CENTRAL ARIZONA SALINITY STUDY – PHASE I

Technical Appendix P

ACCUMULATION AND MANAGEMENT OF SALT IN SOUTH CENTRAL ARIZONA

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Introduction

The only source of fresh water on this planet is atmospheric precipitation. Some of this precipitation evaporates and returns to the atmosphere. Some of it runs off the land and forms surface water in lakes and streams, and some of it infiltrates deeper into the soil and moves downward to form groundwater. Some of this groundwater may drain into streams to provide base flow so that the streams keep flowing when it does not rain. Eventually, most of the water not evaporated from the land areas ends up in the oceans from where it evaporates again to form clouds that produce precipitation on the land to close the hydrologic cycle.

All natural waters contain some salt, which is expressed as total dissolved solids or TDS. Rainfall and other atmospheric precipitation have the lowest TDS content, averaging about 10 mg/P (Bouwer, 1978). Surface water in streams and lakes have higher TDS contents because the water has been in contact with soil and rocks from which it picks up dissolved minerals and other constituents and pure water has evaporated from the watershed. TDS contents of surface water typically are on the order of a few tens to a few hundred mg/P. For the Colorado River, a main source of salts is the Mancos Shale in Colorado which is a marine deposit that adds predominantly sodium chloride to the water. For the Salt River, salt springs in the watershed contribute to the TDS of the water. Sometimes toxic chemicals are leached from the soil like the selenium in drainage water from irrigated land in California's Central Valley that was discharged into Lake Kesterson where it caused serious environmental problems (Lemly, 1993). The desirable maximum value of TDS for drinking water is 500 mg/P, but a lot of people drink water with higher TDS contents.

While water itself is indestructible, its use often causes deterioration of its quality. Municipal use typically adds about 200 to 300 mg/P TDS to the water. This is due to the addition of salts and other chemicals in homes and industries, and by removal of distilled or very pure water by evaporation (evaporative coolers or cooling towers) or membrane filtration (reverse osmosis) by industries needing ultra pure water, and putting the reject brine into the sewers. Reverse osmosis also is important in potable reuse of water, because it not only removes salts but also organic compounds. If all the reject brines are returned to the sewer but all the "good" water is not

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because of, for example, outdoor use of the water, sewage effluent has a higher salt content than the input water. A lot of water also evaporates in agricultural and urban irrigation of crops, plants, and turf, leaving salts behind in the soil which must be leached out of the root zone by applying more irrigation water than needed to meet the evaporative needs of the plants. The salty ■deep-percolation• water created by this leaching moves down to underlying groundwater where it increases the salt content of the groundwater and causes groundwater levels to rise where there is not much groundwater pumping. Of course, the biggest evaporators are the oceans themselves, where the salt content of the water now is about 35,000 mg/P. Oceans contain about 97% of the global water (Bouwer, 1978). Of the remaining 3%, about 2% is in the form of snow and ice in our polar regions and mountain ranges. This leaves only about 1% as liquid fresh water, almost all of which occurs as groundwater and very little as surface water which often is fed by groundwater. This shows the importance of groundwater and the need for proper management of that resource to prevent depletion and quality degradation.

Salt loadings

The main renewable water resources, i.e., surface water, for South Central Arizona are the Salt River system (about 0.8 million af/yr with a TDS of about 500 mg/P), and the Central Arizona Project Aqueduct (about 1.2 million af/yr of Colorado River water with a TDS of about 650 mg/P). Groundwater in this area is essentially a non-renewable resource, because natural recharge in a dry climate is very small (on the order of a few mm per year; Bouwer, 1989 and 2002) and there is essentially no ■new• groundwater being formed. Almost all of the recharge in the Phoenix-Tucson area is deep percolation water from irrigated areas, which is a return flow and does not represent ■new• water. Groundwater pumping for irrigation in the Phoenix, Tucson, and Pinal Active Management Area is about 0.9 million af/yr (Drew Swieczkowski, Arizona Department of Water Resources, personal communication 12/18/01) with an estimated average TDS of about 1000 mg/P. This represents a total salt load in surface water and groundwater of about 2.8 million tons per year. For the present population of about 4 million people in the area, this amounts to 3/4 ton or 1500 lbs per person per year or about 4 lbs per person per day. This is much more than the amount of salt ingested with food and drink and excreted again into the sewers or, for that matter, the salt added by other sources like water softeners.

