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Integrated water management for the 21st century: Problems and Solutions

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Abstract

Most of the projected global population increases will take place in third world countries that already suffer from water, food, and health problems. Increasingly, the various water uses (municipal, industrial, agricultural) must be coordinated with, and integrated into, the overall water management of the region. Sustainability, public health, environmental protection and economics are key factors. More storage of water behind dams and especially in aquifers via artificial recharge is necessary to save water in times of water surplus for use in times of water shortage. Municipal wastewater can be an important water resource but its use must be carefully planned and regulated to prevent adverse health effects and, in the case of irrigation, undue contamination of groundwater. While almost all liquid fresh water of the planet occurs underground as groundwater, its long-term suitability as a source of water is threatened by non-point source pollution from agriculture and other sources and by aquifer depletion due to groundwater withdrawals in excess of groundwater recharge. In irrigated areas, groundwater levels may have to be controlled with drainage or pumped well systems to prevent water-logging and salinization of soil. Salty drainage waters must then be handled in an ecologically responsible way. Water short countries can save water by importing most of their food and electric power from other countries with more water, so that in essence they also get the water that was necessary to produce these commodities and, hence, is virtually embedded in the commodities. This "virtual" water tends to be a lot cheaper for the receiving country than developing its own water resources. Local water can then be used for purposes with higher social, ecological, or economic returns or saved for the future. Climate changes in response to global warming caused by carbon dioxide emissions are difficult to predict in space and time. Resulting uncertainties require flexible and integrated water management to handle water surpluses, water shortages, and weather extremes. Long-term storage behind dams and in aquifers may be required. Rising sea levels will present problems in coastal areas.

Key words: Integrated water management, populations, water issues, dams, underground storage, non-point source pollution, sustainability

Introduction

Population growth and higher living standards will cause ever increasing demands for good quality municipal and industrial water, and ever increasing sewage flows. At the same time, more and more irrigation water will be needed to meet increasing demands for food for growing populations. Also, more and more water will be required for environmental concerns such as aquatic life, wildlife refuges, recreation, scenic values, and riparian habitats.Thus, increased competition for water can be expected. This will require intensive management and international cooperation. Since almost all liquid fresh water on the planet occurs underground, groundwater will be used more and more and, hence, must be protected against depletion and contamination, especially from non-point sources like intensive agriculture. While growing populations and increasing water requirements are a certainty, a big uncertainty is how climates will change and how they will be affected by man's activities like increasing emissions of CO_2 and other greenhouse gases, particulate matter, and other contaminants like ozone and nitrous oxides. There still is no agreement among scientists how and when the climate will change, and what changes will occur where. The main conclusion so far seems to be that climate changes (natural and anthropogenic) are likely, that they are essentially unpredictable on a local scale, and that, therefore, water resources management should be flexible so as to be able to cope with changes in availability and demands for water[1,2]. This calls for integrated water management where all pertinent factors are considered in the decision making process. Such a holistic approach requires not only supply management, but also demand management (e.g., water conservation and transfer of water to uses with higher economic returns), water quality management, recycling and reuse of water, economics, conflict resolution, public involvement, public health, environmental and ecological aspects, socio-cultural aspects, water storage (including long-term storage or water "banking"), conjunctive use of surface water and groundwater, water pollution control, flexibility, regional approaches, weather modification and sustainability. Agricultural water management increasingly must be integrated with other water management and environmental objectives.

Global Population and Water Supplies

The present world population of about six billion is projected to almost double in this century. Almost all of this population increase will be in the Third World, where there are already plenty of water and sanitation problems and where about 1400 people (mostly children) die every hour due to waterborne diseases [3]. Also, there will be more and more migration of people from rural areas to cities, creating many large cities including mega-cities with more than 20 million people that will have mega-water needs, produce mega-sewage flows, and have mega-problems. Already, there is talk that people in these mega-cities should have little gardens where they can grow their own food and recycle their own waste. There would then be little difference between mega-cities with a lot of small garden-type farming and rural areas with dense populations, especially in the suburban fringes of the cities. All these people and their animals living closely together could present serious health problems as viruses and other pathogens that normally affect only animals can be transferred to humans. This could cause epidemics of potentially global proportions because of lack of immunity and vaccines, much like the Ebola and AIDS viruses and the various flu outbreaks caused by swine or chicken viruses. If the animals are also given regular doses of antibiotics to promote faster growth, antibiotic resistant strains of pathogens could be created which could cause serious human pandemics. For adequate living standards as in western and industrialized countries, a renewable water supply of at least 2000 m^3 per person per year is necessary [11]. If only 1000-2000 m^3 is available, the country is water stressed, while below 500 m^3 per person per year it is water scarce. Nomadic desert people can subsist on only a few m^3 per person per year (not including their animals). The global renewable water supply is about 7000 m^3 per person per year (present population). Thus, there is enough water for at least three times the present world population. Hence, water shortages are due to imbalances between population and precipitation distributions. Almost all of the planet's water (97%) occurs as salt water in the oceans [4]. Of the remaining 3%, two-thirds occur as snow and ice in polar and mountainous regions, which leaves only about 1% of the global water as liquid fresh water. Almost all of this (more than 98%) occurs as groundwater, while less than 2% occurs in the more visible form of streams and lakes which often are fed by groundwater. Groundwater is formed by excess rainfall (total precipitation minus surface runoff and evapotranspiration) that infiltrates deeper into the ground and eventually percolates down to the groundwater formations (aquifers). For temperate, humid climates, about 40% of the precipitation ends up in the groundwater. For Mediterranean type climates, it is more like 10 to 20%, and for dry climates it can be as little as 1% or even less [5,12]. These natural recharge rates give an idea of the safe or sustainable yields of aquifers that can be pumped from wells without depleting the groundwater resource. In many areas of the world, especially the drier ones, groundwater is the main water resource. Natural recharge rates are difficult to predict with any accuracy [13] and often pumping greatly exceeds recharge, so that groundwater levels are declining. It is frightening to consider what will happen in these areas when the wells go dry and no other water resources are available.

