Abstract

While the earth's renewable water resources are finite, the earth's population continues to increase and requires more and more water for municipal, industrial, agricultural, environmental, recreational and other needs. Water resources must be better managed on a local, regional, national, and international scale. This includes providing more storage of water during times of water surplus, minimizing water losses, increasing food production per unit of water, transferring water to uses with higher socioeconomic returns, and reusing wastewater. Sewage effluent often already is indirectly used, but water reuse in the future must be better planned as sewage flows increase, the public health and surface water quality need to be protected, and edible crops need to be irrigated. Planned water reuse requires adequate treatment so as to meet the quality requirements of the intended reuse. Agricultural and urban irrigation will play an important role in water reuse, especially in dry climates.

Keywords: International water competition; Water resource management; Water reuse; Sewage effluent; Groundwater recharge; Wastewater treatment; Health effects; Water conservation

1. Introduction

The earth's population is projected to double from the present 5.6 billion to about 10 billion by the year 2050 (U.N. Population Fund, 1993). Most of this increase will occur in the Third World, where close to 90% of the world population will then live. Also, people will continue to migrate from rural areas to cities and already by the end of this century, there will be 22 megacities (population more than 10 million), 18 of which will be in the Third World. Such cities have mega water needs, produce mega sewage flows, and will have mega problems. Already now, it is estimated that half the people in the Third World have no access to safe drinking water, that one billion get sick every year from water-borne diseases, and that 12 million die, 80% of which are children. Also, more water will be
needed for irrigation of crops to provide enough food for the expanding population. Competition for water will become increasingly intense.

Populations in industrialized countries will remain rather stable, except perhaps in the U.S. where the population may double in the next century, depending on immigration policies. However, increasing environmental concerns in First World countries will increase water demands for instream benefits, wetlands and other nature areas, and recreation. This often leads to conflicts and polarization between interest groups, as for example, in the western U.S. where there are issues like fish vs. farming, fish vs. hydropower, river beaches vs. hydropower, and riparian habitats vs. grazing.

The most common limiting factor in population expansion is the availability of water resources. As a rough estimate, a renewable water supply of at least 2000 m$^3$ per person per year is required to provide an adequate standard of living (Postel, 1992). When the water supply drops to between 1000 and 2000 m$^3$ per person per year, the area is considered water-stressed, and below 1000 m$^3$ per person per year, it is considered water-scarce. Water resource planning in China is based on about 500 m$^3$ per person per year, including planned water reuse.

2. Water resource management

Water resources can be locally or regionally increased by cloud seeding. The significance of this practice is still debated and studied. Desalination will enable use of seawater in coastal areas and/or salty groundwater in inland areas. Desalination is expensive; i.e. about $1 per 1000 m^3$ for every 10 mg/l salt removed with reverse osmosis, or about $2000 to $3000 per 1000 m^3$ for seawater. For inland areas, large-scale desalination presents problems of disposal of the reject water (brine), which may have to be flash-evaporated with disposal of the salts in landfills or other designated depositories. Above all, increasing demands for water will require more intensive management of water resources and water conservation. There must be more storage and regulation of stream flow to store water during times of water surplus for use in times of water shortage. The traditional approach of building more dams may not be the best solution because the world is running out of good dam sites and dams have a finite useful life, structurally as well as due to sediment accumulation. Also, environmental and social opposition to dams is growing (Pearce, 1992). Thus, there must be more underground storage of water through artificial recharge with infiltration basins or recharge wells. While basins currently are the most common technique, recharge through wells will increase in the future as good sites for surface infiltration will no longer be available. The transition from basin recharge to well recharge is already taking place in The Netherlands, where the population density is very high, land is at a premium, and people do not want to change land use and disturb natural ecosystems. Future water management must also emphasize water conservation which means different things to different people, but can best be defined as minimizing water losses (i.e. movement of good quality water to places from where it cannot readily be recovered, such as evaporation, transpiration, discharges into oceans or salt lakes, seepage to salty groundwater, formation of perched groundwater or other water in the vadose zone, etc.), and avoiding such serious deterioration of water quality that treatment is too expensive. Treatment and planned use of sewage
effluent or other wastewater also will become increasingly necessary. Reuse and recycling are the ultimate forms of resource management, and water is no exception.