Since there is little export of water and salt away from the Phoenix-Tucson area, the salts accumulate in the area itself, and mostly in the groundwater below irrigated areas where most of the water evaporates back into the atmosphere and salts accumulate in the root zone. These salts must be leached out with excess irrigation water to create drainage or deep percolation water that moves down to underlying groundwater. Hydrologically, irrigated areas basically are large evaporators like oceans where distilled water is returned to the atmosphere and salts remain behind.

Movement of irrigation water, salts, and nitrate to groundwater

Irrigated agriculture and urban irrigation of residential yards, parks, golf courses, playgrounds, landscaping, etc. are sustainable only if the salts and other chemicals that are in the irrigation water are leached out of the root zone to avoid accumulation of plant damaging salt levels in the root zone itself. In dry climates this is achieved by applying more irrigation water than needed for evaporation. This extra water can be applied with each irrigation, or it can be applied seasonally with special ■deep• irrigations. Usually, the normal ■inefficiency• of irrigation and resulting over-irrigation are sufficient to create enough deep percolation water to maintain a salt balance in the root zone. In addition to salts, the deep-percolation water moving down through the vadose zone and to the groundwater contains all the other chemicals in the irrigation water that are not absorbed by the plants or bio-degraded in the root zone. In Mediterranean climates with winter rains or in other areas with significant periodic rainfalls, the leaching can be achieved naturally with excess rainfall. The vadose zone is the mostly unsaturated zone between the groundwater and land surface. Some salts like calcium carbonate or sulfate may precipitate in the vadose zone. This reduces the salt load on the underlying groundwater but may create undesirable caliche like deposits that could hamper drainage. More research is needed to see how significant this precipitation can be.

Leaching of salts and other chemicals out of the root zone must be managed in an environmentally responsible way to avoid undue rises of groundwater levels and contamination of underlying groundwater, and to protect the surface water into which the drainage water eventually is discharged after it leaves the aquifer through natural drainage into surface water, through tile or ditch drainage systems, or through vertical drainage with pumped wells. Chemicals that are naturally present in soils and deeper geologic formations of vadose zones and aquifers also can be leached by the deep percolation water, like, for example, salts and selenium in marine shales (Lemly, 1993). This can add to the contamination of groundwater and of surface water into which the groundwater is ultimately discharged. For relatively unpolluted irrigation water, the main chemicals of concern are dissolved salts naturally occurring in the water, and the agricultural chemicals like fertilizers and pesticides that are added to the water, plants, or soils (Bouwer 1990). Where sewage effluent or sewage contaminated water is used for irrigation, other compounds like pharmaceuticals, disinfection byproducts, THM precursors, and other synthetic organic compounds may also be of concern (Bouwer 2000; Daughton and Jones-Lepp, 2001; Drewes and Shore, 2001).

To illustrate the concepts of leaching and groundwater contamination, an irrigated area will be taken in a dry, warm climate with negligible rainfall that is continuously cropped and requires about 5 ft of water per year for evapotranspiration (evaporation from the soil plus transpiration by the plants), like in south-central Arizona. Defining the irrigation efficiency as evapotranspiration divided by water applied and assuming an irrigation efficiency of about 80%, the required irrigation application would then be about 6 ft of water per year of which about 1 ft per year will move through the root zone and downward as drainage or deep percolation water to the underlying groundwater. If the salt concentration of the irrigation water is 700 mg/P, the salt content of the deep percolation water will then be 6 x 700 = 4200 mg/P, well above the desired upper limit of 500 mg/P for drinking, and also well above the value of 2000 mg/l where use of that water for irrigation becomes severely restricted (Ayers and Westcott, 1985). This means that it can then only be used for very salt tolerant crops, preferably after mixing with lower TDS water, if normal crop yields are desirable. Yields of less salt tolerant crops would be greatly reduced (Ayers and Westcott, 1985; Tanji, 1990). Concentrations of other chemicals in the irrigation water not absorbed by the plants or attenuated in the root zone also will be six times higher in the deep percolation water than in the irrigation water.

Nitrogen fertilizer requirements are about 240 lbs/acre per crop (Baier and Fryer, 1973; Bouwer and Idelovitch, 1987). As a rule-of-thumb, half of this nitrogen is absorbed by the crop, one-fourth is lost by denitrification and returns to the atmosphere as nitrogen gas and oxides of nitrogen, and one-fourth or 60 lbs/acre in this case is leached out of the root zone as nitrate in the deep percolation water (Bouwer, 1990). For the above example of 1 ft/yr deep percolation water, this would give a nitrate nitrogen concentration in the deep percolation water of 60 lbs per acrefoot or 22 mg/P. This is well above the maximum limit of 10 mg/l for drinking water.