Water Storage via Dams

Future climatic changes may also include more weather extremes, like more periods with excessive rainfall and more periods with low rainfall that cause droughts. Also, in relatively dry climates, small changes in precipitation can cause significant changes in natural recharge of groundwater. To protect water supplies against these extremes and changes, more storage of water is needed, including long-term storage (years to decades) to build water reserves during times of water surplus for use in times of water shortage. Traditionally, such storage has been achieved with dams and surface reservoirs. However, good dam sites are getting scarce and dams have a number of disadvantages like interfering with the stream ecology, adverse environmental effects, displacement of people for new dam reservoirs, loss of scenic aspects and recreational uses of the river, increased waterborne diseases and other public health problems, evaporation losses (especially undesirable for long-term storage), high costs, potential for structural problems and failure, and no sustainability since all dams eventually lose their capacity as they fill up with sediments [14,15,16]. For these reasons, new dams are increasingly difficult to construct, except in some countries (mostly Third World) where the advantages of abundant and cheap hydro-electric power are considered to outweigh the disadvantages of dams. One of the advantages of dams is that they can be operated to even out the flow in the downstream river, regardless of seasonal or longer-term variations in rainfall. On the other hand, the ease to turn the turbines off and on to meet peaking power or other short-term fluctuations in electricity demands can adversely affect the downstream ecology. For example, as stated by Newcom [17]: "Dams in California have been blamed by scientists and many in the environmental community as being one of the major catalysts responsible for moving salmon species in California - and through the Northwest - to the endangered and threatened lists of the federal Endangered Species Act (ESA). The reasons for the demise of these anadromous fish because of dams are varied and include limited spawning habitat; decreased downstream flows that limit backwater habitats serving as rearing areas for fry and juveniles to mature; increased predation by non-native fish species; entrainment from pumps and turbines; varying water temperatures; reduced nutrient-rich sediment and spring migration flows; and dissolved gases." One way to make dam operation for generation of hydropower environmentally more acceptable and in compliance with environmental laws is to increase the capacity for generation of thermal power so that hydropower that produces undesirable extremes in flows and temperatures of the water below dams can be avoided. For California, such laws are the Endangered Species Act, the California Environmental Quality Act, the National Environmental Policy Act, and the Water Quality Act. Under federal law, non-federal hydropower facilities must be relicensed every 40 to 50 years - a process that can take years to complete [17] .The relicensing process also can mean the end for older, often obsolete dams where modifications to meet new regulations would be so expensive that destroying the dam is the best solution. However, dam decommissioning and demolition often is not a simple process. It can be very complex and expensive [18] and it has been the subject of special short courses [19]. Dams on international rivers require intensive cooperation among the countries involved, so that countries downstream from the dam are not adversely affected and have a voice in the location, design, and operation of the dam. New dam projects require careful planning to minimize adverse environmental, public health, and socio-cultural effects.

Water Storage via Artificial Recharge of Groundwater

If water cannot be stored above ground, it must be stored underground, via artificial recharge of groundwater. Already, more than 98% of the world's fresh liquid water supplies occurs underground [4] and there is plenty of room for more. Artificial recharge is achieved by putting water on the land surface where it infiltrates into the soil and moves downward to underlying groundwater [6,7]. Such systems require permeable soils (sands and gravels are preferred) and unconfined aquifers with freely moving groundwater tables. Infiltration rates typically range from 0.5 to

3 m/day during flooding. With continued flooding, however, suspended particles in the water accumulate on the soil surface to form a clogging layer that reduces infiltration rates. Biological, chemical, and physical actions further aggravate the clogging. Thus, infiltration basins must be periodically taken out of service to allow drying, cracking, and, if necessary, mechanical removal of the clogging layer. Taking drying periods into account, long-term infiltration rates for year round operation of surface recharge systems may be in the range of 100 to 400 m/yr.

Artificial recharge may be implemented with in-channel and off-channel infiltration systems. In-channel systems consist of low dams across the streambed or of T or L shaped levees in the streambed to back up and spread the water so as to increase the wetted area and, hence, infiltration in the streambed. Off-channel systems consist of specially constructed shallow ponds or basins that are flooded for infiltration and recharge. Where streamflows are highly variable, upstream storage dams or deep basins may be necessary to capture short-duration high-flow events for subsequent gradual release into recharge systems. Also, recharge systems can be designed and managed to enhance environmental benefits (e.g., aquatic parks, trees and other vegetation, and wildlife refuges).

Since sand and gravel soils are not always available, less permeable soils like loamy sands, sandy loams, and light loams are increasingly used for surface infiltration recharge systems. Such systems may have infiltration rates of only 30 to 60 m/yr for year round operation. Thus, relative evaporation losses are higher and in warm, dry climates could be about 3 to 6% of the water applied, as compared to about 1% for basins in more permeable soils. Systems in finer textured soils also require more land for infiltration basins. However, the larger land requirements enhance the opportunity for combining the recharge project with environmental and recreational amenities.

