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Urban and Agricultural Competition for Water, and Water Reuse

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ABSTRACT *Competition for water can be resolved by construction of more facilities for storing water in wet years for use in dry years, by weather modification, watershed management, urban and agricultural water conservation, reuse of sewage effluent and other wastewater, desalination of saline water, water banking and transfer of water rights or other changes in water use. Reuse of wastewater requires treatment so that the water meets the quality requirements for the intended reuse. Groundwater recharge and recovery can play an important role in the treatment and storage of wastewater for reuse—agricultural, urban, and industrial, as well as potable. Often, water shortages are only shortages of cheap and abundant water, and competition problems can be resolved by good planning and management if the public is willing to pay the price and to accept changes in water use.*

Introduction

Competition for water inevitably develops when there is not enough water to satisfy all demands. Such competition typically ocurs between farmers themselves for irrigation water and between farmers and non-agricultural users of water such as cities (including industries and power plants) and environmental cocnerns (recreation, fish and other wildlife). The first reaction, at least in the USA, is litigation, where each entity tries to get as much water as possible through the courts. Unfortunately, this is costly, slow, does not create any extra water, and, as stated by US Senator Mark Hatfield "the courts are the least competent and qualified to run our natural resources of any group in the goverment" (Center for Irrigation Technology, 1991). Serious water conflicts within a country can lead to unrest and, when more countries are involved, to war (Priest, 1992). Technical solutions to water shortages and competition obviously include development of additional water resources by increasing storage of water during wet periods or other times of surplus water (dams for surface storage and aquifer recharge for underground storage), transporting water long distances from areas of water surplus to areas of water shortages, augmenting precipitation by cloud seeding, watershed management to reduce evapotranspiration, and desalination of sea water or brackish water. Where this is not feasible, the next step is water conservation, urban as well as agricultural. Also, sewage effluents and other wastewaters should be effectively reused. Administrative solutions include equitable distribution of water, transfer of water rights and water banking or marketing. These are voluntary systems where the water essentially goes to the highest bidder while protecting third-party interests (National Research Council, 1992).

Water Conservation

Urban water conservation is achieved by using less water inside and outside the home. Where the sewage effluent from the city is already used for irrigation or other purposes, reducing water use inside homes will not be effective as a water conservation measure. The major water 'losses' in such cities are then due to the outdoor use of water. For example, the city of Phoenix, Arizona, uses about 1000 litres per person per day, but of that only about 400 litres are used inside homes and returned as sewage effluent which is used for power plant cooling and agricultural irrigation. The difference, or 600 litres per person per day, is used for urban irrigation and other outdoor purposes. Almost all of that water, of course, is lost to the atmosphere through evaporation and transpiration. Significant water conservation benefits can then only be obtained by reducing the outdoor use of water, using, for example, more landscaping plants with a low water demand (xeriscapes). Where the sewage effluent is discharged into an ocean or is otherwise wasted or disposed so that it can no longer be reused, reducing indoor water use with low-flush toilets, low-flow showerheads, mandatory water use reductions, fines for excessive water use and rate increases, will also be effective for conserving water. An experimental home in Tucson, Arizona (Casa del Agua) with water conservation features showed that residential water use can be cut from about 600 to 200 litres per person per day (Karpiscak *et al.*, 1990). In many areas of the world, however, domestic water use already is less than 50 litres per person per day and further reductions may be difficult to achieve.

Agricultural water conservation is achieved by using less water for irrigation. Field irrigation efficiencies of surface irrigation systems (basins, borders, furrows, etc.) often are notoriously low and seldom exceed 60%, meaning that less than 60% of the water applied to the field is actually used by the crop (evapotranspiration). The rest of the water (more than 40% of the water applied) is perceived as a loss by many people, especially urbanites and other non-agriculturists. These people often think that agriculture can conserve or 'save' water by increasing the irrigation efficiency with better design and management of the surface irrigation systems or by using sprinkler or drip irrigation systems. The water thus 'saved' could then be used for municipal or other non-agricultural purposes. This, of course, is not true. Water 'losses' from surface-irrigated fields consist of runoff at the lower end of the field (tail water) and/or deep percolation of water that passes through the root zone and moves on down to the groundwater. In many cases, however, tail water is collected by lower ditches or pumped back, and deep percolation water joins underlying groundwater from where it can be pumped from wells or drain to surface water for further use. Because of this reuse of tail water and deep percolation water, irrigation efficiencies of large irrigated areas (basins, valleys, etc.) are much higher than those of individual fields; for example, 90% or more. The main problems with reuse of deep percolation water have to do with water quality degradation, since this water contains much more salt than the original irrigation water and possibly also residues from agricultural chemicals such as nitrates and pesticides