Conventionally treated secondary sewage effluent (activated sludge) may contain about 30 mg/l total N, mostly as ammonium (Bouwer et al., 1974). If this effluent were used for irrigation with a total application of 6 ft per year or growing season, the amount of nitrogen applied with the water would be about 490 lbs/acre per year or growing season, more than twice the normal requirements. Assuming no luxury uptake of nitrogen by the crop so that again one-fourth of this nitrogen is leached out as nitrate with the deep percolation water, and assuming also that the irrigation efficiency again is about 80%, would then give a nitrate nitrogen concentration in the drainage water of about 45 mg/P. Thus, irrigation with sewage effluent and no additional application of nitrogen fertilizer already can cause more nitrate contamination of underlying groundwater than irrigation with normal water and the nitrogen applied as fertilizer. Nitrate contamination of groundwater due to irrigation with reclaimed municipal wastewater can be reduced by removing nitrogen in the sewage treatment plant with nitrification-denitrification or other processes. Also, nitrogen can be removed naturally from water in the underground environment by denitrification, ammonium adsorption, and possibly by the recently discovered anammox process (Van de Graaf et al., 1995) if both ammonium and nitrate occur in the groundwater under anaerobic conditions.

If sewage effluent is used for irrigation, the nitrogen in the effluent often is more than enough to satisfy the nitrogen requirements of the crops and fertilizer nitrogen should not be given. As a matter of fact, the effluent may already contain too much nitrogen which can not only adversely affect underlying groundwater but also the crop itself. Adverse crop effects due to excess nitrogen include delay of harvest, too much vegetative growth and not enough reproductive growth (seeds), impaired quality of crop (reduced sugar contents in beets and cane, reduced starch content in potatoes), reduced yield of marketable fruit, and nitrate toxicity in people and animals consuming the crop (Baier and Fryer, 1973). Contamination of groundwater with other sewage chemicals like synthetic organics and pharmaceuticals is also possible (Lim et al, 2000). Not much is known about the underground fate of these chemicals. Some pharmaceuticals have been detected in groundwater below losing streams that carried effluent-contaminated water, and in systems of artificial recharge of groundwater with sewage effluent (Drewes and Shore, 2001). Thus contamination of groundwater with pharmaceuticals and other organic compounds below sewage irrigated areas may be possible. Since irrigation with sewage effluent can be expected to drastically increase in the future as populations increase and water reuse will become increasingly necessary, more research on adverse effects of effluent irrigation on plants and groundwater will be needed.

The minimum leaching requirement for salt balance in the root zone depends on crop salinity tolerance and salt content of irrigation water (Tanji; 1990; Ayers and Westcott, 1985). Typically, a leaching ratio of 10% is suitable for most cases, giving a maximum irrigation efficiency of 90%. Most farm irrigation systems have efficiencies well below 90%. Well designed and well managed irrigation systems may have an efficiency of about 80%. Many surface irrigation systems have much lower efficiencies, for example 60% or less. The higher the TDS of the irrigation water, the larger the amounts and frequencies of leaching need to be. Thus, normal inefficiencies of irrigation systems often are more than sufficient for adequate leaching of salts and other chemicals out of the root zone. This leaching avoids buildup of salts and other chemicals in the soil and maintains a salt or chemical balance for the root zone. Eventually, however, these chemicals will show up in underlying groundwater and from there in surface water via natural drainage of groundwater into surface water, via discharge from ditch or tile drains or from pumped drainage wells, or via sewage effluent discharges in areas where the affected groundwater is first used for municipal water supply. A sustained irrigation efficiency of 100%, as advocated by some, is only possible if distilled water or other water with a TDS content of zero is used for irrigation,