Increasing demands for water will lead to fierce competition for water. On a national scale, this can lead to unrest and internal strife. Internationally, wars can erupt. Diplomacy and conflict management will become increasingly important in settling water disputes (Fried, 1992). Hopefully, countries eventually will have to spend so much money on water projects that there is no money left for war!

3. Food production and irrigation

The increasing population will also require more food and in many areas this will mean more irrigation. Of course, this presents a collision course because while more and more irrigation is needed for food production, less and less water will be available for irrigation because of municipal and industrial demands. At the beginning of this century, 90% of all the water use in the world was for irrigation. By 1960 it was about 80%, currently it is about 70%, and by the year 2000 it is expected to be about 60% (Biswas, 1993). Water use for irrigation is still increasing, but at a slower rate and not as fast as municipal and industrial use. Thus, the mandate is clear: more food must be grown with less water. This means more intensive agriculture and use of more fertilizer and pesticides, but this will cause more groundwater pollution with agricultural chemicals (Bouwer, 1990). This is very serious, considering that groundwater is a major water resource and that there is about 67 times more fresh water stored underground within drillable distance than in all the rivers and lakes of the world (Bouwer, 1978). Surface water can also be affected. Most of the fresh water of the world is stored in polar ice caps, but this is not of much use to people. Best management practices (BMPs) for groundwater and surface water quality protection, low input sustainable agriculture (LISA) and concerns about pesticide residues and nitrates in groundwater will be hard to promote in Third World countries, where the main problem often is where the next meal is coming from and not long-term health effects and environmental concerns. In addition to nonpoint source pollution by agriculture, which can involve vast areas, groundwater in the future also will be very much at risk because of tendencies toward groundwater overdraft in water-short areas.

Since irrigation uses so much water, there will be pressure to increase the irrigation efficiency, particularly since the public often perceives irrigation as a wasteful use of water (Bouwer, 1993a). The inefficiency of irrigation is mainly due to deep percolation and tail water runoff losses, which cause individual field efficiencies to be low (less than 40% with poor design and management). However, since these "losses" are often used again by drainage of groundwater and surface water into streams, by pumping groundwater, and/or by collecting drainage or tail water for irrigation of lower fields, the irrigation efficiencies of large irrigated areas (valleys, districts or basins) often are much higher than those of individual fields, and can reach more than 90%. In many large irrigated areas, very little water actually leaves the system, in accordance with the principle that "the upper basin's inefficiency is the lower basin's water source". The main water loss in irrigated agriculture is evapotranspiration. This is a consumptive use of water that really cannot be reduced by
increasing irrigation efficiency. The only way to reduce the consumptive use of water in irrigated agriculture is to reduce the irrigated area (with possible increases in crop yield per unit water used so that total production remains the same), to grow more cool season crops and fewer warm season crops, to reduce evaporation by mulching or microirrigation, to grow more drought tolerant crops, and to grow fewer forage and grain crops for conversion into animal meat and more crops for direct human consumption.

Irrigated areas basically are large evaporation pans where distilled water is returned to the atmosphere in the vapor phase, and salts remain behind in the soil. Thus, salinity must be very carefully managed to ensure a sustainable irrigated agriculture. For coastal areas, salty irrigation return flows can be discharged into the ocean. Where river water is used for irrigation, these salts would have reached the ocean anyway, but with more water and in lower concentrations. For inland areas, salts can be “stored” for a while in vadose zones, aquifers, lakes, and evaporation ponds, but eventually salt depositories must be created where salts from irrigated areas can be concentrated and stored “forever.” Such depositories include evaporation ponds for drainage water, brine disposal areas for reverse osmosis (RO) reject water, and salt disposal areas for final residues of evaporation ponds and salts from desalting of water.

