for water supply in communities throughout the world. Water resources for many cities are already proving inadequate. Additional water resources are inherently more costly and are often not available because other communities and/or land owners have the water rights. Although conservation, particularly through demand management, may delay the need for additional sources for a short period, the need is inevitable. One approach that has been found to provide substantial additional water for communities is the reclamation of wastewaters produced by the communities themselves for unrestricted nonpotable purposes, such as for landscape and market crop irrigation, industry, cooling towers, air conditioning, toilet flushing, construction, vehicle washing, and environmental enhancement. This is done by providing dual distribution systems.

Nonpotable reuse is already widely practiced despite the fact that the reclaimed water distribution systems needed to be installed in existing communities. Inasmuch as additional water is needed for growing populations, the costs would be substantially reduced if the two systems were to be built at the same time in the newly developing areas. Reuse of reclaimed water for potable purposes may be feasible, but it imposes added public health risks that need to be accepted only as a last resort.

INTRODUCTION

A public water supply service is essential to people who live in urban areas; they cannot forage water for themselves. Population growth, increasing urbanization, and higher standards of living have created demands for water that increasingly exceed the safe yields of the water resources now available to communities throughout the world.

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In 1996, some 46% of the world population already lived in cities (30). In the more developed countries, 75% of the population already lives in urban areas and this is expected to grow to about 84% by 2030 (Figure 1). (The year 2030 is an appropriate target date for consideration, as water reclamation projects conceived now will take at least ten years to consummate and will need to be designed to be adequate to serve at least 20 years.) In the less developed regions of the world, which do not include the least developed countries, urbanization in 1996 was 38% and is expected to grow to about 57% by 2030.

Of the 15 largest megalopolises in the world, each with a population of ten million or more, all but two are now experiencing serious water supply shortages. Thirteen of these are in less developed countries.

Although the problems of the major conurbations attract the greatest attention, the smaller so-called secondary cities generally suffer much more from inadequate resources and infrastructure because they have fewer financial, political, and personnel resources to address their problems than do the major capital cities. Nevertheless, they all continue to grow in population. As water-using appliances have grown in number in both the developed and less developed countries, per capita water use has risen from about 100 liters (25 gallons) per capita per day in poorly served cities to about 600 liters (150 gallons) per capita per day in the cities in the more developed countries. By 2030, many thousands of cities of more than 100,000 population will be in existence and most can be expected to have severe water supply problems.

This paper is directed at water reclamation and reuse for cities in the more developed countries because, with a few exceptions, they are most likely to be in a position to initiate water reclamation. However, experience with water reclamation projects in the United States, Japan, and Australia can provide a basis for the more developed and larger cities of Asia, Africa, and Latin America to initiate these practices. Furthermore, this paper emphasizes water reclamation for unrestricted nonpotable reuse in urban areas, although agricultural reuse is also discussed. Some attention is given to water reclamation for potable purposes, although, for public health reasons, this is an option of last resort.

Water Conservation

In the face of urban water supply shortages, the first effort that communities are obliged to make is conservation. Some measures are of an emergency ad hoc nature, intended to reduce demand until the shortage is over. As the perception grows that the shortages may not be short term, measures are instituted in a formal approach to "demand management." The employment of water-saving devices and appliances has garnered the greatest attention, although some have been the source of annoyance because they oblige users to suffer restricted water flow in showers, for example, even during periods of ample rainfall and excess water supply. On the other hand, such measures are useful in getting the public to realize that water is a limited resource which needs to be used wisely.

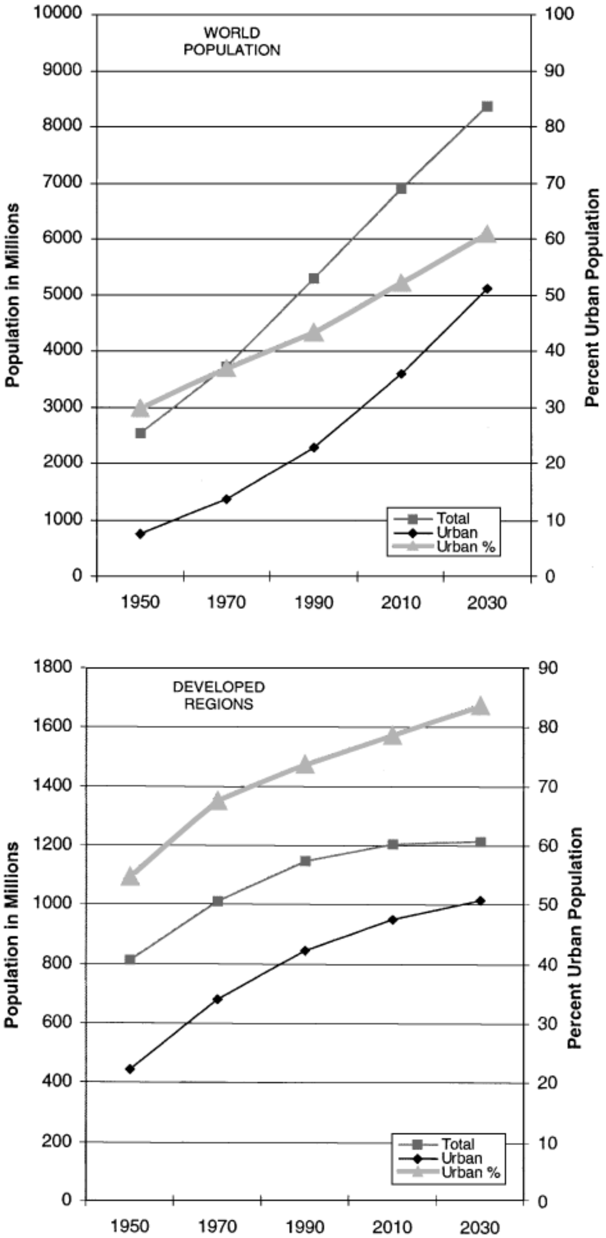

Figure 1 Urbanization of world population and population in developed regions (Northern America, Europe, Australia, New Zealand, Japan).