While downward flow of deep percolation water below the root zone is unsteady and occurs in pulses after each irrigation, the pulses flatten out with depth so that actual downward water velocities or pore velocities deeper in the vadose zone can be estimated as the average deep percolation Darcy flux divided by the volumetric water content of the vadose zone. Thus, for the previous example with a deep percolation rate of 1 ft/yr and assuming a water content of 15% in the vadose zone, the pore velocity of the deep percolation water would be 1/0.15 = 6.75 ft/yr. Where groundwater is deep, for example at about 300 ft as in south central Arizona, it would thus take the deep percolation water about 45 yrs to reach the groundwater. In many areas irrigation has been going on much longer so that significant amounts of deep percolation water already have joined the groundwater. This can also cause groundwater levels to rise. For example, if the aquifer is unconfined and the fillable porosity in the vadose zone is 20%, the arrival of 1 ft of water per year would cause the water table to rise 1/0.2 = 5 ft/yr, assuming no other recharges or discharges of groundwater or pumping from wells that affect groundwater levels or produce lateral flow in the aquifer away from the irrigated area. The fillable porosity is the difference between the water content in the vadose zone and that below the rising water table.

Where an irrigation project has just been started and deep percolation water begins to move downward for the first time, the time for the first deep percolation water to arrive at underlying groundwater can be estimated from the difference between the original water content of the vadose zone and the water content in the zone wetted by the deep percolation water. This flow is like that in an infiltration system where dry soil is flooded, water infiltrates into the soil and moves downward to create a wetted zone as the wetting front continues to advance downward. The rate of downward movement of the wetting front can be estimated from the infiltration rate and the difference between the water content of the wetted zone and that of the drier vadose sone below it. For example, if the water content is 15% in the wetted zone and 5% in the relatively dry vadose zone below it, and the deep percolation rate is 1 ft per year, the wetting front will move downward at the rate of 1/(0.15-0.05) = 10 ft per year. Thus, where the groundwater is at a depth of 400 ft and a new irrigation project is started, it would take 400/10 = 40 years for the deep percolation water to reach the groundwater and to start causing TDS increases in the well water, especially if the well is perforated or screened to the top of the aquifer or even higher.

The pore velocity in the vadose zone of 6.7 ft/yr and the water table rise of 5 ft/yr in the previous example are based on year-round irrigation. For more seasonal irrigation, with only one crop per year and fallowing between crops, these values will be less and closer to about 3 ft/yr for the pore velocity in the vadose zone and about 2 ft/yr for the rise of the groundwater table. For mixed irrigated agriculture with a combination of seasonal and year-round irrigation, downward pore velocities in the vadose zone thus may range between 2 and 5 ft/yr, and groundwater rises may be between 3 and 6 ft/yr. Thus, the long-term effects of irrigation on underlying groundwater are water quality degradation and rising groundwater levels. On the other hand, where overpumping occurs and groundwater levels are dropping, arrival rates of deep-percolation water at the groundwater are reduced and can even reach zero if groundwater levels are dropping faster than the pore velocity of the deep-percolation water in the vadose zone. If groundwater pumping and groundwater level declines then are reduced to where the deep-percolation water can ■catch up• with the water table, rising groundwater levels and significant groundwater quality reductions can be expected.

The calculated increases in groundwater TDS, nitrate levels, and groundwater levels themselves agree with observed values in a study conducted by the Salt River Project in the southeastern part of the Salt River Valley where groundwater pumping was greatly reduced and irrigation was mostly done with surface water starting in the late 1970s and continuing throughout the 1980s (Karol O. Wolf, Salt River Project, personal communication, 2002). For example, nitrate levels in groundwater pumped from the aquifer below the affected area increased from a range of 2 to 7 mg/P as nitrogen to a range of 10 to 20 mg/P. TDS increased from about 500 mg/P to about 1000 mg/P for some wells, and from 500 to 1800 and from 700 to 1500 mg/P for others, while groundwater levels rose about 2 ft/yr. The TDS values are significantly lower than expected from the TDS contents of the deep percolation water, which for efficient irrigation systems would be about 2500 mg/P. Nitrate levels were lower than expected in the deep percolation water. This is because the wells are perforated or screened for a significant depth interval, whereas the deep percolation water accumulates at the top of the aquifer. Thus, the well water consists of a mixture of salty deep percolation water from the upper part of the aquifer and much less salty natural groundwater from deeper in the aquifer. Simple calculations can be made to predict the TDS increase of the well water as a function of time after the arrival of deep percolation water. If the situation is more complicated, like well screens only in the deeper portion of the aquifer and/or presence of a middle fine-grained unit or other layers of low permeability, modeling techniques can be used to predict TDS increases in well water as a function of time of pumping. Since the contaminated water will remain mostly in the upper part of the aquifer according to the vertical stacking principle, wells with their screen or perforated section near the water table will show the quality degradation first. Wells in unconfined aquifers with deeper screens will be affected later, as pumping produces vertical flow components in the aquifer and upper groundwater is drawn deeper into the aquifer and into the well, even if the deeper aquifers are semi-confined. Eventually, wells may produce mostly deep percolation water from the irrigation practices. Such water will not meet drinking water standards and also may be too salty for general agricultural use. Options then include blending the well water with better quality water, drilling the wells deeper or sealing off upper portions of screens to buy more time before the well water gets saltier, and treatment of the well water with, for example, reverse osmosis which, of course, produces a reject brine that may give disposal problems.