4. Greenhouse effects and climate change

The CO₂ concentration of the atmosphere is increasing, and climate modelers have predicted a consequent global warming and changes in precipitation patterns. The report of the Intergovernmental Panel on Climate Change edited by Houghton et al., (1990) projects CO₂ increasing from present day concentrations of about 350 μmol/mol (0.035%) to over 800 μmol/mol (0.08%) by the end of the next century if no steps are taken to limit CO₂ emissions. They predict this increase in CO₂ plus that of other radiatively active “greenhouse” gases – methane, nitrous oxide, chlorofluorocarbons (CFCs), ozone – would cause an increase in global mean temperature of about 4.2°C. Some regions might receive increases in precipitation, while others might receive less. However, these climate change predictions are very uncertain. The climate models are greatly simplified representations of very complex systems, and there is disagreement within the scientific community regarding the validity of the predictions (Brooks, 1989).

Regardless of whether climates change or not, the increasing atmospheric CO₂ concentration is likely to affect the growth of all plants, including agricultural crops. In the absence of climate change, a doubling of CO₂ concentration is likely to increase yield of most crops, perhaps 30% or more on the average (Kimball, 1983, 1986). Moreover, there appears to be a strong interaction with temperature, such that crops growing in warm climates are likely to benefit more from increased CO₂ than those growing in cooler climates (Idso et al., 1987; Allen et al., 1990). Elevated levels of CO₂ also tend to cause stomates to partially close, thereby reducing water loss per unit of leaf area (Kimball et al., 1993). However, leaf temperatures also tend to increase, and with larger leaf areas under high CO₂, water use per unit of land area appears to be minimally affected (Kimball et al., 1993). Nevertheless, the greater growth with high CO₂ on roughly the same amount of water represents a substantial increase in crop water use efficiency. On the other hand, increasing levels of ozone and other pollutants in the atmosphere and photochemical smog will damage plants
enough to cause significant reductions in crops. This effect will be most noticeable in industrialized countries, where also most of the world's food is produced (Chameides et al., 1994).

5. Water transfers

As water resources become scarcer, there will be a trend of shifting water use from low economic returns to higher economic returns, which will include transfers of water from agricultural to urban uses (National Research Council, 1991). In some countries, water is owned by the state and water transfers can be handled by decree. In other countries, water rights belong to individuals and private interests. Water transfers must then be based on three principles: voluntarism, infrastructure, and third party interests. Firstly, voluntarism is necessary because water cannot just be confiscated from the farmers. There must be willing sellers and buyers, and economic incentives. If, for example, farmers can make more money with their irrigation water by selling it to a city instead of using it for growing low value crops, they may be more than willing to sell it. Also, farmers may have both surface water rights and rights to groundwater which they can pump with their own wells. If they can sell their surface water for more money than it costs them to pump groundwater, they can sell their surface water to cities and pump groundwater for their own use. Of course, this should be carefully managed to make sure that there is no unacceptable groundwater overdraft. The second principle for successful transfer of water is that the area must have a good infrastructure of water conveyance facilities so that water can be moved around. The third principle is that third party interests must be protected. These interests can include various aspects of the local rural economy, like agricultural jobs and businesses that depend on agriculture. Loss of jobs and business often is offered as a serious argument against transferring water from agricultural areas to urban areas. However, these economic effects tend to be gradual as water transfers start small and increase slowly. Also, they are not different from the general economic dynamics that are occurring all the time (for example, layoffs and plant closings by industries large and small, closing of military bases, urban expansion, etc.).