The most effective demand management has resulted from the adoption of incentive pricing of water. Until recently, water rates, and the concomitant rates for disposal of the wastewater produced, have been so low that demand for water was deemed inelastic; an increase in price was not seen to affect the demand. Water is so little valued in many cities that residential services are not yet metered. Many cities in the United States and many more outside the United States do not yet meter residential users. New York City has just begun to install residential meters. Denver did not have residential metering at the time it proposed to obtain additional water by damming rivers in the Rocky Mountains, and it had one of the highest per capita water uses of any major city in the United States at that time. The project was difficult to justify because the city was seen to be so derelict in its husbanding of its existing water resources. Denver is now engaged in water reclamation and nonpotable reuse.

Metering of all water services has begun to become mandatory and rates that are adequate to meet the necessary costs for providing safe water and for the proper treatment and disposal of wastewater are being adopted. Whereas in the past the unit price of water decreased as the amount of water used by a customer increased, rising block rates are now being adopted. A base rate per cubic meter (m^3) for a household might apply to the first "life sustaining" 40 m^3 (10,000 gallons) per month, but each additional increment of 10 m^3/month for uses such as lawn watering and car washing would have a higher rate per cubic meter. The higher rates that have been adopted in many communities in summer, when landscape irrigation is a major use, have significantly reduced demand (9).

Additional Water Resources

Conservation measures have effected reductions in per capita demand but have hardly impacted the increasing demand that results from urban population growth. More water is needed.

Many cities draw water from surface sources, either from impoundments on upland streams, which generally provide a high quality of surface water, or from rivers where they need to accept water that has been diminished in both quantity and quality by cities and/or industries upstream. The latter sources are so-called run-of-river supplies and were selected because they were easily available at a time when it was believed that water treatment technology would be adequate to assure the safety of the water. Philadelphia, Cincinnati, New Orleans, and London are examples. On the other hand, New York, San Francisco, Seattle, and all the other major cities in Britain elected to develop higher-quality upstream sources.

Some cities are fortunate enough to have groundwater sources available which are generally of high quality. Unfortunately, many cities have overdrawn their groundwater sources and have been obliged to turn to surface waters. Houston is a good example; having originally been served by artesian (free flowing) wells, increasing population drew down the groundwater, requiring deeper and deeper wells and pumps and causing land subsidence, which is now responsible for frequent flooding.

Developments on watersheds and recharge areas have reduced the yields of water from watersheds and groundwater recharge areas both in quantity and quality. The quantity is reduced because development renders land surfaces impermeable, preventing rain water from percolating into the ground that sustains groundwater levels and the basic flows of rivers during dry periods, while also increasing flood flows to a point where they may be too large to be captured for water supply. Land use controls to sustain water quantity and quality are slowly being introduced but face inexorable pressures from development interests.

When cities perceive the need for additional water, and additional sources are available, they try to acquire these sources as best they can. However, the most available and economical sources were the first to be developed, and additional sources are likely to be at greater distance, more costly, and often not available because other communities or jurisdictions have dominion over them. Furthermore, the construction of new reservoirs on upland streams, even for so high a use as public water supply, is faced with heavily organized opposition in today's environmental climate.

Sometimes groundwater sources may be available. Where easily identified, they are economical and exploited, often to excess. However, where surface sources are easily and economically developed, the potential for groundwater development is often ignored. At one time, for example, New Orleans and Cincinnati might have developed their groundwater resources but opted for run-of-river sources of poor quality.

Desalination of brackish and salt waters has been widely adopted in areas where the value of water is quite high, such as in arid, oil-rich countries in the Middle East, where a gallon of water may cost more than a gallon of gasoline, and in resort areas in the Caribbean. The cost of desalination in energy and money is high, generally too high for most urban applications and certainly for agricultural irrigation. Furthermore, many of the cities that need water are far from the sea. Nevertheless, developments of high value that need water may find it appropriate to invest in desalination.

Other approaches, such as towing icebergs and using tankers to carry water from water-rich regions to water-short regions, do not offer significant promise, although, in the Bahamas, dedicated water tankers are used for carrying water from a water-rich island to a nearby water-short island. Such practices are not perceived as feasible to address the water needs of many urban areas in the future.

Water Reclamation: A "New" Resource

The only significant "new" water resource for most cities is the wastewaters they themselves generate. In urban areas in the more developed countries, wastewaters receive treatment prior to being discharged to rivers, lakes, and the sea. In the United States, the treatment is intended, under the Clean Water Act, to render the waters of the nation "fishable and swimmable." The minimum treatment for almost all wastewaters in the United States includes sedimentation (primary treatment), biological treatment (secondary treatment), and disinfection. Such an

TABLE 1 Numbers of states with regulations for wastewater reclamation, 1992

Unrestricted urban reuse	22
Restricted urban reuse	27
Agricultural irrigation of food crops	19
Agricultural irrigation of nonfood crops	35

effluent wastewater may be feasible for some agricultural irrigation, such as for nonfood crops and food crops that are to be commercially processed. For discharge to many environmentally critical ambient waters, additional treatment of various types may be required. Tertiary treatment involves the addition of rapid sand filtration or possibly membrane filtration. For discharge to waters subject to eutrophication, nutrient removal, particularly reduction in concentrations of phosphorous and/or nitrogen, may be required.

The United States Environmental Protection Agency (EPA) has established regulations for wastewater discharged to public waters, enforced through an elaborate program requiring each discharge to have a National Pollution Discharge Elimination System permit. The EPA has no jurisdiction over wastewaters that are reused. Nevertheless, in 1992 it published a manual, *Guidelines for Water Reuse*, which recommends water quality standards for a wide range of uses including various types of agricultural irrigation, several urban restricted uses, unrestricted urban reuse, environmental enhancement, industrial uses, groundwater recharge, and indirect potable reuse (33). The *Guidelines* do list standards, guidelines, and/or recommendations adopted by the states for wastewater reclamation for many types of reuse. The numbers of states with regulations as of 1992 are listed in Table 1.

Many more states have since adopted some type of regulation for many uses, particularly for unrestricted urban reuse, which, with irrigation of market crops, is the highest quality use; reclaimed water of such quality can serve all customers, both urban and agricultural. Industries that require water of especially high quality, such as, for example, boiler feed, are obliged to provide the additional treatment, as they are required to do even where they use public water supplies.