Urban irrigation can also cause groundwater levels to rise. For example, groundwater levels rose from a depth of about 120 ft to a depth of about 50 ft in a few decades below an old residential area with flood irrigated yards in north central Phoenix. This rise was mainly in response to the shutting down of several large capacity irrigation and water supply wells in the area. The rate of rise of the groundwater level in the affected area was about 1 to 2 ft per year. At one area (Camelback and Central), rising groundwater levels flooded the lowest level (level No. 5) of an underground parking garage below an office building. Initially, groundwater levels were adequately controlled by draining the ABC layer below the concrete floor slab. Eventually, however, wells had to be installed around the building to lower groundwater levels. The discharge water from the wells was contaminated by local leaking underground storage tanks. This required expensive treatment of the water before it could be discharged into a storm drain.

Evaporation from vadose zone

Where deep percolation rates are very small, as with very efficient irrigation systems, deficit irrigation, or low water use landscaping (xeriscapes), evaporation of water deeper in the vadose zone may become significant and deep percolation rates will then decrease with depth to the point where TDS concentrations become so high that salts precipitate in the vadose zone and maybe even in the root zone itself which would have adverse effects on the plants. Low deep percolation rates would cause low water contents in the soil of the vadose zone which would increase the permeability of the soil to air. Evaporation of water in the vadose zone could then be caused by diurnal barometric pressure variations that typically occur in a desert environment in the absence of major weather systems moving through. Barometric pressures then increase during the night when the air cools down and becomes heavier, and decrease during the day as the air warms up again and becomes lighter. This could cause the vadose zone to "breathe," "inhaling" dry atmospheric air during the night that causes vadose zone water to evaporate into the soil air and "exhaling" damp vadose zone air into the atmosphere during the day. This "deep" evaporation could cause significant amounts of salt to be stored in the vadose zone which reduces the salt load on the underlying groundwater. More research on this phenomenon is necessary, especially on long-term effects to determine if salts could build up to the point where they form caliche-like layers that impede downward movement of water and could cause water logging of the upper soil, evaporation from the soil surface, and formation of salt flats where nothing will grow.

Salt tolerance of plants

Increasing TDS contents of well water or, for that matter, any water, are undesirable because for health and aesthetic reasons they should be below 500 mg/P for potable water. TDS increases are also undesirable because they shorten the useful life of pipes, water heaters, etc., and make water treatment more expensive for industrial uses where high water qualities, including ultra pure water, are needed. TDS increases are also undesirable for urban and agricultural irrigation of plants and crops. As a rule, water with a TDS content of less than 500 mg/P can be used to irrigate any plants, including salt sensitive plants. Between 500 and 2000 mg/P TDS, there can be slight to moderate restrictions on its uses, and above 2000 mg/P there can be severe restrictions like growing salt tolerant crops only and adequate leaching of salts out of the root zone (Ayers and Westcott, 1985; Tanji, 1990). For agricultural purposes, salt contents of irrigation water and water in soils and aquifers are often measured as electrical conductivity, EC, expressed in deciSiemens/meter or dS/m. For most natural waters 1 dS/m is equivalent to a TDS content of about 640 mg./P. Basic relationships between the EC of irrigation water and relative crop yields are shown in Figure 1 taken from Ayers and Westcott (1985). Typically, such relations show no decrease in crop yield with increases in the salt content of the irrigation water, as expressed by ECw, as long as ECw is small. Then, as ECw of the irrigation water is increased, a threshold value is reached where crop yields start to decrease linearly with further increases in ECw. This threshold value is about 0.7 dS/m (450 mg/P) for salt sensitive crops, 1.8 dS/m (1150 mg/P) for moderately salt sensitive crops, 4.0 dS/m (2600 mg/P) for moderately salt tolerant crops, and 6.5 dS/m (4200 mg/P) for salt tolerant crops. Examples of crops in these categories are shown in Table 1. The lines in Figure 1 show that if the ECw of the irrigation water increases beyond the threshold value, farmers have to accept a reduction in crop yield, or switch to a more salt tolerant crop. There is considerable research being done to increase the salt tolerance of crops (Apse et al., 1999; Ayers and Westcott, 1985).