(Bouwer, 1990). Where groundwater levels are high and deep percolation water is collected by agricultural drains, the effluent from such drains can pose severe water quality problems and may have to be isolated from the water resources system by disposal into evaporation ponds, salt lakes or oceans. Where deep percolation water and tail water are not used again, increasing field irrigation efficiencies will indeed save water. Where these 'losses' are used again, however, increasing field irrigation efficiencies will not save water. The only incentive for increasing field irrigation efficiencies then will be application of less water to the fields, which will reduce energy costs where the water is pumped, and also reduce leaching of fertilizer out of the root zone.

Where deep percolation and tail water runoff are used again for irrigation, agricultural water use can only effectively be reduced by reducing evapotranspiration. This can be achieved by reducing the irrigated area, by growing fewer warm-season crops like cotton and more cool-season crops like vegetables, by growing more short-season or low water-use crops (jojoba, guayule, lesquerella and similar new, industrial crops), by reducing soil evaporation (mulching, drip irrigation), and by growing more crops for direct human consumption and fewer crops that are converted into animal products (production of 1 kg of meat requires a lot more water than 1 kg of wheat or soybeans).

Water Banking and Transfers

A new tool to mitigate problems of competition for water is water banking. California, for example, instituted a water banking or marketing system in 1991, which was prompted by four years of drought and serious competition for water. Under this system, entities with excess water, wastewater, alternative water resources (groundwater, for example), or no critical need to use their water, can sell their water to the bank. Entities with critical water needs can then buy the water from this bank with the proceeds going to the seller. There are two key factors for such a bank to be successful: volunteerism and a good water distribution network. Volunteerism is essential. No entity likes to be forced to give up water. However, if a farmer can make more money with his water by selling it to the bank then by growing a low-value crop with it, depositing the water into the water bank will be financially attractive. Farmers with their own wells and access to groundwater can make money with the banking system by selling their surface water entitlements to the bank for more money than it costs them to pump their own groundwater. The second factor, a good water distribution system, is, of course essential so that the water can be moved from one place to another. California has such a system in place with its California Aqueduct and other water-conveyance facilities. These make it possible, for example, for a rice farmer in northern California to sell his water for irrigation of orchards and vineyards in central California or for municipal use by the cities in southern California. The water bank is so successful that it already acquired 850 million m^3 or 700 000 acre feet in the first year and water purchases may ultimately total about 1200 million m^3 or one million acre feet (Vaux, 1991). Municipal wastewater could also be deposited in the bank, if properly treated so that it can be used for unrestricted irrigation and if it does not mix with water to be used for drinking.

A more permanent approach is water transfer, which is the transfer of water or water rights from existing uses to other uses at market value in response to changing values (i.e. more environmental concerns) and changing needs (i.e. more water for cities) in a dynamic society (National Research Council, 1992). In the western USA, for example, water is moving from agriculture and mining to urban and environmental uses. The latter includes instream values like fish, aquatic life, recreation and riparian habitat; and lakes, wetlands and wildlife refuges. While such transfers are basically voluntary and in response to mutual needs, the interests of third parties not directly involved in the transfers should be protected (National Research Council, 1992). Such third parties may be nature lovers or recreationists whose streams, lakes and wetlands may be threatened by the transfers, and farmers whose irrigation water may become polluted with sewage effluent as municipalities transfer good quality water from streams or canals for their own use and put it back as sewage effluent further downstream. The sewage must then be treated so that yields and quality of crops of downstream farmers are not unfavourably affected (Baier & Fryer, 1973), and the health of irrigators and people consuming the crops (especially fruits and vegetables eaten raw) is not jeopardized (see section on quality standards for irrigation with sewage effluent).