Where sufficiently permeable soils are not available or surface soils are contaminated, artificial recharge also can be achieved via infiltration trenches or recharge pits or shafts [6,7]. If the aquifers are confined, i.e., between layers of low permeability, artificial recharge can be achieved only with recharge or "injection" wells drilled into the aquifer. The cost of such recharge often is much higher than the cost of infiltration with basins because wells can be expensive and the water must first be treated to essentially remove all suspended solids, nutrients, and organic carbon to minimize clogging of the well-aquifer interface. Since such clogging is difficult to remove, prevention of clogging by adequate pretreatment of the water and frequent pumping of the well is better than complete well remediation. Increasingly, recharge wells are constructed as dual purpose wells for both recharge and extraction to allow recharge when water demands are low and surplus water is available (i.e., during the winter), and pumping when water demands are high like in the summer. Such SAR (storage and recovery) wells are used for municipal water supplies so that water treatment plants do not have to meet peak demands but can be designed and operated for a lower average demand, which is financially attractive[20]. The big advantage of underground storage is that there are no evaporation losses from the groundwater. Evaporation losses from the basins themselves in continuously operated systems may range from 0.5 m/yr for temperate humid climates to 2.5 m/yr for hot dry climates. Groundwater recharge systems are sustainable, economical, and do not have the eco-environmental problems that dams have. In addition, algae which can give water quality problems in water stored in open reservoirs do not grow in groundwater.Because the underground formations act like natural filters, recharge systems also can be used to clean water of impaired quality. This principle is extensively used as an effective low-technology and inexpensive method to clean up effluent from sewage treatment plants to enable unrestricted and more aesthetically acceptable water reuse (see "Water Reuse" section). The systems then are no longer called recharge systems but soil-aquifer treatment (SAT) or geopurification systems.

Conjunctive Use and Water Banking

Nature's way of storing water is underground, where about 98% of all the world's liquid and fresh water occurs[4]. The other 2% mostly occurs in streams and lakes, which often are fed by groundwater. Groundwater is a dependable source of water and less affected by the vagaries of climate than surface water. Often, surface water and groundwater are used conjunctively, surface water when available, and groundwater when the streams or lakes are low or dry. Where water requirements have been increasing, there often has been a tendency to pump more groundwater with all the undesirable effects such as aquifer depletion, land subsidence, salt water intrusion, and higher pumping costs. The solution then is either to build more dams for surface storage, or to store more water underground via artificial recharge of groundwater. Underground storage is preferred where dams are not feasible and also when the water may have to be stored for long periods (years to decades) and evaporation losses from the dam reservoirs are not acceptable. Such long-term underground storage is often called water banking[2]. Some of the issues in groundwater banking have to do with water rights, especially where surface water and groundwater are governed by different water right systems. For example, surface water may be governed by prior appropriation or the riparian principle, whereas groundwater rights maybe in the hands of the owner of the overlying land[4]. Thus, when surface water is used for groundwater recharge, the question is who owns the water after it has joined the aquifer? Also, after long-term storage (decades, for example), is the recharge water still recoverable from the aquifer or has it moved laterally away from the region over which the recharging entity has jurisdiction? There may also be water quality issues, for example, where the groundwater is of better quality than the surface water used for recharge, or where the recharge water is of good quality and picks up undesirable chemicals from the aquifer such as arsenic, boron, and dissolved salts. Effects on groundwater levels must also be considered to avoid undue groundwater rises during recharge and undue declines during extraction. Some states (California, for example) allow extraction of groundwater in excess of the amount put into the aquifer by artificial recharge. This excess would then consist of the natural recharge. However, such natural recharge is difficult to predict, especially in dry climates where recharge may only be a small percentage (1% for example) of an already very small precipitation[13]· Other states like Arizona, where natural recharge is very low, require groundwater extractions to be no more than 95% of the artificial recharge inputs, thus leaving 5% of the recharge in the aquifer. The best approach is to monitor groundwater levels in the area of water banking and groundwater pumping so that pumping rates can be increased where groundwater levels are rising, and decreased where they are falling.

Groundwater and Salinity Control for Sustainable Irrigation

There are many serious cases of pollution of surface water and groundwater by point-sources (e.g., sewage and industrial wastewater discharges, leaking ponds or tanks, and waste disposal areas). However, point source pollution is, at least in principle, relatively simple to control and prevent. A much greater threat to the planet's liquid fresh water resources is non-point source pollution of groundwater. A significant non-point source of groundwater pollution is agriculture, with its use of fertilizer, pesticides, and salt containing irrigation water that contaminate the drainage water as it moves from the root zone to the underlying groundwater. The problem can be expected to get worse in the future as agriculture must intensify (including use of more agricultural chemicals) to keep up with the demands for more food and fiber by increasing populations. Pollution of groundwater also causes pollution of surface water wherever the contaminated groundwater moves into streams where it maintains the base flow, and also into lakes and coastal waters.

In humid areas with rainfed agriculture, the main contaminants in the drainage water from the root zone are nitrate and pesticide residues[8]. In irrigated areas, the drainage water also contains the salts that were brought in with the irrigation water. To avoid accumulation of salts in the root zone, excess irrigation water must be applied to leach the salts out of the soil so as to maintain a salt balance in the root zone. For efficient irrigation systems, the excess water may be about 20 % of the total irrigation water applied. In dry climates, this means that the salt concentrations in the drainage water are about five times higher than in the irrigation water, which often is much too high for drinking and for irrigation of all but the most salt tolerant crops. For more efficient irrigation, the salt concentrations in the drainage water will even be higher. For less efficient irrigation, and also where there is significant rainfall, the salt concentrations in the drainage water will be lower. Recent successes in genetically altering plants to make them more salt tolerant offers hope for widening the choice of crops that can be grown with salty water [21].