The major focus of this paper is on unrestricted urban nonpotable reuse, which involves "dual systems": the conventional potable water distribution system and a similar system for reclaimed water that can serve almost all the residential, commercial, industrial, and environmental nonpotable needs in a community.

History of Water Reclamation and Reuse

The history of wastewater reclamation and reuse had its birth in the mid-nineteenth century with the introduction of piped water into homes, the adoption of flush toilets, and the construction of sewerage systems for conducting household wastes away from communities into the nearest water courses. The considerable pollution

of the Thames as it passed through London not only caused nauseating conditions in the city but also was responsible for repeated epidemics of cholera among those being served with public water supply taken from the Thames. The solution in the late nineteenth century was the construction of a vast interceptor incorporated in the Thames Embankment that carried the wastewater downstream for spreading on "sewage farms." Such "land treatment" was widely adopted by the larger cities in Europe, with crops produced being incidental to the need for wastewater disposal.

The considerable health impact of the polluted water courses on communities drawing water from such water courses was mitigated at about the turn of the century first through filtration of the water and then through the adoption of chlorination, which sharply reduced enteric disease in the industrialized countries. However, in the cities of Asia, Africa, and Latin America, waterborne disease rates continue to be high and the threats of cholera epidemics are ever present when contaminated waters are used as sources of water for drinking. In addition, the use of these waters for irrigation of market crops continues to be a major hazard to the residents of these cities, and to visitors as well, as generally no treatment is afforded to the wastewater or to the water abstracted from the rivers for irrigation. These problems have been well documented (21).

Using reclaimed water for nonpotable purposes in cities requires the provision of two distribution systems, one for potable water and the other for myriad nonpotable purposes. According to Frontinus, one of the new aqueducts drawing water to Rome almost 2000 years ago was so unwholesome that it was used for nonpotable purposes "to avoid drawing upon the better sources of supply" (5). In 1958, the United Nations Economic and Social Council stated, "No higher-quality water, unless there is a surplus of it, should be used for a purpose that can tolerate a lower grade" (31). Preserving limited quantities of high-quality water for potable purposes today constitutes the major impetus for the development of dual systems.

History of Dual Systems

The first dual distribution system in the United States was built to provide water supply for a rapidly growing Grand Canyon village in Arizona on the south rim of the canyon where no sources of water exist and rainfall is sparse. Water for the village was originally brought in by tankers over roads and rails until a spring about 1 km (0.6 mi) deep in the canyon was developed from which water was pumped up to the village. The wastewater produced in the village was too valuable to be discharged; in 1926 it began to be treated and reclaimed for landscape irrigation and toilet flushing (6). As the village grew, the system was renovated and enlarged, most recently in 1989, even after an additional source of water was developed on the north side of the canyon and piped down to the river and up to the village (4). In addition to the original uses for landscape irrigation and toilet flushing in the visitor area, its uses have extended to serving the permanent village for staff employees, including schools and service buildings, as well as for vehicle washing, cooling water make-up, construction, and other nonpotable uses.

Many reclamation and nonpotable reuse projects in urban settings were thereafter developed for single or groups of large users not necessarily involving comprehensive dual reticulation systems. One of the most noteworthy was the construction in 1942 of a 2.4-m (96-inch) pipeline 7.2 km (4.4 mi) from the Baltimore Back River wastewater treatment plant to deliver about 4.5 m^3/s (100 mgd) to the Sparrows Point plant of the Bethlehem Steel Company for process use, cooling water being provided by once-through passage of water obtained from a nearby watercourse. This reclamation program served to significantly reduce the demand on Baltimore's limited upland water supply and simultaneously reduced wastewater discharges from the city to local receiving waters (19). Power plants began to be major users of reclaimed water for cooling tower make-up (33). A related power plant use was that for the TECO Power Plant, near Tampa, Florida, which uses seawater for once-through cooling but purchases almost the entire production of a small municipal reclamation plant for stack gas scrubbing to reduce air pollution.

Committing all or most of the available reclaimed water from a city to a single user may be a mistake. In 1982, a 58-km (36-mi) transmission main was placed in operation to carry secondary effluent from Phoenix, Arizona to a 4-m^3/s (90-mgd) reclamation plant at the Palo Verde Nuclear Power Plant for cooling. The several owners of the power plant and the City of Phoenix were sued by a Phoenix land developer over the rights to the reclaimed water, which he asserted was needed for residential and commercial development in and around the city. Although the suit was lost, pressure for conservation of the reclaimed water resulted in the power plant increasing the efficiency of its cooling towers, reducing its need for make-up to only about half the original demand, releasing reclaimed water for other nonpotable uses within the city.

Dual water supplies had been suggested by the late Professor Gordon M Fair of Harvard at meetings of the Subcommittee on Water Supply of the Committee on Sanitary Engineering and Environment of the National Research Council in the 1950s and developed by Paul Haney, who wrote the first paper on dual systems in 1965 (7).

A large-scale municipal dual system for the sale of reclaimed water to urban customers was established on a limited basis in Colorado Springs in 1960 (19). Because of the demand for high-quality sources of water for the rapidly growing region at the foot of the Rocky Mountains, about one third of the secondary effluent from Colorado Springs was given tertiary treatment for sale for landscape irrigation to college campuses, golf courses, cemeteries, and other large urban users. The desirability of this water was evinced by the fact that it was sold at two thirds the price of that of the available potable water.

Planning for the first major comprehensive urban dual system in the United States to serve residential, commercial, and industrial customers was initiated in St. Petersburg, Florida in 1969 by the late Lloyd Dove, then director of public works, after extensive discussions with the author (18). The initiative for the St. Petersburg system came principally from the economies that might be realized as

a result of new Florida regulations requiring nutrient removal prior to discharge of effluents to Tampa Bay and the Gulf of Mexico. The lower cost of tertiary treatment for reclamation, compared with nutrient removal, made reclamation and reuse more economical. Because the initial objective was wastewater disposal, customers were not metered but were charged a flat rate per month per acre to be irrigated. St. Petersburg was typical of many of the early dual systems; the main purpose was wastewater disposal, so that customers for landscape irrigation, the principal users initially, were encouraged to use as much as they could. This resulted in shortages of reclaimed water.