Water Reuse

In arid to semi-arid areas, the consumptive use of water by irrigated agriculture often is much more than the municipal-industrial water use. In California and Arizona, for example, irrigation uses about 80–85% of the total amount of diverted water. Needless to say, during water shortages and competition for water the cities would like to see the agricultural use reduced so that more water is available for urban use. This is acceptable only if done through a voluntary water banking, marketing or other transfer system. However, the cities could also reduce their outdoor use of water so that more of the water going into the city is used in a non-consumptive manner and comes back as sewage effluent, which can then be reused. Although potable recycling is now technically possible and economically feasible (Bouwer, 1992a, b), it is generally considered an option of last resort and most of the reuse of sewage effluent presently will be for irrigation (municipal as well as agricultural) and other non-potable purposes (cooling water, industrial process water, toilet flushing, car washing, construction, etc.). Municipal irrigation includes road plantings, parks, playgrounds, golf courses and cemeteries. New housing developments are increasingly equipped with dual water distribution and plumbing systems, so that treated municipal wastewater can also be used for irrigating private gardens and indoors for non-potable purposes such as toilet flushing. For agricultural irrigation, cities can sell the treated effluent to farmers or other irrigation districts, or they may exchange it for good quality irrigation water that can then be used to augment municipal water supplies. Such exchanges can also be worked out on a larger scale through a water banking system. For effective wastewater reuse, the effluent must then be treated so that it meets the requirements for unrestricted municipal and agricultural irrigation and for water based recreation. Also, sewage treatment plants should be located near the point of water reuse or existing distribution systems to avoid high conveyance costs. This requires a change in the philosophy of sewage treatment systems from treatment and disposal to treatment and reuse. Increasingly, small, satellite plants are built to provide reclaimed water for local reuse. These plants often are in populated areas so they should be 'neighbourhood friendly' (attractive buildings and landscaping, no odours, no noise). Normally, they do not process sludge but return it to the sewer for processing in the main plant further downstream.

Quality Standards for Irrigation with Sewage Effluent

Agricultural irrigation with sewage effluent typically requires that the effluent be treated for unrestricted irrigation, so that farmers can grow the crops they want to grow and use the irrigation system they want to use. If the effluent is only partially treated, there should be negotiations beteeen the municipalities and the farmers to see how the farmers should be financially compensated for not being able to grow the crops they want.

There are now two main pubic health water quality criteria for unrestricted irrigation with municipal wastewater. One standard is mostly for developed countries which are technically and financially capable of high-technology treatment. The other is a set of guidelines mostly for developing countries which cannot support expensive, high-technology treatment and where stringent health standards would lead to no treatment at all and the use of raw wastewater for unrestricted irrigation, which of course is completely unacceptable. The standard for developed countries is patterned after California's Title 22 Effluent Reuse Standards (Bouwer & Idelovitch, 1987; Pettygrove & Asano, 1985; Shelef, 1990), and calls for treatment of wastewater so that it is essentially free from pathogenic organisms (no faecal coliforms, no viruses, no eggs of parasitic worms) and has low turbidity (less than 2 nephelometric turbidity units). This can be achieved with conventional primary and secondary treatment followed by coagulation (sometimes with sedimentation), granular media filtration, and chlorination or other disinfection. After this treatment, the water is also suitable for urban irrigation (including parks and playgrounds). recreational lakes and most other non-potable uses. Where hydrogeological conditions are favourable for groundwater recharge with inflitration basins, the movement of partially treated wastewater through soils and aquifers may clean the wastewater sufficiently so that it can be collected from the aquifer as such for unrestricted irrigation, as discussed later in this paper. The guidelines for unrestricted irrigation in developing countries, as established by the World Health Organization (1989), call for a maximum faecal coliform concentration of 1000/100 ml and a maximum concentration of helminthic eggs of 1 per litre. This can be achieved by lagooning with sufficient detention times (for example, one month in warm regions). The lagoon effluent will then also have greatly reduced concentrations of bacteria and viruses.

The WHO standards are based on public health effects as manifested by documented disease outbreaks (epidemiology), and on feasibility of treatment system. Case histories of disease outbreaks due to irrigation with poorly treated wastewater showed that they were mainly caused by intestinal nematodes or parasitic worms (helminthic eggs such as *Ascaris* and *Trichuris* species and hookworm, where endemic). It was also concluded that the presence of pathogenic organisms in the wastewater does not necessarily mean disease outbreaks, especially if the organisms are present in sufficiently low concentrations and/or there is local immunity. On the other hand, the much more stringent California-type standards are based on avoiding the presence of pathogens in wastewater, regardless of whether they are capable of causing diseases or not, and the essentially complete elimination of such pathogens in the treatment process. This may be the preferred approach where such treatment is feasible, where the public demands zero or minimum risk, and where municipalities, irrigation districts and farmers need to protect themselves against lawsuits in case of disease outbreaks where contaminated agricultural products are implied (Shelef, 1990). Another factor to consider is whether the crops will be entirely consumed by local people with built-up immunities to certain diseases, or whether the crops will also be consumed by outsiders (visitors to the region or people in other regions to which the crops are exported). If the crops are also consumed by outsiders, the more stringent standards should apply.