Where groundwater levels are high, drains need to be installed to remove the drainage water from the soil and to avoid waterlogging and salinization of the soil. Discharges from the drains then contain salt and residues of agricultural chemicals and, hence, they are a source of water pollution. The least undesirable ultimate disposal of this water may be in the oceans. Inland disposal can degrade surface water. Disposal in evaporation ponds requires considerable land for "salt lakes" that could eventually become environmental hazards. Use of the salty drainage water for sequential irrigation of increasingly salt tolerant plants (including trees like tamarisk, eucalyptus, and salt tolerant poplars) and ending with halophytes like salicornia and certain grasses will concentrate the salts in small volumes of water[22]. The volume of the final drainage water may then only be a few percent of the original irrigation water so that salt concentrations could be 20 to 100 times higher than that in the original irrigation water. Disposal into evaporation ponds will then require much less land. Another alternative is desalination of the drainage water by, for example, reverse osmosis. The desalted water can then be used for potable and other purposes, but the process still leaves a reject brine that requires disposal. Concentrating the salts into smaller volumes of water by sequential irrigation, evaporation ponds, or membrane filtration also reduces the cost of transporting the salty water to oceans, salt lakes, or other places for "final" disposal. Leaving the water in evaporation ponds will eventually cause the salts to crystallize, which can then be disposed as solid waste in designated landfills.

Where groundwater levels are deeper (often due to prior groundwater pumping), the drainage water will move down to the groundwater and reduce its quality to the point where it becomes useless for drinking and general irrigation. Without desalting of groundwater, the further use and pumping of groundwater will stop. If irrigation is continued, groundwater levels then will rise (typically about 0.3 to 2 m per year) and eventually threaten underground pipe lines, basements, gravel pits, landfills, cemeteries, deep-rooted old trees, etc. Finally, they can cause waterlogging and salinization of the soil, so that nothing will grow anymore and the areas become salt flats. Inability to control groundwater below irrigated land has caused the demise of old civilizations and is still the reason why so much irrigated land in the world is losing productivity or is even being abandoned today[16]. To prevent this waterlogging and salinization, groundwater pumping must be resumed or deep agricultural drains must be installed to keep groundwater levels at safe depths. The salty, contaminated water from these wells or drains must then be managed as discussed in the previous paragraph. Irrigation without groundwater control ultimately causes waterlogging and salinity problems, and irrigation can only be sustainable if salts and drainage water are adequately removed from the underground environment and managed for minimum environmental damage.

An intriguing possibility is to use the evaporation ponds as solar ponds to produce hot water for heating and/or electric power generation. In an experimental solar pond project in El Paso, Texas, the pond is 3 m deep with a 1 m layer of low salinity water on top, a 1 m layer of medium salinity in the middle, and a 1 m layer of high salinity (brine) at the bottom [23]. Sun energy is then trapped as heat in the bottom layer while the lighter top layers prevent thermal convection currents and act as insulators. The hot brine from the bottom layer is pumped to a heat exchanger where a working fluid like iso-butane or freon is vaporized which then goes through a turbine to generate power. The working fluid is condensed in another heat exchanger that is cooled with normal water which is recirculated through a cooling tower. The working fluid then returns to the brine heat exchanger where it is preheated by the brine return flow from the heat exchanger to the pond before it is vaporized again. The El Paso pond has a surface area of 0.3 ha and generates 60 to 70 kW. At this rate, a solar pond system of about 5,000 ha could generate about 1,000 megawatts of electricity, which is typical of a good sized power plant. There is enough heat stored in the hot brine layer to also generate power at night. Sequential irrigation, membrane filtration, and solar ponds for power generation have the advantage that they treat the salty water as a revenue producing resource that helps offset the cost of final disposal of the salts. Where sewage effluent is used for irrigation, a whole new spectrum of pollutants can be added to the soil [7]. If not attenuated in the root zone, these pollutants can show up in the drainage water at much higher concentrations than in the effluent (about five times higher for efficient irrigation in dry climates, less for inefficient irrigation and/or areas with significant rainfall). Thus, in addition to the usual nitrates and salts, the drainage water could also contain disinfection byproducts (DBPs) like trihalomethanes (THMs) and haloacetic acids (HAAs) that were formed in the drinking water when it was chlorinated for public water supply and the chlorine reacted with natural dissolved organic carbon in the water to form chloroform, bromodichloromethane, and other DBPs [24]. Then, when it became sewage effluent and was chlorinated again and this time with high chlorine doses and long contact times to kill all the pathogens, a whole new suite of DBPs could be formed. There is great concern about cancer, adverse pregnancy outcomes, and other health effects of DBPs in drinking water. The U.S. Environmental Protection Agency will lower the maximum contaminant level for THMs from 100 ng/l to 80 ng/l, and for HAAs to 60 ng/l, with further reductions being expected [24]. A recently discovered DBP is N nitrosodimethylamine (NDMA), which is an extremely carcinogenic compound formed by the reaction of chlorine with dimethylamine (DMA). The California Department of Health Services has set an NDMA drinking water action level of 20 ng per liter [25] and has recently lowered it to 10 ng/l. However, adequate dose-response relations for humans are not available. Thus, while chlorination effectively kills bacteria and viruses to avoid infectious disease outbreaks from sewage irrigation, it also creates chemicals that may have adverse long-term health effects. Alternative disinfection procedures that do not use chlorine, like ultra-violet irradiation, soil-aquifer treatment, or "time" should be considered.

In addition to DBPs, the treated sewage effluent and, hence, the waters into which it is discharged can also be expected to contain pharmaceuticals, industrial chemicals like PCBs and others that may have biological effects, and personal care products. These chemicals enter the wastewater with discharges from pharmaceutical and other industries, hospitals and other medical facilities, households where unused medicines are flushed down the toilets, and human excreta which contain incompletely metabolized medicines [26,27,28,29].