Third party effects also include environmental considerations. For example, if a city begins to divert more water from a stream and returns that water to the stream in the form of sewage effluent, the interests of downstream users of that water must be protected. Affected persons can include farmers that use the water for irrigation which may require additional nitrogen removal from the sewage effluent when the crops include sugar beets, malting barley, alfalfa, or others that cannot have nitrogen in the later stages of the growing season. Also, the water should be pathogen-free to permit unrestricted irrigation if farmers want to grow lettuce and other vegetables consumed raw or brought raw into the kitchen. Recreational uses of the stream also may have to be protected, so that the city must treat the sewage to meet the requirements for primary contact recreation (no pathogens). To protect aquatic life, cities may have to remove more nitrogen, organic compounds, metals like copper, and other chemicals from the effluent that are toxic to aquatic life. Often, these problems and conflicting interests are resolved by litigation. A better approach is for the cities, farmers, environmentalists, etc. to get together and work out the best scheme of water diversion for urban use, sewage treatment before returning the effluent to the stream, and
seasonal storage. In California, water transfers are handled through a water banking system, where farmers can sell their water to the bank and municipalities and other entities in need of more water can buy the water. At the end of the California drought from 1987 to 1993, the water bank handled about 1000 million m³ per year (Bouwer, 1993a). Of course now that the drought is over, the interest in water banking is decreasing.

6. Water reuse

Another water management technique that will become more and more necessary in the future is reuse of wastewater, especially the planned and controlled reuse, where the wastewater receives proper treatment to meet the quality requirements for the intended use. Uncontrolled and indirect use of sewage effluent for irrigation and other purposes is occurring in many countries, even though it generally means that poorly treated or even raw sewage is used for irrigation of vegetables and other crops consumed raw or brought raw into the kitchen. This is, of course, completely unacceptable from a public health standpoint. If this practice is allowed to continue and spread in the future, there can be major epidemics such as cholera (including the new Bengal strain discovered in Bangladesh in 1992 which is resistant to vaccination), typhoid, hepatitis A, B, and E with the new E-strain having a much higher mortality than A and B, giardia, cryptosporidium, and others, including new ones that are not yet known. Controlled water reuse will be done for various reasons. One is that sewage effluent simply is an important water resource that is needed in water-short areas. With more and more people living in cities, more and more sewage effluent will be produced (megafloows from megacities!) and must be used again to reduce the stress on available water resources. Secondly, reuse may become increasingly attractive to reduce pollution of surface water. For example, in the face of increasingly stringent discharge requirements to protect aquatic life and downstream users of the stream, cities may find it cheaper to treat their sewage effluent for nonpotable use than for discharge into surface water.

While flush toilets and sewer systems are marvels of home and urban sanitation, from a water quality and water reuse standpoint they are great water wasters and polluters. First of all, toilets use a lot of water that is severely degraded by what is flushed down. This "water" then mixes with the other household wastewater (gray water) which in itself is fairly innocuous and suitable for various uses, to produce a domestic effluent that is loaded with pathogens that can spread acute infectious diseases and death, with nutrients that can eutrophy surface water, and with toxic chemicals that can have long-term adverse health effects such as cancer on the people drinking that water. Then, to make things worse, this effluent is discharged into streams or other surface water where it degrades the quality of much more water that often is the water source for downstream people (dilution is not the solution to pollution!). Thus, our modern systems of flush toilets and sewers require two types of treatment plants as barriers to pollutants: sewage treatment plants before discharge and water treatment plants before municipal uses. Where such plants do not exist or function improperly, serious health effects can be expected. Conventional sewage treatment plants do not take out all the contaminants, and end-of-pipe treatment and disposal into surface
water will be more and more replaced by local treatment of sewage for reuse and recycling to eventually achieve zero discharge.