Management of salty water

The first reaction to a decreasing quality of well water often is to shut the well down and use other sources of water. However, where groundwater is not pumped at adequate rates, water tables will then continue to rise due to continued arrival of deep percolation water until they become so high that they flood basements, damage underground pipelines, come too close to landfills or cemeteries, kill trees, reduce crop yields, and eventually water-log the surface soil so that water can evaporate directly from the soil, leaving the salts behind and creating salt flats. Failure to control groundwater levels in irrigated areas and resulting salinization of the soil has been the demise of old civilizations and is still causing irrigated land to go out of production at alarming rates (Postel, 1999). In addition to developed and developing countries, there now are also deteriorating countries. Where there are rises of salty groundwater, groundwater must eventually be pumped again to keep groundwater levels at a safe depth. For agricultural areas where higher groundwater levels can be tolerated than in urban areas, water tables can be controlled by tile or ditch drainage.

Great care must be taken that the poor quality salty water that comes out of out of these wells and drainage systems is discharged into the surface environment in an ecologically responsible manner. Options include discharge into oceans or big rivers where dilution is the solution to pollution, or into dedicated ■salt• lakes for accumulation and storage of salts in perpetuity. Where the salty water needs to be transported over long distances to proper disposal areas, concentrating the salts into smaller volumes of water may be needed to reduce the cost of pipelines, aqueducts or other conveyance systems, and to reduce the volume of water that leaves the area. One way to concentrate the salts into smaller water volumes while making economic use of the desalted water is membrane filtration. The desalted water could then be used for potable or industrial purposes. As a matter of fact, mildly brackish groundwater could be an important reserve water resource in periods of drought since desalting this water is relatively inexpensive compared to desalting much saltier water like seawater.

Concentration of salts into smaller water volumes can also be achieved with sequential irrigation of increasingly salt-tolerant crops where the deep-percolation water from one crop is used to irrigate a more salt-tolerant crop, etc., starting with salt-sensitive crops and ending with halophytes (Shannon et al., 1997). This can increase the salt concentrations of the drainage water to sea water levels (about 30,000 mg/l) and in volumes that are a small fraction of the original irrigation water volume, as illustrated in Table 2. Depending on local conditions, sequential irrigation to halophytes may not be needed and the sequence may be stopped if the salt content of the deep percolation water has become high enough to achieve sustainable disposal at acceptable costs. The wells for pumping salty deep percolation from the aquifer in sequential irrigation projects should be rather shallow so that they pump primarily deep percolation water from the top of the aquifer and a minimum of deeper native and less salty groundwater. Also, sequential irrigation is best carried out by growing increasingly salt tolerant crops in relatively large blocs so that there is not much lateral flow in the aquifer that could interfere with proper control of the deep-percolation water from the different crops.

A third option for concentrating salts into smaller volumes is via evaporation ponds. For the Salt River Valley, evaporation rates of free water surfaces are about 6 ft/yr. Thus, if flows of drainage water are significant, large land areas will be required for such ponds. The ponds may also become environmental hazards. For example, if the irrigation amount is 5 ft/year, and the irrigation efficiency is 75%, evaporation ponds with a surface area of about 20% of the irrigated area would be required if all the deep percolation water must be evaporated. This will eventually increase salt concentrations in the ponds to values well in excess of those for sea water as happened in the Salton Sea in California with about 40,000 mg/L and the Dead Sea between Jordan and Israel with about 340,000 mg/L. However, complete evaporation may not be necessary if the main purpose of the pond is to concentrate the salts into manageable smaller volumes of water that can then be more economically exported to an ocean or designated inland salt lake. In that case pond areas will be less. Another possibility for concentrating the salts into smaller volumes of water by evaporation is to use the salty well water for power plant cooling. For example, the 3810 megawatt nuclear power plant west of Phoenix is cooled with about 65,000 acrefeet per year of treated sewage effluent. The effluent is recycled 15 to 20 times through the plant and is then discharged into 500 acres of evaporation ponds where it completely evaporates. At an annual evaporation of about 6 feet, the evaporation from the ponds is about

3,000 acrefeet per year. Thus, the salts in 65,000 acrefeet of effluent are concentrated into 3,000 acrefeet of cooling tower outflow, giving a volume reduction of about 95% and a 20 fold increase in salt concentration.