Pharmaceutically active chemicals also include certain industrial chemicals like dioxin, pesticides and chlorinated organic compounds. While not directly toxic or carcinogenic, these chemicals may produce adverse health effects by interfering with hormone production (endocrine disruptors), by weakening immune systems, and by other biological responses. So far, most studies of pharmaceuticals and pharmaceutically active chemicals have been carried out on aquatic animals where adverse effects on hormone production and reproductive processes, including feminization of the males, have been observed[30]. Since their long-term and synergistic effects on humans are not known, pharmaceuticals and similar chemicals should be kept out of the water environment as much as possible[31]. Farm animals with their ingestion of hormones, antibiotics and veterinary medicines, can also be a source of pharmaceuticals in water as their manures and wastewater from animal feeding operations are spread on land from where they can run off into surface water or percolate down to groundwater [27].

Other potential contaminants in the drainage water from sewage irrigated crops and plants are humic substances like humic and fulvic acids. These are known precursors of DBPs when the water is chlorinated. The humic substances are formed as stable endproducts wherever organic matter is biodegraded. Since effluent with its nutrients can be expected to produce lush vegetation when used for irrigation, there will be more biomass on and in the soil which upon biodegradation could produce increased levels of humic substances in the drainage water and, eventually, in the underlying groundwater. When this water is pumped from wells and chlorinated for potable use, increased levels of DBPs can then be expected in the drinking water. Thus where sewage effluent is used or planned to be used for irrigation, careful studies should be made of the potential effects on groundwater, especially where the groundwater is, or will be, used for drinking.

Water Pollution and Total Maximum Daily Loads (TMDLs)

Pollution of natural waters will become increasingly serious as growing populations demand more high quality water while at the same time producing more wastes that will often be returned to those waters. Until recently, the focus in the USA has been mostly on point sources of water pollution (discharges of sewage effluent and industrial water) which are controlled through discharge permits under the authority of the 1972 Clean Water Act and specified in the National Pollutant Discharge Elimination System (NPDES). While this program has led to considerable improvement in surface water quality, fishable and swimmable conditions have not always been met. As a matter of fact, the report "Assessing the TMDL Approach to Water Quality Management" recently published by the National Research Council mentions that the USA still has about 21,000 polluted river segments, lakes, and estuaries making up over 300,000 river and shore miles and 5 million lake acres[32]. Thus, whereas until now pollution control has been based on controlling effluent discharges, the next phase will also control non-point sources of pollution, mainly due to urban and agricultural runoff, drainage of groundwater into surface water, and atmospheric fall-out. The main pollutants of concern are nutrients and sediment, but they could also include certain pesticides, pharmaceuticals, and other chemicals of emerging concerns. Control of these contaminants will be based on entire watersheds and it will be achieved by establishing TMDLs for the entire system. The TMDL approach was already included in the 1972 Clean Water Act as Section 303d. However, it was largely overlooked until EPA in response to lawsuits and other pressures from environmental groups developed TMDL regulations that were promulgated on 13 July 2000. Cost estimates by EPA for implementing the TMDL program range from $900 million to $4.3 billion per year [33], which primarily would be borne by dischargers. TMDLs could also be developed for groundwater, especially where it drains into surface water such as gaining streams or groundwater-fed lakes.

The TMDL concept is a dramatic switch from effluent based standards to ambient water standards, and from controlling point sources to controlling entire watersheds. In view of the high cost of implementing the program, attainment of the desired water quality may be questionable, particularly since the underlying scientific principles may not be fully understood. However, while attainment may be an issue, there is interest in moving ahead with the program while practicing adaptive management to make adjustments in the program where the results are not as expected [34,35,32] and to minimize administrative complications [36]. Others, especially those who will be financially affected by TMDLs, favor delay or modification of TMDLs and their implementation [35]. For agriculture, this may mean more use of best management practices for control of erosion, and of nutrients and pesticides in runoff water. Vegetated buffer strips on a watershed scale also may be effective in controlling nonpoint source pollution of surface water [37,38,39].

Global Change

Few issues have received so much attention and have generated so much controversy as the effects of increasing concentrations of CO_2 and other greenhouse gases in the atmosphere on temperature and climate. Predictions range from serious effects on ecosystems and our health[40], increased flooding, and desertification [41] to everything is normal and just part of the natural climate fluctuations that have been going on for ages as a result of the dynamic nature of planet earth. Sometimes it appears that conclusions are based primarily on consensus and majority opinions. What all this controversy shows, however, is that it is not known to a sufficient degree of accuracy what is going to happen in space and in time. Thus, it is difficult to make adequate plans. In addition to gradual, long-term climate changes, more abrupt changes within the span of a human generation may also happen [42]. Models for predicting global precipitations are based on models for predicting global temperatures in response to increasing CO_2 concentrations in the atmosphere. However, the temperature predictions are fraught with uncertainties (Kimball, in press), which makes precipitation prediction very difficult. The models don't even do well in predicting present precipitation patterns (Kimball, in press). However, because temperatures are projected to rise globally, average evaporation from oceans and other bodies of water will also increase, and therefore, globally averaged precipitation will also increase.However, the precipitation patterns may change[43]. Over the higher latitudes, precipitation is predicted to increase. Decreases are projected for Central America in the summer and for South Africa and Australia. Over much of the United States, projections are inconsistent, but with small increases indicated for winter in both Western and Eastern North America. Albritton et al.[43] also note that a strong correlation exists between inter-annual variability and mean precipitation. Consequently, future increases in mean precipitation are likely to lead to increases in precipitation variability.