Sewage effluent primarily will be used for nonpotable purposes, including industrial uses (power plant cooling, processing plants, construction), municipal uses (fire fighting, toilet flushing especially in high rises or industrial buildings), urban irrigation (parks, playgrounds, landscaping, private yards), agricultural irrigation (including crops consumed raw), environmental applications (wildlife refuges, in-stream benefits) and groundwater recharge. Potable use is also possible, but that usually will be a practice of last resort because of high treatment costs (on the order of $0.5 to $1 per m³) and public acceptance, aesthetic, psychological, and cultural or religious reasons (Bouwer, 1993b). However, if wastewater is used extensively for nonpotable purposes, there often will be enough high quality water left for potable uses. The main principle of water reuse is that the sewage effluent be treated to meet the quality requirements for the intended use. The necessary treatment technologies are available, even to make distilled water out of sewage effluent if the user is willing to pay the price. Because transport of water over long distances can be very expensive, water reuse generally will be concentrated in and around the cities producing the effluent. Irrigation may then require treatment of the effluent to permit “unrestricted” irrigation, which includes urban irrigation of parks, playgrounds, golf courses, sports fields, residential yards, etc., and agricultural irrigation of fruit and vegetables consumed raw or brought raw into the kitchen. Vegetable growing around cities is very common and economically attractive because of proximity to markets, and sewage effluent should be adequately treated so that farmers can grow such crops.

Use of sewage effluent for cooling water for power plants usually requires treatment to minimize scaling in the pipe system. For a 3810 MW nuclear power plant west of Phoenix which is entirely cooled with sewage at a design flow of 3.2 m³/s, the effluent first receives conventional primary and secondary (activated sludge) treatment in the sewage treatment plant. It is then transported about 60 km through a pipeline to the nuclear power plant where it is treated on-site with lime precipitation, trickling filters, and sand filters to minimize scaling in the plant. The cooling water is recycled about 15 times after which it has reached a salt concentration of about 15000 mg/l, or half of that of seawater. The brine is then discharged into a 196-ha evaporation lake from which the salts eventually will be removed for disposal as solid waste in designated landfills.

7. Irrigation with sewage effluent

For agricultural irrigation, the effluent first of all has to meet the normal chemical requirements for irrigation water, such as total dissolved solids, sodium adsorption ratio, nitrogen concentration, chloride concentration, and trace element concentrations (Ayers and Westcot, 1985; Bouwer and Idevolitch, 1987). Usually, most sewage effluents from residential areas will meet these standards. If there is a lot of industrial waste going into the sewer system, some chemicals may exceed maximum limits. In that case, source control is necessary to minimize the concentrations of the undesirable chemicals. The most important parameter of sewage effluent for irrigation is its concentration of viruses, bacteria, protozoa, and eggs of parasitic worms (helminths) that can cause diseases in the people consuming
the crops or contacting the water (Bouwer, 1993b; U.S. Environmental Protection Agency, 1992). For unrestricted irrigation, including urban irrigation and irrigation of vegetables consumed raw or brought raw into the kitchen, the sewage effluent should be treated to remove all pathogens, according to California standards and standards patterned thereafter (U.S. Environmental Protection Agency, 1992). The indicated treatment to achieve this typically is primary and secondary treatment followed by coagulation, sand filtration, and chlorination (Asano et al., 1992) to produce fecal coliform concentrations of essentially zero. Tests have shown that viruses, pathogenic bacteria, parasites, and protozoa are then also absent. However, this is a high technology and expensive process (about $200 to $500 per 1000 m$^3$; Richard et al., 1992) that may not be suitable for countries with insufficient capital or human resources to build, maintain, or operate such plants. For those countries, the World Health Organization guidelines may be used (WHO, 1989) which allow a

---

Fig. 1. Schematic of soil aquifer treatment systems with natural drainage of renovated water into stream, lake, or low area (A), collection of renovated water by subsurface drain (B), infiltration areas in two parallel rows and line of wells midway between (C), and infiltration areas in center surrounded by a circle of wells (D).
maximum fecal coliform concentration of 1000 per 100 ml and up to one helminthic egg per liter. These guidelines can be achieved with “low technology” treatment systems such as lagooning, if sufficient detention times are used (about one month in warm climates) to get die off or removal of most of the pathogens.