Perhaps the evaporation ponds can be constructed as solar ponds which can be used to generate hot water and/or electricity. For example, in an experimental solar pond project in El Paso, Texas, the pond was 9 ft deep with a 3 ft layer of low salinity water on top, a 3 ft layer of medium salinity water in the middle, and a 3 ft layer of high salinity (brine) at the bottom (Xu, 1993). This created a density gradient so that sun energy was trapped as heat in the bottom layer while the lighter top layers prevented thermal convection currents and acted as insulators. The hot brine from the bottom layer was pumped to a heat exchanger where a working fluid like iso-butane or freon was vaporized which then went through a turbine to generate power. The working fluid was condensed in another heat exchanger that was cooled with normal water which was recirculated through a cooling tower. The working fluid then returned to the brine heat exchanger where it was preheated by the brine return flow from the heat exchanger to the pond before it was vaporized again. The El Paso pond had a surface area of 0.8 acres and generated 60 to 70 KW. At this rate, a solar pond system of about 12,500 acres or an area of about 5 x 5 miles could generate about 1000 megawatts of electricity, which is typical of a good sized power plant. There was enough heat stored in the hot brine layer to also generate power at night. The El Paso studies have demonstrated the principles of solar power generation. Considerable research is still necessary to see how a large scale system should be designed and managed.

Concentrating the salts into smaller and smaller volumes with revenue producing techniques will be of special benefit to inland or other areas where salts need to be transported over long distances to reach suitable (or least objectionable!) places for final disposal like, for example, an ocean or a dedicated lake. Concentrating the salts into small volumes of water will then minimize the cost of pipelines and other conveyance structures. The ultimate concentration of salt is, of course, achieved by complete evaporation of the water, so that the salts crystallize and can be stored in perpetuity in landfills, or used commercially if beneficial uses can be developed.

PROGNOSIS

As the population in south-central Arizona continues to increase and the Phoenix-Tucson corridor expands into a Prescott-Nogales corridor, more and more water will be needed for municipal water supply and more and more sewage effluent will be produced. If all the main renewable water resources, i.e., the Salt river and Colorado river, were solely used for municipal water supply, the 2 million acre feet per year brought in by these rivers could support a population of about 9 million, assuming a gallons per capita per day use of 200, which is between the present gpcd of 250 for Phoenix and 150 for Tucson. At a sewage flow of 100 gallons per person per day, the 9 million people would produce 1 million acre feet of effluent per year. At an application rate of 5 ft per year, this could irrigate almost 200,000 acres, urban as well as agricultural. The salt content of the effluent would be below the 1000 mg/P which is the center of the range where moderately salt sensitive plants or crops can be grown (Fig. 1). The effluent could also be used for potable water reuse via artificial recharge of groundwater (Crook et al., 1999), for cooling water for power plants, and for environmental purposes like restoration of stream flow and riparian habitats. Potable reuse of the effluent could add another 2 or 3 million people to the sustainable population. Such reuse would require more membrane filtration, which produces a reject brine that adds to the salt burden. Groundwater will be used where still available and of good quality. However, without incidental recharge from irrigation or without artificial recharge in engineered projects, natural recharge rates in dry climates are so low that groundwater basically is a non-renewable resource (Bouwer, 2002).

As described earlier, the salts in the water used for irrigation are concentrated in the deep percolation water that moves from the root zone to underlying groundwater where it will increase the salt content of the groundwater. It will also cause groundwater to rise where there is no serious over pumping of groundwater. Eventually, groundwater must then be pumped to prevent groundwater levels from rising too high. The salty water from the pumped wells then should be reduced in volume so that the salt in this water can be exported in relatively small amounts of water. Such concentration of salt into smaller volumes can be achieved with revenue producing processes, including membrane filtration that also produces drinking water, sequential irrigation of increasingly salt tolerant crops, and evaporation ponds that may be used as solar ponds for power generation. Final disposal of salt to obtain regional salt balances may then be via export to an ocean, or storage in perpetuity in inland salt lakes or land fills.

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Table 1. Relative salt tolerance of agricultural crops (Ayers and Westcot, 1985).