It is not surprising that some countries, especially small ones with little geographic and hydrologic diversity, are concerned about future water resources management and have tried to make some predictions as to what may happen to them in the long term. Such countries include The Netherlands which is concerned about increased flooding caused by the Rhine due to larger peak flows and rising sea water levels, and Israel which is concerned about water resources. The Dutch predictions[44] are based on estimated average temperature increases (4°C by 2100), from which they estimate precipitation increases (4% in summer and 25% in winter) which then go in their hydrological model to predict flood flows. These predictions are useful for long-range planning and they indicate that for the next 20 years, flood control dikes will still be feasible. As time proceeds, climate and climate science will develop further so that more detailed and reliable climate scenarios can be formulated. Sea level rises by the year 2100 are predicted to be in the range of 20 to 110 cm. Analyses such as these are useful for long range planning for other river basins. If, indeed increasing flood flows are expected, raising levees ultimately may no longer be feasible and construction of parallel flood ways may be the best approach. Normally, these flood ways would be farmed and there would be no expensive structures, so that when they are used for flood control and the "green" rivers become real rivers, there is minimum damage.

The green river concept can also be applied to small rivers or streams. An example is the Indian Bend Wash in Scottsdale, Arizona, which drains a watershed of about 500 km^2 of urban and mountainous areas with short concentration times. Rainfall averages about 20 cm/year with occasional downpours of 2 to 5 cm in a few days. For the last 15 km, the wash runs through urban Scottsdale before it discharges into the Salt River. This normally dry wash is about 150 m wide and was an eyesore of weeds, old tires, discarded washing machines, etc. that flooded every few years or so and made level street crossings unpassable. In the 1960s flood control plans were developed which started with the usual approach of a concrete channel with levees on each side and houses and other urban developments right up to the levees. However, this plan was opposed by the public who did not want a Los Angeles-type "concrete canyon" and instead opted for a greener solution with a soft edge channel and recreational facilities. The result was a green river about 150 m wide with levees along the outer edges, a meandering low-flow channel a few m wide in the middle, and lakes, golf courses, sports fields, picnic areas, playgrounds and hiking and biking trails in the rest of the wash. The area now is a prime, high density and very popular recreation facility, and an example of what can be achieved with normally dry stream beds in urban settings. Small floods occur every few years, and large floods that cover most of the green river about every 20 years. The 100-year flood is 850 m^3/sec. The flood of record so far is 570 m^3/sec, which occurred in 1972 and has a recurrence interval of 70 years. Floods are short lived. They reduce or interrupt recreation for only a few days to about a week, and cause little or no damage. Israel also has made predictions of future climates for various scenarios based on local climatic trends and on national and regional climatological research and models [46]. The projected changes between now and for the year 2100 are: mean temperature increase 1.6 - 1.8°C; reduction in precipitation 4 - 8%; increase in evapotranspiration 10%; delayed winter rains; increased rain intensity and shortening of the rainy season; greater seasonal temperature variability; increased frequency and severity of extreme climatic events, and greater spatial and temporal climatic uncertainty.

Because of the uncertainties in global change predictions, especially in space and in time, the best policy for water resources management is flexibility so as to be able to handle floods and droughts, and surpluses and shortages. This is best achieved through integrated water management, as defined earlier. Global change may also affect infectious disease outbreaks. The occurrence of such diseases already shows distinct geographical distributions and dependancy on seasonal variations. Thus, prediction of climate changes and their effects on disease outbreaks will be useful in developing appropriate public health programs to prevent or control such outbreaks [45]. For irrigation, the effects of climatic changes on water supplies must also be considered in relation to the effects of increasing CO_2 concentrations in the atmosphere on crop water use efficiencies and yields. As stated by Kimball (in press) : "The degree of influence of global change on future water resources is difficult to predict because various components are likely to be affected in opposing ways. Global warming [surface temperature projected to increase 1.2 to 5.8°C (mean of 3.5°C) by 2100, depending on CO_2 emissions scenario and on the particular general circulation model (GCM) used for the projection] would tend to increase evapotranspiration (ET) rates and irrigation water requirements. At the same time, precipitation is projected to increase globally, which would both decrease irrigation water requirements and increase water supplies, although regional pattern changes are very uncertain. The direct effects of elevated CO_2 (projected to reach 540 to 950 $\mu mol\ mol^{-1}$, depending on CO_2 emissions scenario) on plants likely will cause increases in stomatal resistance (about 20-40% for a 350 $\mu mol\ mol^{-1}$ increase in CO_2 concentration for most herbaceous plants, with woody plants affected less), which will also tend to reduce evapotranspiration. At the same time, the elevated CO_2 will stimulate increases in plant leaf area (probably on the order of 10% in peak leaf area index for a 350 $\mu mol\ mol^{-1}$ increase in CO_2 concentration for C_3 plants with C_4 plants responding less) and canopy temperature, both of which increase evapotranspiration. The sensitivity of "reference" ET for alfalfa to the several opposing future influences was examined using a form of the Penman-Monteith equation that is under consideration for adoption as a standard by the American Society of Civil Engineers. For constant future relative humidity, annual reference ET at Maricopa, Arizona, would increase 2.1%/°C (or 7.1% for the projected mean 3.5°C rise in global temperature). Increasing stomatal resistance reduces ET 0.16%/% (or 3.0 to 5.7% for a 20 to 40% increase in resistance), whereas increasing leaf area increases ET 0.16%/% (or 1.6% for a 10% increase in leaf area). The combined effect of these three influences would be a net increase of 2.7 to 5.7% in ET. However, irrigation requirement is the difference between seasonal ET for a well-watered crop and the amount of water available from precipitation and soil storage, and the latter two likely will also be affected by global change. Modeling studies which have been done using scenarios of future weather projected by various GCMs predict that irrigation requirements will increase substantially, on the order of 35% for the U.S. overall but with wide variability depending on GCM, region, and crop. Fortunately, overall precipitation is also projected to increase, which will have favorable effects on runoff or streamflow or irrigation water supply. One study projected global runoff to increase 10%. However, the regional variability is large and uncertain, and another study predicted water yields for 2030 to decrease in Southern U.S. and the Great Plains and to increase in the East and Far West, whereas for 2095 they predicted no change to substantial increases for much of the U.S. Another aspect of global warming is that greater proportions of annual precipitation will fall as rain rather than snow and that snowpacks will melt faster, which means that some important agricultural regions in the U.S. may lose a substantial part of a huge free snowpack "reservoir" that presently stores winter precipitation at higher elevations for summer irrigation at lower elevations. Both the projected climate changes and the direct physiological effects of elevated CO_2 on plants likely will cause shifts in optimal production regions for many crops. Further, human economic and social factors likely also will cause changes in land use and associated demands for irrigation water. In addition, there likely will be shifts in natural vegetation on the upstream watersheds, which may change the supplies of water available for irrigation in the future.