8. Soil-aquifer treatment

Another “low technology” treatment system that can considerably improve the quality of the sewage effluent to the point that it can be used for unrestricted irrigation and most other nonpotable purposes is groundwater recharge with infiltration basins (Bouwer, 1985). The systems then are operated as infiltration-recovery systems to recover the water from the aquifer with wells or drains (Fig. 1), and to use the underground formations as a treatment facility. For this reason, they are called soil-aquifer treatment (SAT) or geopurification systems. The water obtained from the recovery systems after SAT usually has a very low suspended solids content, essentially zero biochemical oxygen demand (BOD), significantly reduced concentrations of nitrogen, phosphorus, organic compounds, and heavy metals, and essentially zero levels of pathogens as shown in Table 1 (Bouwer, 1985, 1993b). Such water can then be used for unrestricted irrigation and most other nonpotable purposes without further treatment. Other advantages of SAT are that the systems are inexpensive and “low technology.” They are robust and simple to operate, they offer underground storage to absorb seasonal or other differences between supply and demand.

Table 1
Quality parameters from Phoenix, Arizona, SAT system for mildly chlorinated secondary effluent (activated sludge) as it entered the infiltration basins (left column) and after SAT and pumping it from a well in the center of the infiltration basin area (right column).

<table>
<thead>
<tr>
<th></th>
<th>Secondary effluent (mg/l)</th>
<th>Recovery well samples (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total dissolved solids</td>
<td>750</td>
<td>790</td>
</tr>
<tr>
<td>Suspended solids</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Ammonium nitrogen</td>
<td>16</td>
<td>0.1</td>
</tr>
<tr>
<td>Nitrate nitrogen</td>
<td>5.5</td>
<td>5.3</td>
</tr>
<tr>
<td>Organic nitrogen</td>
<td>1.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Phosphate phosphorus</td>
<td>5.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Fluoride</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Boron</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Biochemical oxygen demand</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Total organic carbon</td>
<td>12</td>
<td>1.9</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Fecal coliforms per 100 ml</td>
<td>3500</td>
<td>0.3</td>
</tr>
<tr>
<td>Viruses, PFU/100 l</td>
<td>2118</td>
<td>0</td>
</tr>
</tbody>
</table>
of water, and they enhance the aesthetics of water reuse by breaking the pipe-to-pipe connection of direct recycling with an underground transport and storage phase.

Some aspects of SAT that need further attention are the health effects, especially if the water after recovery is used for drinking, and the sustainability of the system. Most of the underground treatment processes are renewable and should go on indefinitely, but some compounds like phosphate, heavy metals, and some synthetic organic compounds may accumulate in the underground environment. More knowledge is also needed about the role of the clogging layer in infiltration basins and how to manage the basins for minimum infiltration reduction by clogging and maximum quality improvement benefits as the water moves through the clogging layer. More research on control of clogging is also needed for recharge wells, especially "dry wells" or recharge shafts in the vadose zone, because such "wells" cannot be pumped to reverse the flow and remove clogging materials.

9. Conclusions

Water resource management will become increasingly challenging in the future as populations continue to grow and require more and more water, and renewable water resources are finite. Competition for water and its various uses will increase and could become violent if equitable solutions are not found. Agriculture is the largest consumptive user of water because of soil evaporation and plant transpiration, which must be reduced as much as possible (especially evaporation) to produce more crops with less water. Municipal and industrial uses are much less consumptive, but they produce wastewater that, however, can be reused after suitable treatment. Agricultural and urban irrigation can be major users of properly treated sewage effluent, especially in dry climates. Increased storage of water with dams or groundwater recharge is necessary to save water in times of water surplus for use in times of water need. Water, health, and agricultural professionals will be increasingly challenged to provide adequate and safe water supplies. Even then, severe droughts and water problems will occur, especially in areas with too many people for the available water resources, where water shortages are not resource but population-driven.

References


Postel, S., 1992. Last Oasis, Worldwatch Institute, Washington, D.C.