St. Petersburg draws its potable water supply from well fields some 70 km (40 mi) to the north, in another political jurisdiction. As the population in the region grew, the increased draft on the groundwater aquifers by the many communities in the region caused a lowering of the water table to the point where lakes in the region, promoted as a “Land of Lakes,” began to dry up. St. Petersburg was the only city in the region that, despite its growth in population, through the use of reclaimed water was reducing its demand for water from the well fields (23).

A study sponsored by the Water Environment Research Foundation that examined management and operating practices in urban nonpotable water reclamation systems throughout the world revealed that, as of 1998, about 60% of the 90 reclamation systems surveyed had been initiated because of the need for additional water supply, with the reduction in water pollution control costs being an added economic benefit (35). Some 30% of the systems were initiated to reduce the costs of wastewater disposal.

The rates for reclaimed water service are highly variable compared with the rates for the potable water supply. In some instances, to induce customers to connect to the service, lower rates are introduced initially. However, in many areas, the reliability of the reclaimed water, which is available during drought periods when those on the conventional potable water system are obliged to curtail their uses, has induced customers to connect to the reclaimed water system. This has been particularly important for industry, for commercial enterprises such as car washes, and for those customers who treasure their shrubbery. In such instances, reclaimed water rates may be only slightly lower than the rates for the potable water supply. Several surveys indicated that a substantial number of utilities charged about 75% of the potable water price for reclaimed water (3, 35). Some systems charged the same rates, and several even adopted rising block rates for reclaimed water.

DUAL-SYSTEM TECHNOLOGY

All water-related engineering projects are “site specific.” Water sources are variable in their origins, in their quality, and in their yields. Even where the water source may remain the same for any one supply, the water quality and quantity are highly variable with the seasons—sometimes, for “flashy” streams, changing sharply in hours. The topography of the cities to be served ranges greatly; some

cities are relatively flat, with water sources and points of wastewater disposal at about the same elevation, whereas others are at high elevations with highly variable topography. Wastewater treatment plants are almost always located near the receiving body of water, so that the sewerage system can collect and carry the wastewater to the plant by gravity. However, the markets for the reclaimed water are in the city, generally some distance and often at higher elevation than the wastewater treatment plants.

No two cities are alike, especially in their water-related facilities. Furthermore, although the technologies for water and wastewater treatment are fairly well standardized, no two facilities are alike. Whereas two different cities might build identical hospitals, it is impossible to have identical water supply facilities and identical sewerage and wastewater treatment facilities serve any two cities. And because water reclamation and reuse involves both water supply and wastewater services, no two systems are likely to be even similar, let alone identical.

In the United States, most cities already have water supply and wastewater collection and treatment facilities, so that where a water reclamation system is to be introduced, both the additional wastewater treatment and the reclaimed water distribution systems need to be retrofitted. (In the developing world, however, while most large cities have water supply facilities, though generally inadequate in treatment capability and in capacity, few have adequate sewerage systems and very few have any wastewater treatment facilities.)

In the United States, where an adequate water supply, sewerage system, and wastewater treatment plant are in operation, additional water supply for nonpotable purposes may be provided by the introduction of a water reclamation system to conserve high-quality resources for drinking and other uses requiring high quality. The quality of the reclaimed water to be provided is generally appropriate for unrestricted nonpotable reuse, which would serve many urban uses, such as:

- Landscape irrigation—public and private.
- Recreational irrigation—golf, tennis, playgrounds, ball fields.
- Toilet flushing—commercial/residential buildings.
- Fire protection.
- Cleaning—vehicles, streets, buildings.
- Commercial air conditioning.
- Construction—concrete, dust control.
- Industry—cooling, processing.
- Environmental enhancement—ponds, fountains, urban streams.

Of these uses, the most neglected in the United States is toilet flushing in residential, commercial, and industrial properties. However, it is the most important use in Tokyo and other large cities in Japan, where irrigation is a minor use. The Irvine Ranch Water District is the first utility in the United States to require that all high-rise buildings use reclaimed water for toilets and air conditioning.

Arrangements are often initially made for wastewater to be provided for one large user, such as a major power plant requiring evaporative cooling or an industry that uses large quantities of water for its processing, later expanding to serve commercial and residential areas.

Sewerage and Wastewater Treatment Systems

Inasmuch as the sewerage system is the source of the water for the proposed reclaimed water system, it requires special attention. The wastewaters discharged to the system, particularly those from industries, must be characterized to assure that troublesome wastewaters do not reach the sewerage system. Programs for industrial wastewater management and pretreatment are already well established in the United States and most industrialized countries but because this wastewater will become a product to be sold rather than waste to be discarded, knowledge concerning the sources of the wastewater is essential. For example, if home water softeners discharge saline wastewater into the sewers, or if sewers are near seashores and permit infiltration of seawater, the reclaimed water might be unfit for landscape irrigation. Some industrial wastewaters are toxic to the microorganisms necessary for the biological wastewater treatment processes that precede reclamation; pretreatment requirements in the United States and other industrial countries should have already addressed this problem.

If the existing wastewater treatment plant is near the point of wastewater effluent disposal (such as a river or an ocean) at a considerable distance from and at a lower elevation than the potential existing or new water markets in the city, the construction of a so-called satellite reclamation plant near the water markets may be more appropriate than enlarging the existing wastewater treatment plant at its downstream location. Figure 2 shows a profile of such a plant, which withdraws

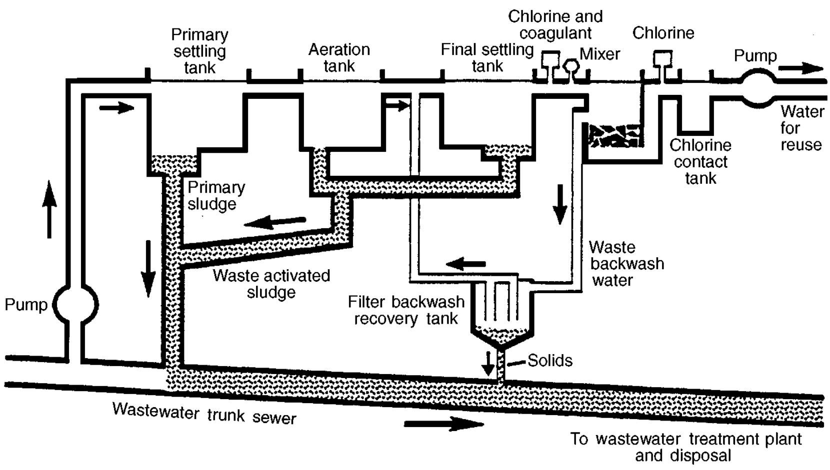

Figure 2 Profile of a “satellite” water reclamation plant.

wastewater from a trunk sewer in the city and reclaims it for reuse nearby. The satellite plant reduces the capacity requirements for expansion of the existing treatment plant.