In conclusion, global change very likely will affect future irrigation and water resources. The effects of climate and CO_2 on seasonal crop water use are relatively well understood slight increases (2-6%) are predicted for plausible scenarios of future temperature and CO_2. The effects on irrigation requirements and on water supplies are much more uncertain due to the uncertainties in projected precipitation patterns. It behooves future water resource planners and future growers to try to be as flexible as possible."

Most of the studies of the effects of elevated CO_2-concentration in the atmosphere on crop yield and water requirements have been done with pure CO_2. In reality, however, concentrations of other gases in the atmosphere may also increase. Some of these could have adverse effects on crop yields. For example, levels of ozone have more than doubled in the past 100 years and are predicted to continue rising at an even faster rate in the future [47]. In one experiment, yield increases in potatoes induced by elevated CO_2 levels in the air were substantially reduced by the presence of elevated ozone [48]. Another consequence of increasing temperatures and global change is rising seawater levels, primarily due to melting of polar ice sheets and thermal expansion of oceans [49]. As stated by Anderson et al[50]: "Coastal change occurs in response to natural processes that operate across a wide range of spatial and temporal scales. Long-term, century-scale impacts of climate change that will affect coastal environments include decimeter-scale sea-level rises; shifts in sea-surface temperatures, which will likely influence tropical storm tracts, as well as storm frequency and magnitude; and precipitation variations that may impact sediment flux to coastal areas. Other effects may include changes in coastal and ocean currents and wave regimes".

In many parts of the world, people have been migrating toward coastal cities, which already causes serious stresses on coastal environments that can only get worse as rates of global sea-level rise increase. In addition to direct flooding of low areas, additional backing up and flooding problems can be expected where surface water and wastewater (pipelines) are discharged into the ocean. Groundwater levels in coastal areas will also rise as natural discharge of groundwater in the ocean is reduced. Salt water intrusion into coastal aquifers can also increase, especially where groundwater is pumped from wells.

Carbon emissions can be reduced by conservation and efficient use of energy, by using non-fossil energy sources (hydropower, wind, solar, nuclear, and ethanol or other biofuels) and by growing more plants for carbon sequestration in biomass and soil [51]. Biofuels still emit carbon into the atmosphere but, unlike carbon from fossil fuels, it is recycled carbon via photosynthesis. Oceans also hold considerable amounts of carbon [51]. This requires international cooperation as reached at the 1997 Kyoto and the 2001 Marrakech conferences where delegates from 165 countries agreed to limit carbon emissions or cut them to below 1990 levels.

Water Reuse

All water is recycled through the global hydrologic cycle. However, planned local water reuse is becoming increasingly important for two reasons [9,10]. One is that discharge of sewage effluent into surface water is becoming increasingly difficult and expensive as treatment requirements become more and more stringent to protect the quality of the receiving water for aquatic life, recreation and downstream users. The cost of the stringent treatment may be so high that it becomes financially attractive for municipalities to treat their water for local reuse rather than for discharge. The second reason is that municipal wastewater often is a significant water resource that can be used for a number of purposes, especially in water short areas. The most logical reuse is for non-potable purposes like agricultural and urban irrigation, industrial uses (cooling, processing), environmental enhancement (wetlands, wildlife refuges, riparian habitats, urban lakes), fire fighting, dust control, and toilet flushing. This requires treatment of the effluent so that it meets the quality requirements for the intended use. Adequate infrastructures like storage reservoirs, and canals, pipelines, and dual distribution systems are also necessary so that waters of different qualities can be transported to different destinations. Aesthetics and public acceptance are important aspects of water reuse, especially where the public is directly affected. Treatment plant processes for unrestricted non-potable reuse are primary and secondary treatment followed by tertiary treatment consisting of flocculation, sand filtration and disinfection (ultraviolet irradiation or chlorination) to make sure that the effluent is free from pathogens (viruses, bacteria, and parasites). Such tertiary effluent can then be used for agricultural irrigation of crops consumed raw by people or brought raw into the kitchen, urban irrigation of parks, playgrounds, sports fields, golf courses, road plantings, etc., and urban lakes, fire fighting, toilet flushing, industrial uses, and other purposes. The tertiary treatment requirement was developed in California and is followed by most industrialized countries [9]. The California tertiary treatment is relatively high technology and expensive and is, therefore, often not feasible in Third World countries. To avoid use of raw sewage for irrigation, and to still make such irrigation reasonably safe from a public health standpoint, the World Health Organization[52] has developed guidelines that are based on epidemiological analyses of documented disease outbreaks and that are achievable with low-technology treatment such as in-series lagooning with long detention times (about one month). While this treatment does not produce pathogen-free effluent, epidemiological studies have indicated that use of such effluent for irrigation of crops consumed raw greatly reduces health risks compared to untreated sewage. As a precaution, however, the vegetables and fruit grown with such effluent should only be consumed raw by the local people that hopefully have developed some immunity to certain pathogens. Tourists and other visitors from the outside should not eat the local raw fruits and vegetables, and the produce should not be exported to other markets. Also, the lagooning treatment must be viewed as a temporary solution and full tertiary treatment plants should be built as soon as possible, especially when the lagoons become overloaded, detention times become too short for adequate pathogen removal, and the lagoon system cannot be deepened or expanded. Additional treatment of secondary or tertiary effluent and lagoon effluent can also be obtained by using the effluent for artificial recharge of groundwater where underground formations function as natural filters that can significantly reduce concentrations of suspended solids, nitrogen, phosphorus, organic carbon, trace elements, and microorganisms [9,7,6]. The resulting soil-aquifer treatment (SAT) greatly enhances the aesthetics of water reuse because the purified water comes from wells and not from sewage treatment plants and, hence, has lost its identity as "treated sewage." Water after SAT also is clear and odorless. SAT is especially important in countries where there are social or religious taboos against direct use of "unclean" water [53,54] or where expensive advanced treatment plants are not feasible.