Of course, all these comments apply to unrestricted irrigation, which includes irrigation of crops consumed raw or brought raw into the kitchen. For other crops (fibre and forage crops, orchards, etc.), the standards are less strict (Bouwer & Idelovitch, 1987; Pettygrove & Asano, 1985). In addition to public health considerations, agronomic factors should also be considered and the wastewater should meet the normal quality requirements (salinity, sodium adsorption ratio, nitrogen, toxic and trace elements, etc.) for irrigation water (Bouwer & Idelovitch, 1987, and references therein; Pettygrove & Asano, 1985).

Potable Recycling of Wastewater

Where there is no irrigated agriculture near the city or where it is otherwise not feasible to use water for municipal purposes first and then, after suitable treatment, for irrigation, cities with insufficient water resoures may have to go to complete internal recycling of the water, including potable use. There is, of course, nothing mysterious or sinister about wastewater reuse, but the wastewater has to be treated so that it meets the quality requirements for the intended reuse. Indirect recycling of municipal wastewater has, of course, been going on for ages along rivers that are used both for disposal of wastewater and for municipal water supply. If the pollution level in such rivers is moderate, cities are giving the water essentially conventional treatment (coagulation, sedimentation, sand filtration and disinfection) before using it for drinking. If the pollution is severe, activated carbon adsoption in included, usually as powdered activated carbon added during the flocculation-sedimentation process. Sometimes, granular activated carbon adsorption, cascade aeration and ozonation are also used. Where streamflows and/or source water quality vary, surface storage of raw water may be desirable so that water can be stored during high flows with good dilution of pollutants for use during periods of low flows or other episodes when the river water is of low quality and should be avoided. This is done, for example, by the city of Rotterdam in The Netherlands (Kuyt, 1978). Some systems use bank filtration or other groundwater recharge and recovery systems to take advantage of the quality improvement obtained when wastewater or polluted water moves through soils and aquifers (see section on soil-aquifer treatment).

Direct recycling requires advanced wastewater treatment (AWT) of the sewage effluent after conventional primary and secondary treatment. Normal drinking water standards cannot be used to determine whether the water after AWT is suitable for drinking, because such standards apply only to situations where the water source is relatively unpolluted. Wastewater, however, contains many chemicals, perhaps hundreds or thousands, that enter the sewer system with residential and industrial discharges. Since it is practically impossible to develop maximum contaminant levels (MCLs) for all these chemicals in drinking water and to monitor for all these chemicals in the water after AWT, potable recycling of wastewater requires that the treatment processes be specified, rather than setting a multitude of MCLs for chemicals that may be in the product water. The AWT processes must then be tested in pilot or demonstration-type projects where the suitability of the product water for drinking can be ascertained by chemical analyses, biomonitoring and bioassays. For full-scale operations, only biomonitoring and monitoring of certain surrogate-type quality parameters (pH, turbidity, TOC, etc.) then need to be done routinely to make sure that the treatment processes are working correctly. Such pilot-demonstration type projects can also serve as public information centres to develop proper community relations and to gain public acceptance. Without such acceptance, potable recycling of wastewater is impossible.

An example of a pilot/demonstration project is the Denver, Colorado, Potable Water Reuse Demostration Project (Lauer, 1990). This project takes conventionally treated effluent (activated sludge, plus coagulation and sedimentation, and some denitrification) and converts it into drinking water with the following treatment train: lime clarification, recarbonation, granular media filtration, ultraviolet irradiation, granular activated carbon adsorption, reverse osmosis, air stripping, ozonation and chloramination. These steps were selected to provide the necessary treatment, redundancy and multiple barriers against the various contaminants. For example, bacteria and viruses are removed by lime clarification, ultraviolet irradiation, reverse osmosis, ozonation and chloramination. These processes, except chloramination, also remove protozoa. Organic compounds are removed by lime clarification, activated carbon adsorption, reverse osmosis and air stripping. Except for air stripping, these processes also remove inorganic compounds, including metals. The total costs (amortization plus operation and maintenance) of this advanced treatment in August 1988 US dollars and projected to a 0.4 million m^3/day plant were about \$600 per 1000 m^3 (personal communication, W. C. Lauer, 1990). To this amount must be added the costs of the primary and secondary treatment, which was approximately \$100 per 1000 m^3.