Also, such a satellite plant is much smaller than a conventional treatment plant because the sludges produced are discharged to the trunk sewer to be carried to the treatment plant for final treatment and disposal. Because no noise or odors need be emitted, the reclamation plant can be completely enclosed and located in residential or commercial areas (it is the management of the sludges at wastewater treatment plants that makes them poor neighbors). The City of Los Angeles has a large satellite reclamation plant in the city at a considerable distance from its main treatment plant at the coast and at a much higher elevation. The plant is architecturally attractive and is entirely enclosed. Part of the reclaimed water produced is used to provide water for a new park adjacent to the plant that is rented for celebratory occasions. Elsewhere, smaller satellite reclamation plants have been designed to fit into residential communities.

Seasonal variations in demand for reclaimed water are common, especially when irrigation is a major use. Because the production of wastewater is relatively uniform throughout the year, provision of seasonal storage is often necessary. Underground storage in aquifers not used for potable purposes, as is done in Tucson, Arizona, is ideal because water quality is maintained and water is not lost by evaporation. In Irvine, California, on the other hand, storage is provided in surface impoundments similar in construction to water supply reservoirs. The nutrients in the reclaimed water, exposed to sunlight, permit the growth of algae in the reservoir. Refiltration and additional disinfection are necessary. Diurnal differences between production and demand are provided for by covered water tanks, often elevated in the same manner as service storage in conventional water supply systems.

Even though facilities may not need to be built for a decade or more, plans for reclamation and reuse are best made early because the routing of the trunk lines of the sewage system and the siting of the future reclamation facilities should be guiding the construction of interim facilities.

Wastewater Reclamation

The important reclaimed water quality requirements for unrestricted urban nonpotable reuse recommended in the *Guidelines* (33) are shown in Table 2.

The fecal coliform requirement is the same as for drinking water and is intended to eliminate any health risk from inadvertent ingestion of the reclaimed water. It can be met by the treatment train shown in Figure 2, which involves well-established treatment processes. This level can be assured because the magnitude of chlorine dosage and the maintenance of a chlorine residual need not be limited as is necessary for drinking waters, because health consequences from the ingestion of disinfection by-products (DBPs) are of concern only when exposure is continuous over long periods of time. Little attention needs to be given to limiting trace

TABLE 2 Unrestricted nonpotable urban reuse water quality

Parameter	Standard	Monitoring
Fecal coliform	Nondetectable per 100 ml	Daily
Chlorine residual	Minimum 1 mg/L	Continuous
Turbidity	2.0 NTU* on average	Continuous
pH	6–9	Weekly

* NTU, nephelometric turbidity units.

chemical contaminants generally, or to disinfection byproducts, if the water is not intended for drinking.

For assurance of quality, continuous on-line real-time monitoring of the reclaimed water for chlorine residual and turbidity is provided. The turbidity requirement of an average of 2.0 nephelometric turbidity units (NTU) and a maximum of 5 NTU helps assure water quality by providing automatic diversion of the reclaimed water should the turbidity of the reclaimed water exceed a predetermined limit. Water of this turbidity is not perceptibly different from drinking water. The maintenance of the chlorine residual throughout the distribution system helps prevent aftergrowth and the formation of biofilm within the pipes. This is a common problem with all water supply systems and could be acute with reclaimed water systems that have much higher concentrations of nutrients if heavy chlorination is not provided.

As a public health precaution, even though the reclaimed water is not to be ingested, periodic monitoring for certain biota, particularly pathogens resistant to chlorination such as *Cryptosporidium* oocysts, is advisable. Most viruses and bacteria are readily inactivated by chlorination but periodic monitoring for these also is advisable. Monitoring for trace organics, so important for drinking water, is not necessary for reclaimed water used for nonpotable purposes.

Urban wastewater is rich in nutrients, particularly nitrogen and phosphorus. Often, for discharge to nutrient-sensitive waters, water pollution control regulations require quite costly reductions in the concentrations of nitrogen and phosphorus. Wherever reclaimed water is intended to be used for landscape irrigation, the presence of the nutrients is an advantage in communities where the drinking water supplies are low in these nutrients, often making it unnecessary to add fertilizers. In St. Petersburg, where the potable water system is drawn from deep wells and contains no nutrients, and where the soils are sandy, the introduction of reclaimed water resulted in production of lush lawns that promoted the use of the reclaimed water. For some industrial applications, such as evaporative cooling towers, the nutrients in the make-up water are a problem but such systems require special water treatment even where waters free of nutrients are used. Any water will create biofilm after repeated recirculation in the towers, so that biocides are

necessary even with potable water. Evaporative cooling towers are among the largest industrial users of reclaimed water.

Reclamation plants provide a product for which a relatively high price is paid and to which people in large numbers may be exposed. Public health considerations are important. Customers depend on a continuous supply of reclaimed water of appropriate quality. The situation with wastewater treatment plants that discharge wastewater to ambient water is that they do not need to meet continuous quality or quantity requirements. Managers and operators of water reclamation plants are obliged to have a more responsible approach to reliability than that of operators of conventional wastewater treatment plants. Too often, where water reclamation and irrigation is the major use for the reclaimed water, and where the primary objective of the irrigation has been to get rid of the water by an economical means, reliability is not perceived as being important.

Using Reclaimed Water for Fire Protection Can Improve Public Water Supply

Conventional potable water systems are designed to provide water for fighting fires. The minimum-size pipe for this purpose is generally six inches (150 mm). With no obligation to provide water for fire protection, the minimum size would be determined by the demand on a street for potable water, which might often be as little as one inch (25 mm). Except during fires, which are infrequent, the flow is very slow because the pipes are greatly oversized, allowing the water to stagnate. As a result, chlorine residuals cannot be maintained and biota aggregate in the pipes, causing biofilms to form on the sides of the pipes, often to an extent that they interfere with the flow in the pipe. The most serious problems are that these biota cause corrosion and shield pathogens that may be present in the water from what little chlorine residual may be in the water.