Potable use of sewage effluent basically is a practice of last resort, although unplanned or incidental potable reuse occurs all over the world where sewage effluent is discharged into streams and lakes that are also used for public water supplies[55] and where cess pits, latrines, septic tanks, and sewage irrigation systems leak effluent to underlying groundwater that is pumped up again for drinking. In-plant sewage treatment for direct potable reuse requires advanced processes that include nitrogen and phosphorous removal (nitrification/denitrification and lime precipitation), removal of organic carbon compounds (activated carbon adsorption), removal of dissolved organic and inorganic compounds and pathogens by membrane filtration (microfiltration and reverse osmosis), and disinfection. Even when all these treatment steps are used and the water meets all drinking water quality standards, direct potable reuse where the treated effluent goes directly from the advanced treatment plant into the public water supply system (pipe-to-pipe connection) may never be practiced. People see this as a "toilet-to-tap" connection and public acceptance will be very difficult to obtain. Rather, to protect against accidental failures in the treatment plant and to enhance the aesthetics and public acceptance of potable water reuse, the potable reuse should be indirect, meaning that the effluent should first go through surface water (streams or lakes) or groundwater (via artificial recharge) before it can be delivered to public water supply systems. The surface water route has several disadvantages, including algae growth that can cause taste and health problems since some algal metabolites are toxic. To minimize algae growth, the wastewater may then have to be treated to remove nitrogen and phosphorus, which increases the reuse costs. Also, water is lost by evaporation and the water is vulnerable to recontamination by animals and human activities. These disadvantages do not exist with the groundwater route, where the water also receives SAT benefits. Groundwater recharge also enables seasonal or longer storage of the water to absorb differences between water supply and demand, and mixing of the effluent water with native groundwater when it is pumped from wells. Water reuse basically compresses the hydrologic cycle from an uncontrolled global scale to a controlled local scale. Since all water is recycled in one way or another, the quality of the water at its point of use is much more important than its history.

Virtual Water

Water-short areas can minimize their use of water by importing commodities that take a lot of water to produce like food and electric power, from other areas or countries that are blessed with more water. The receiving areas then are not only getting the commodities, but also the water that was necessary to produce them. Since this water is "virtually" embedded in the commodity, it is called virtual water [56]. For example, for every kg of wheat imported, the country also gets about one m^3 of virtual water at much less cost than the price or value of local water resources, if available, in the country itself. Using a lot of water just to satisfy a national pride of being self sufficient in food production (especially staple foods) will then not be economical if these foods can be imported much cheaper from water rich countries [57] . More and more areas in the world will face serious water shortages with little prospect of having adequate water for their inhabitants, even by trying to move more water to people or more people to water. Imports of virtual water embedded in food and other commodities may then economically and politically be a very good solution, and probably the easiest way to achieve peaceful solutions to water conflicts.

As economies and trade become more and more global in scope, global movement of food from water rich to water poor countries should be just as feasible as moving petroleum products from oil rich to oil poor countries. To ensure that global distribution of food will not be used as political weapons, it should be internationally controlled with representation of the importing countries. Other opportunities for saving local water resources by importing virtual water include import of electric power from areas with more abundant water for cooling of thermal power plants, with dams for hydro-electric power production, or with coastal areas that provide ocean water for cooling. The virtual water concept could also be useful in protecting wetlands of international ecological significance against water diversions and drying up to produce more irrigation water, such as the Sudd wetlands in the Sudan and the Okovanggo Basin in Botswana[16]. International cooperation could then be established to develop eco-tourism in these areas that will provide revenues for import of staple foods and the virtual water therein. Moving virtual water will be much cheaper than moving the water itself, which is also being considered. Proposals range from building huge pipelines or aqueducts to hauling water in tankers and towing icebergs from polar regions or large rafts with fresh water from river discharges into oceans [58,59]. For water rich countries, such water exports can be a significant source of revenue.

Conclusions

Increasing populations and uncertain climatic changes will pose heavy demands on water resources in the future. Holistic approaches, integrated water management principles, and international cooperation will be necessary to develop sustainable systems and prevent catastrophes. Agricultural water management must be integrated with other water management practices, since the actions of one user group will affect the water interests of others. More research needs to be done to make sure that management of water and other resources is based on sound science and engineering. Much greater local, national, and international efforts, cooperation, and expenditures are needed to meet future food and water requirements in sustainable, peaceful, and environmentally responsible ways. The challenges are there.

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