An example of an operational facility is the El Paso, Texas, Water Recycling System. This system has a capacity of about 40 000 m^3/day and presently treats about 27 000 m^3/day. The treatment train consists of primary treatment, secondary treatment (aeration) with addition of powdered activated carbon, denitrification with addition of methanol as energy source, lime clarification, recarbonation, sand filtration, ozonation and granular activated carbon adsorption. The water is then injected through wells into an aquifer, from where it is pumped for municipal use from production wells about 3 km downgradient from the injection wells. Projected underground travel times from the injection wells to the production wells were in the order of 2 to 4 years, but may actually be shorter due to faster flow through the more permeable layers of the aquifer. The total cost of the treatment process (excluding well injection) is about \$700/1000 m^3. Well injection, rather than groundwater recharge with infiltration basins, was selected for the El Paso project because the groundwater was relatively deep, undesirable chemicals could leach from the vadose zone, and the groundwater at the top of the aquifer was of poor quality. Thus, water after

AWT was directly injected into the deeper layers of the aquifer system where the groundwater was of good quality. For additional discussion of the role of well injection and recovery from the aquifer in the recycling process, see the section on well injection at the end of this paper.

Soil-Aquifer Treatment

Where surface soils are permeable, vadose zones have no restricting layers, aquifers are unconfined and there are no undesirable chemicals in the vadose zone and aquifer, groundwater can be artificially recharged by surface infiltration systems (special basins or spreading systems like dams or T-levees in streambeds or floodplains; Bouwer *et al.*, 1990). When this recharge is done with partially treated sewage effluent, considerable quality improvement of the effluent water is obtained as it moves downward through the vadose zone and laterally through the aquifer. The effluent water can then be recovered as renovated water from strategically located wells (Figure 1) or other recovery facilities (drains if the groundwater is high). This 'treatment' benefit often is the main purpose of the recharge and recovery system, and the process is no longer called artificial recharge of groundwater or recharge and recovery, but soil-aquifer treatment (SAT) or geopurification. Where there are natural groundwater gradients, modelling of the groundwater flow system may be needed to obtain the best location for the recovery wells (Ratzlaff *et al.*, 1992).

The infiltration basins are intermittently flooded (for example, two-weeks flooding, two-weeks drying) to provide for aeration of the soil and removal of biodegradable material, for proper nitrogen transformations to enhance nitrogen removal by denitrification, and to restore infiltration rates that normally decline during flooding because of the accumulation of fine particles and other clogging material on the bottom. Periodically, the basins may also have to be cleaned by removing the clogging layer by 'shaving' the bottom with a front-end loader, raking or other technique. Disking or ploughing mixes the clogging layer into the soil. This may give temporary improvement in infiltration but in the long run the entire upper soil layer will become clogged with fines and must be replaced or removed.

The performance of SAT systems depends on local conditions of soil, hydrogeology, climate and wastewater quality. In new areas where there is no local experience with SAT systems, pilot or experimental projects should be installed to evaluate the local feasibility of SAT and how the full-scale system should be designed and managed for optimum performance. Typical quality improvements obtained in a pilot and a demonstration project west of Phoenix, Arizona are shown in Table 1 (Bouwer & Rice, 1984; Bouwer, 1991, 1992a). Heavy metal concentrations in the recovery well samples were not determined. Older analyses for the pilot project indicated significant removal of most metals in the soil and very low concentrations after SAT (Bouwer, 1992a). The virus level of 2118 PFUs per 100 litres was determined when unchlorinated secondary effluent was used for the pilot project. The vadose zone and the aquifer in the demonstration project consisted mostly of sand and gravel layers. The groundwater table was at a depth of about 17 m. There were four parallel infiltration basins totalling 16 ha of wetted area. The recovery well was in the centre of the basin area and pumped renovated sewage water from 30 m to 55 m depth.