To try to maintain adequate chlorine residuals would pose the risk of producing excessive disinfection by-products (DBPs), some of which have been characterized as carcinogenic when consumed over long periods.

If fire protection is provided from the reclaimed water system, adequate chlorine residuals can be maintained because the water is not ingested. Also, being much smaller, the potable water pipelines can be made of higher-quality materials without joints and thus be less likely to cause leakage and infiltration of contaminated ground water when the pressure in the system is low. The purpose of using reclaimed water for fire protection is not to save potable water, because the savings would be exceedingly small, but to improve the potable water system.

Where reclaimed water lines are being placed in existing streets, the potable water lines are already in place and it is not feasible to profit from using reclaimed water for fire protection, although St. Petersburg uses reclaimed water lines for fire protection in addition to the protection afforded by the conventional system. For new developments, installing both lines at the same time is economical. Such a system has been built for a large new development, Rouse Hill, outside Sydney, Australia (23).

To avoid cross connections between the potable and nonpotable lines, regulations for dual systems are directed at both reticulation systems and the plumbing on private properties. The regulations stipulate color coding and marking using purple for all pipes, pumps, valves, and other fittings used for reclaimed water and blue for pipes and fittings for potable water supply.

WATER SUPPLIES CONTAMINATED BY WASTEWATER

When water supplies are drawn from rivers that receive discharges of wastewater from cities and industries upstream, that water can be said to have been reclaimed and reused, a practice sometimes called "indirect potable reuse." Another example of such reuse is where wastewaters are introduced into aquifers, either by spreading or injection, and then withdrawn for potable water supply.

Early cities throughout the world were built near rivers, most generally at the mouths of large rivers where they established hubs for water and land transportation. Obvious and expedient sources of water for such cities at that time were these rivers, regardless of their upstream history.

The city of London was typical. A cholera outbreak in the summer of 1854 was initially traced to a well on Broad Street in central London by Dr. John Snow, the first epidemiologist (26). He plotted deaths on a map of the city; the pattern of the plot resembled a firing range target with the well at its center. Snow confirmed his hypothesis that water was responsible for outbreaks of cholera when another outbreak hit London that same year. At that time, epidemics were attributed to the miasmas: wafting noxious fumes from the Thames in summer, which was polluted by discharges to storm sewers from the recently introduced water closets, which were made possible by the provision of piped water into private homes.

Two private water companies competed for customers for their piped water on the south bank of the Thames. One of the companies, to improve the taste and appearance of its product for marketing purposes, had just moved its intake upstream above most discharges of London's wastewater to the Thames. Its customers suffered only 37 deaths per 10,000 households during that epidemic, compared with 315 deaths per 10,000 households for the water company that continued to draw its water from the Thames in the center of the city. This confirmation of the hypothesis that water was the cause of cholera took place decades before the germ theory of disease had evolved (22).

In the United States, typhoid rates in 1902–1906 in cities using run-of-river supplies were 61.6 per 100,000, more than threefold greater than in cities using groundwater (22). However, the availability of filtration and then chlorination at the turn of the century made it attractive to continue to use run-of-river supplies because doing so was less costly than developing upland supplies or groundwater of higher quality.

London opted for continuing to take its water supply from the Thames, despite the fact that many cities upstream were discharging their wastewater into the river. London had the option of developing an upland supply from Wales, but doing so

was dismissed as being too costly (20). Philadelphia could have drawn its water from the upper Delaware River in 1900 but instead continued to draw its water from the mouth of this heavily industrialized river because doing so was less costly (10).

In North Carolina, with 46 communities of over 10,000 population serving a total of 2.2 million people with water drawn from surface sources, just about 50% of that population is served from protected upland sources while the other 50% draws from sources receiving significant upstream pollution including many run-of-river supplies (29). Many of these cities had, and many still have, the option of using upland or groundwater sources. Wilmington, North Carolina is a good example: The city draws water from near the mouth of Cape Fear River—which receives more wastewater than all other rivers in North Carolina combined—despite the fact that Wilmington is situated over groundwater of high quality that flows into the ocean.

Such systems, with wastewater discharges upstream, are obliged to upgrade their treatment continually because upstream discharges increase both in quantity and in the complexity of the contaminants they contain. Some cities have found it feasible to move their sources. When the EPA found that the Mississippi River at New Orleans contained a large number of synthetic organic chemicals (SOCs), and an epidemiological study revealed higher rates of some cancers in populations using Mississippi River water compared with those in the area using groundwater, Vicksburg switched its supply from the Mississippi to groundwater [the EPA's findings and the results of the epidemiological study were two factors leading to passage in 1974 of the Safe Drinking Water Act (SDWA)]. Cincinnati takes its drinking water from the Ohio River, which upstream receives wastewater from many industrial cities including Pittsburgh. Cincinnati has been obliged to add granular activated carbon filtration to its treatment stream to reduce concentrations of SOCs that are present in the water.

SYNTHETIC ORGANIC CHEMICALS IN WASTEWATER

The United States Public Health Service (USPHS) Drinking Water Standards of 1962 (34) did not include SOCs, which burst upon the scene following World War II and were scrutinized following publication of Rachel Carson's *Silent Spring* (2). The USPHS introduced a standard for carbon chloroform extract that did not distinguish between natural organics and SOCs, although some SOCs were identified as having long-term chronic detrimental health effects. The 1976 United States EPA Drinking Water Regulations, adopted after passage of the SDWA, included six SOCs—all pesticides (32).

Shortly thereafter it was found that chlorine itself reacted with natural organics in water to produce disinfection by-products (DBPs), some of which are carcinogenic to animals. A maximum contaminant level (MCL) of 0.10 mg/L of total trihalomethanes was set in 1979, without much scientific basis but with a decrease to 0.08 mg/L in 1999 and further reductions proposed for the future. MCLs for other DBPs, haloacetic acids, were added as well. The SDWA Amendments of 1986 obliged the EPA to add 25 new contaminants to the drinking water regulations

every three years. However, this rather unreasonable approach was replaced in the Amendments of 1996 by a more considered protocol, that the EPA develop a Contaminant Candidate List every five years and decide whether to select at least five for regulation (16).