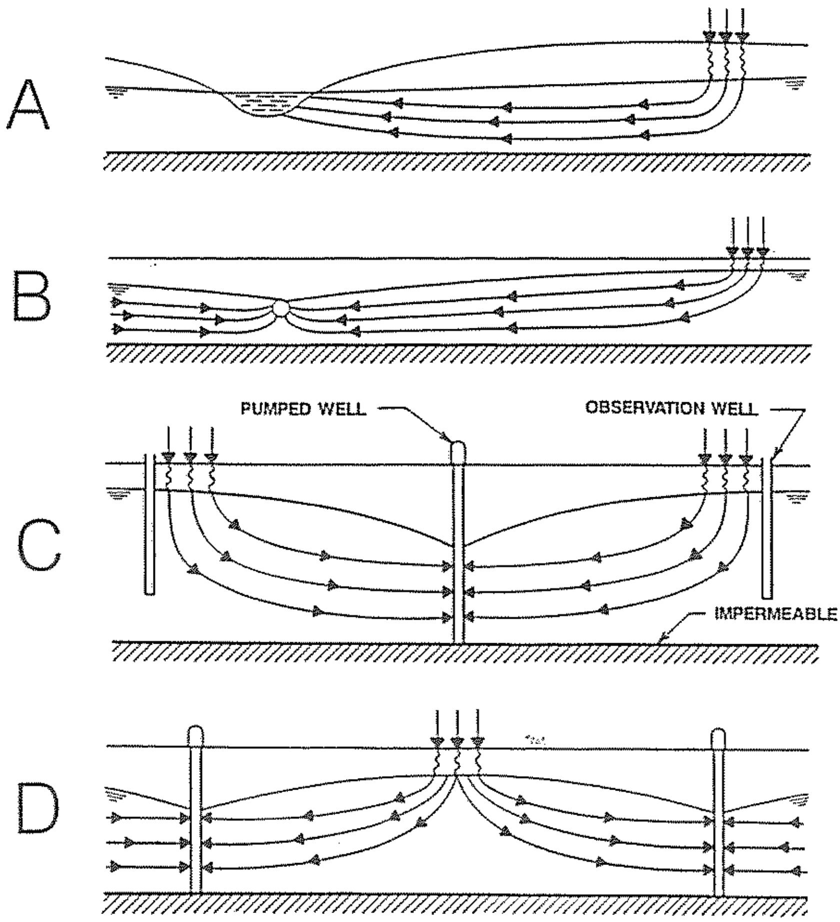

Figure 1. Schematic of soil-aquifer treatment systems with (A) natural drainage of renovated water into stream, lake, or low area, (B) collection of renovated water by subsurface drain, (C) infiltration areas in two parallel rows and line of wells midway between, and (D) infiltration areas in centre surrounded by a circle of wells.

The water in Table 1 after SAT meets the stringent, California-type health requirements and the chemical quality requirements for unrestricted irrigation and recreation (Pettygrove & Asano, 1985; Shelef, 1990). Most of the cost of treating water with a soil-aquifer treatment system consists of the cost of pumping the water from the recovery wells, which may be in the order of \$20 to \$50 per 1000 m^3, depending on the depth to groundwater. Thus, treating municipal wastewater with SAT is much cheaper than tertiary in-plant treatment to meet the requirements for unrestricted irrigation and recreation, which may cost \$100 to \$500 per 1000 m^3 (Ashcraft & Hoover, 1991; Richard *et al.*, 1991). In addition to cost savings, SAT also offers an opportunity for underground storage of water by, for example, allowing groundwater levels to rise during the winter when irrigation demands are low and pumping groundwater levels down in the

Table 1. Quality parameters from Phoenix, Arizona, SAT system*

	Secondary effluent mg/l[a]	Recovery well samples mg/l[b]
Total dissolved solids	750	790
Suspended solids	11	1
Ammonium nitrogen	16	0.1
Nitrate nitrogen	0.5	5.3
Organic nitrogen	1.5	0.1
Phosphate phosphorus	5.5	0.4
Fluoride	1.2	0.7
Boron	0.6	0.6
Biochemical oxygen demand	12	0
Total organic carbon	12	1.9
Zinc	0.036	
Copper	0.008	
Cadmium	0.0001	
Lead	0.002	
Faecal coliforms per 100 ml	3500	0.3
Viruses, PFU/100 l	2188	0

*For midly chlorinated secondary effluent (activated sludge): [a] as it entered the infiltration basins and [b] after SAT and pumping it from a well in the centre of the infiltration basin area.

summer when irrigation demands are high. In-plant tertiary treatment does not have this built-in opportunity for seasonal storage, thus making it necessary to build surface storage facilities which makes the reuse process more expensive.