A nine-volume study by the National Academy of Sciences entitled *Drinking Water and Health* estimated that less than 10% of the total organic carbon (TOC) in drinking water has been identified, and a smaller percentage has been characterized for health significance (11); only about 50% of DBPs have been identified (24). The continual recognition of emerging contaminants in drinking water resulting from the presence of human wastewater in the source waters was illustrated by the publication of the results of studies in England and in Switzerland. In 1998 researchers in Britain reported evidence suggesting that pollution from wastewater in rivers from which water supplies are drawn is sufficiently potent to cause fish to be born half male and half female. The study provided new evidence that hormone-altering pollution might well be a global ecological threat. The affected fish were found in eight rivers throughout Britain and elicited the statement, "The incidence and severity of intersexuality...is both alarming and intriguing" (8).

At about the same time, studies in Switzerland revealed that prescription and other commonly used pharmaceutical drugs find their way into wastewater discharges, then rivers into which they discharge, and then drinking water drawn from these rivers (27). Neither wastewater treatment prior to discharge to rivers nor water supply treatment commonly used today are directed at removing SOCs. It was estimated that 50% to 90% of an administered drug may be excreted from the body in its original or its biologically active form while, in other cases, partially degraded drugs may be converted back into their active form through chemical reactions in the water. The studies revealed that 30 of 60 common pharmaceuticals being tested were detected in water. These included lipid-lowering drugs, antibiotics, analgesics, antiseptics, and beta-blocker heart drugs.

The number of contaminants regulated by the federal government has grown exponentially from four in 1925 to 83 in 1996. That many more will be added is certain. That many contaminants and pathogens will go unrecognized is also certain. When water supplies are drawn from sources that receive discharges of wastewaters from urban and industrial areas, a statement that the water meets drinking water standards provides little assurance that it is safe. The water responsible for the Milwaukee cryptosporidiosis outbreak in 1993 met the EPA primary drinking water regulations. The regulations did not then include *Cryptosporidium*.

THE ISSUE OF POTABLE REUSE

The availability of new technology for treating and reclaiming wastewater, including granular activated carbon filtration, various types of membranes, ozone and ultraviolet disinfection and membrane filtration, has encouraged engineers and scientists to adopt a philosophy that this practice would be no different from the practice in those cities already using some of these technologies for run-of-river

supplies. However, only a handful of cities now use these technologies, even when drawing from heavily compromised sources. From a public health standpoint, the goal should be to prevent contaminants from being discharged to water courses that are currently used for drinking, rather than to purposefully increase the number of people exposed to water containing a vast number of contaminants of unknown significance.

To oblige people to drink reclaimed wastewater is seldom necessary. Direct nonpotable reuse can conserve water resources to the same extent as potable reuse while avoiding the public health risks. Furthermore, despite the necessity for the construction of dual distribution systems, nonpotable reuse has been shown to be generally less costly than potable reuse, especially when the dual-system pipelines are installed simultaneously during the construction of new developments. After all, it is the need for water for new populations that requires the additional water supply. Retrofitting pipelines in existing developments would be appropriate only where it can be shown to be more economical than other options for securing additional sources of water. That many such dual systems now provide reclaimed water in cities in the United States and abroad is evidence that even retrofitting reclaimed water systems for nonpotable purposes may be more economical than other options for additional supply.

The only purposeful potable reuse project extant, where reclaimed water is discharged into a drinking water reservoir, is in Windhoek, Namibia. Water from this reservoir is used during periods of serious water shortage. Introduced by engineers from the Republic of South Africa, the practice has never been adopted in the Republic itself.

Examples of Purposeful Indirect Potable Reuse

Potable reuse projects via surface sources have not yet been adopted in the United States. The cities of San Diego and Tampa have each spent millions of dollars on investigations and health studies on projects proposing to introduce reclaimed water into their surface water sources, but both abandoned these projects, in large measure because of public opposition. The Upper Occoquan Sewage Authority in northern Virginia is often cited as an indirect potable reuse project using a surface source, but its purpose was not to add additional reclaimed water to the Occoquan Reservoir, a source of drinking water supply. It was initiated to improve the quality of wastewater already being discharged into the reservoir. The wastewaters, which amount to about 8% of the yield of the reservoir, might well have bypassed the Occoquan Reservoir and been discharged to the Potomac estuary, which is not a source of drinking water. A Congress-mandated study of reuse for potable supply of water from the estuary, which receives Washington metropolitan-area wastewater, was not given much consideration (12).

Three purposeful indirect potable reuse projects are currently in operation in the United States, all involving the discharge of reclaimed waters to aquifers from which water for potable purposes is withdrawn.

Los Angeles County Sanitation Districts The Los Angeles County Sanitation Districts built the first large-scale water reclamation projects in the early 1960s. Six reclamation plants serving sanitation districts within Los Angeles County reclaim wastewater generally for nonpotable reuse for irrigation and for large industrial customers. One of these, the Whittier Narrows Plant in the Montebello Forebay, after conventional tertiary treatment for nonpotable reuse, recharges an aquifer from which local municipalities draw public water supplies, without additional treatment other than disinfection. At the time the plants were constructed, the State of California had not yet adopted regulations pertaining to water reclamation.

Uncertain about the desirability of this indirect potable reuse, and needing to establish regulations concerning such reuse if it were to continue, in 1975 the State appointed a panel of distinguished scientists to study the issue. Its findings were equivocal, but it did recommend that an epidemiological study be made of the Montebello Forebay project. The results of the study indicated that, while there was some quality degradation of water drawn from the aquifer, little in the way of health effects could be established (17). The state appointed a scientific advisory panel about ten years later to reassess the issue, including the results of the study. Their conclusions can be characterized by the first paragraph of their findings:

> As a general guideline, the panel believes the best available quality water in an area should be reserved for drinking water use. Other factors not withstanding, wastewater should not be used as a source unless it can be demonstrated that natural and engineered treatment can be expected to produce consistently a better quality of drinking water than other alternatives. Accordingly, before recharge projects are undertaken, other alternatives such as nonpotable reuse, conservation, other nonstructural measures, and modifications to water rights regulations should be thoroughly evaluated. (28)

The epidemiology study was not believed to be sufficiently robust to justify a finding of “no health effects.” The problem was the inadequacy of establishing exposures. A more recent study at the same site (25) was even less robust.