If the water after SAT is to be used for drinking, it needs additional treatment. Research may be required to evaluate the optimum treatment process. For the water after SAT in Table 1, the additional treatment may consist of activated carbon filtration to remove the residual organic carbon (TOC), reverse osmosis on about half the flow to lower the TDS to below 500 mg/l and remove additional TOC, and disinfection (possibly ultraviolet irradiation). Since SAT elimates the lime precipitation and other steps in the Denver AWT process to convert secondary effluent to drinking water, and since SAT itself is rather inexpensive, the use of SAT as a pretreatment thus offers considerable cost savings in the potable recycling of sewage effluent. Preliminary cost estimates indicate that the savings may be about 50%, i.e., from about \$600 per 1000 m^3 for complete AWT to about \$300 per 1000 m^3 if SAT is used first and post-treatment is applied to the water after it is pumped from the recovery wells (Bouwer, 1992b). In addition to the monetary benefits, SAT also offers the very important psychological advantage that it breaks the direct, pipe-to-pipe connection of the reuse system, because water after SAT comes out of a well as 'groundwater' and has lost its stigma and identity of municipal wastewater. This enhances the aesthetics and public acceptance of potable reuse of municipal wastewater, which is especially important where there are religious or cultural objections against the use of sewage effluent. The opportunity for underground storage in SAT systems to absorb differences between supply and demand of recycled water can also be important.

Well Injection

Where SAT with infiltration systems is not feasible because suitable surface soils are not available, vadose zones have restricting layers or are otherwise unsuitable, and/or aquifers have poor quality water at the top or are confined, groundwater recharge can be achieved with injection wells. Since aquifer materials often are relatively coarse, the treatment benefits of flow of wastewater through aquifers tend to be small. Also, to prevent clogging of the aquifer interface around the recharge well, the water should first be treated to remove all suspended solids, BOD, nutrients and microorganisms. A residual chlorine content is also necessary to minimize bio-clogging of the well and aquifer. Thus, wastewater for well injection should be treated essentially to drinking water standards before it goes into the well. Also, injection wells should be pumped frequently for short periods of time and periodically redeveloped to maintain injection capacity. For these reasons, groundwater recharge through wells is much more expensive than recharge with infiltration basins. However, the recharge process with wells still offers the benefits of storage in the aquifer, enhanced aesthetics and public acceptance for potable reuse of the water (no pipe-to-pipe connection), and the 'polishing' treatment obtained in the aquifer. To maximize the latter, production wells should be a significant distance (1 km or more, for example) from injection wells to allow for sufficient distance and time of underground travel. An example of the sequence of advanced wastewater treatment-injection wells-pumped wells is the system used by the city of El Paso, Texas, as discussed earlier in this paper.

Conclusions

Several approaches, singly or in combination, can be used to resolve issues resulting from competition for water due to demands that exceed supplies. One approach is to develop more water resources by building more dams and/or groundwater recharge projects to store more water in wet periods for use in dry periods. Also, weather modification to increase precipitation may be successful, especially when done during rainy periods when there is already a lot of water in the atmosphere. Desalination of ocean or brackish water is also an option, but it is expensive. Another approach is water conservation, urban as well as agricultural. Conservation is most effective where it reduces the return of water to the atmosphere by evaporation or evapotranspiration, the movement of water to salt lakes or other bodies of impaired water quality, or to vadose zones or other places from where it is not readily recovered. Another solution for competition issues is to shift water use from uses with low economic returns to those with high economic returns. This can be achieved effectively, with voluntary systems of water banking or transfers, where the water essentially goes to the highest bidder, the entity that gives up its water is satisfied with the financial compensation it receives, and third-party interests are properly protected. Finally, municipal and other wastewater can be reused. This requires that the wastewater be treated so that it meets the quality requirements for the intended use. This can be achieved with various in-plant treatment processes and with soil aquifer treatment or geopurification as obtained with groundwater recharge and recovery systems. The product water from such recharge projects can meet the quality requirement for unrestricted agricultural and urban irrigation and