The State Department of Health Services proposed regulations for groundwater recharge for potable purposes in 1994, but to date the proposal has not been subject to public hearings and is not yet adopted. Part of the problem is that it proposes a limit for total organic carbon (TOC) for which no scientific basis can be established. The carbon in the TOC may be organic materials of no health significance or of great health significance.

Water Factory 21, Orange County, California The Orange County Water District built Water Factory 21 to provide a hydraulic barrier for the prevention of saltwater intrusion into potable water supply aquifers serving Orange County; injection of the reclaimed water into wells 20–75 m deep began in 1976. Withdrawal of some of this water for public water supply was incidental to the barrier.

The source of the reclaimed water is secondary effluent from the Orange County Sanitation District's wastewater treatment plant followed by extensive treatment, including lime clarification for removal of suspended solids, heavy metals, and dissolved minerals; air stripping for removal of ammonia and volatile organic compounds; recarbonation for pH control; mixed media filtration for removal of suspended solids; granular activated carbon adsorption for removal of dissolved synthetic organics; reverse osmosis for demineralization; and chlorination for biological control and disinfection. Such extensive treatment is necessary because deep well injection requires a high-quality clear water to prevent clogging. In addition, the reclaimed water is blended with water from an uncontaminated deep aquifer. Epidemiological studies of the effects of this recharge program have not been conducted.

El Paso, Texas Wastewater from the City of El Paso's reclamation plant is injected into an unconfined aquifer that supplies about 65% of the water needs of El Paso. After secondary treatment, the reclamation processes include lime coagulation, recarbonation, sand filtration, disinfection, and granular activated carbon filtration. Studies of the aquifer indicate that the residence time between injection and extraction would be from five to 15 years.

The Case Against Potable Reuse

The public health issues related to the use of reclaimed wastewater for potable purposes and for irrigation of market crops have been studied recently by three committees of the Water Science and Technology Board of the National Research Council. The reports, *Groundwater Recharge: Using Waters of Impaired Quality* (13), *Use of Reclaimed Water and Sludge in Food Crop Production* (14), *and Issues in Potable Reuse: The Viability of Augmenting Drinking Water Supplies with Reclaimed Water* (15), tend to agree that technology exists for rendering almost any wastewater safe for drinking by current standards, but the uncertainties—particularly regarding trace organics and emerging contaminants in general—impose risks suggesting that the purposeful reclamation of wastewater for potable purposes should be an option of last resort. The use of reclaimed water for market crops is considered safe so long as protective measures are taken for its application and harvesting of the crops.

The National Research Council Committee on Drinking Water Contaminants has examined emerging contaminants in response to the SDWA Amendments of 1996 with the goal of establishing criteria for prioritizing contaminants for future regulatory action (16). Water purveyors that draw from water sources subject to anthropogenic pollution, such as run-of-river supplies, can expect their requirements for monitoring and treatment to become more stringent with time. A fair inference from the fact that an increased number of contaminants will be regulated in the future is that continually greater risks exist for those using compromised sources than for those using supplies drawn from sources relatively free of contamination

from upstream pollution. To purposefully introduce wastewater into relatively well-protected sources has to be seen to be adding to the public health risk to consumers who use such waters. The justification made for potable reuse is that, because some cities already use such water without apparent health effects, potable reuse may provide water as good as or even better than such cities are now using.

Two responses may be made. The first is that the absence of long-term health effects from such exposures has not been and likely cannot be established. Although epidemiology may reveal outbreaks of microbial diseases, establishing the health effects from long-term exposure to trace contaminants, whether microbial or chemical, in water supplies is now beyond the capacity of epidemiology to determine. The degree of exposure to contaminated water is difficult to establish because populations are mobile and their sources of drinking water are highly variable and change over time. Furthermore, populations are subject to exposure to a wide range of contaminants, both microbial and chemical, and establishing which of these is the responsible agent for endemic or chronic disease is difficult.

Second, potable reuse is seldom necessary. Water conservation can be accomplished with nonpotable reuse using dual systems without the health risks associated with continuous ingestion of reclaimed water. Evidence that dual systems represent established practice is the publication in 1994 of the second edition of *A Manual of Practice, Dual Water Systems*, by the American Water Works Association (1). Moreover, the relatively large number of nonpotable systems revealed in the Water Environment Research Foundation study (35) testify to its acceptance. Engineering assessments of the feasibility, including costs and health risks, of the nonpotable option are obligatory before embarking on a decision to select the potable option.

Instances do exist where purposeful potable reuse may not be avoided. One such instance is in Orange County, California. The principal source of water for much of the county is the Santa Ana River, the flow of which, in the lengthy dry periods that characterize southern California, is almost entirely wastewater discharges from communities and industrial and agricultural enterprises upstream. Water from the river percolates into the ground and is withdrawn for water supply downstream. In addition to the natural percolation, some of this river water is impounded in spreading basins for recharging the groundwater. This inherited indirect potable reuse cannot be avoided, but a high degree of treatment of the river water before groundwater recharge can help reduce the health risk.

CONCLUSION

Communities faced with the need for additional water supply for growing populations are routinely adopting a wide array of conservation measures but these are seldom adequate. An option that needs to be evaluated by every community faced with the need for additional water supply is wastewater reclamation for nonpotable purposes in and near the community. Evidence, represented by the many dual

systems that have already been built and that are operating satisfactorily, demonstrates that dual systems are not likely to be more costly than other options available.

Regarding potable reuse, a quotation from the National Research Council report, *Issues in Potable Reuse* (15), is appropriate:

> Our general conclusion is that planned indirect potable reuse is a viable application of reclaimed water—but only when there is a careful, thorough, project-specific assessment that includes contaminant monitoring, health and safety testing, and system reliability evaluation....
>
> Further, indirect potable reuse is an option of last resort. It should be adopted if other measures—including other water sources, nonpotable reuse, and water conservation—have been evaluated and rejected as technically or economically infeasible.

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