TOLERANT

Fibre, Seed and Sugar Crops

Barley	*Hordeum vulgare*
Cotton	*Gossypium hirsutum*
Jojoba	*Simmondsia chinensis*
Sugarbeet	*Beta vulgaris*

Grasses and Forage Crops

Alkali grass, Nuttall	*Puccinellia airoides*
Alkali sacaton	*Sporobolus airoides*
Bermuda grass	*Cynodon dactylon*
Kallar grass	*Diplachne fusca*
Saltgrass, desert	*Distichlis stricta*
fairway crested	
Wheatgrass, tall	*Agropyron elongatum*
Wildrye, Altai	*Elymus angustus*
Wildrye, Russian	*Elymus junceus*

Vegetable Crops

Asparagus	*Asparagus officinalis*

Fruit and Nut Crops

Date palm	*Phoenix dactylifera*

MODERATELY TOLERANT

Fibre, Seed and Sugar Crops

Cowpea	*Vigna unguiculata*
Oats	*Avena sativa*
Rye	*Secale cereale*
Safflower	*Carthamus tinctorius*
Sorghum	*Sorghum bicolor*
Soybean	*Glycine max*
Triticale	*X Triticosecale*
Wheat	*Triticum aestivum*
Wheat, Durum	*Triticum turgidum*

Grasses and Forage Crops

Barley (forage)	*Hordeum vulgare*
Brome, mountain	*Bromus marginatus*
Canary grass, reed	*Phalaris, arundinacea*
Clover, Hubam	*Melilotus alba*
Clover, sweet	*Melilotus*
Fescue, meadow	*Festuca pratensis*
Fescue, tall	*Festuca elatior*
Harding grass	*Phalaris tuberosa*
Panic grass, blue	*Panicum antidotale*
Rape	*Brassica napus*
Rescue grass	*Bromus unioloides*
Rhodes grass	*Chloris gayana*
Ryegrass, Italian	*Lolium italicum multiflorum*
Ryegrass, perennial	*Lolium perenne*
Sudan grass	*Sorghum sudanense*
Trefoil, narrowleaf birdsfoot	*Lotus corniculatus tenuifolium*
Trefoil, broadleaf birdsfoot	*Lotus corniculatus arvenis*
Wheat (forage)	*Triticum aestivum*
Wheatgrass, standard crested	*Agropyron sibiricum*
Wheatgrass, intermediate	*Agropyron intermedium*
Wheatgrass, slender	*Agropyron trachycaulum*
Wheatgrass, western	*Agropyron trachycaulum*
Wildrye, beardless	*Elymus triticoides*
Wildrye, Canadian	*Elymus canadensis*

Vegetable Crops

Artichoke	*Helianthus tuberosus*
Beet, red	*Beta vulgaris*
Squash, zucchini	*Cucurbita pepo melopepo*

Fruit and Nut crops

Fig	*Ficus carica*
Jujube	*Ziziphus jujuba*
Olive	*Olea europaea*
Papaya	*Carica papaya*
Pineapple	*Ananas comosus*
Pomegranate	*Punica granatum*

MODERATELY SENSITIVE

Fibre, seed and Sugar Crops

Broadbean	*Vicia faba*
Castorbean	*Ricinus communis*
Maize	*Zea Mays*
Flax	*Linum usitatissimum*
Millet, foxtail	*Setaria italica*
Groundnut/peanut	*Arachis hypogaea*
Rice, paddy	*Oryza sativa*
Sugarcane	*Saccarum officinarum*
Sunflower	*Helianthus annuus*

Grasses and Forage crops

Alfalfa	*medicago sativa*
Bentgrass	*Agrostis stolonifera palustris*
Bluestem, Angleton	*Dichanthium aristatum*
Brome, smooth	*Bromus inermis*
Buffelgrass	*Cenchrus ciliaris*
Burnet	*Poterium sanquisorba*
Clover	*Trifolium hydridum*
Clover, Berseem	*Trifolium alexandrinum*
Clover, ladino	*Trifolium repens*
Clover, red	*Trifolium pratense*
Clover, strawberry	*Trifolium fragiferum*
Clover, white Dutch	*Trifolium repens*
Corn (forage)(maize)	*Zea mays*
Cowpea (forage)	*Vigna unguiculata*
Dallis grass	*Paspalum dilatatum*
Foxtail, meadow	*Alopecurus pratensis*
Grama, blue	*Bouteloua gracilis*
Lovegrass	*Eragrostis sp.*
Milkvetch, Cicer	*Astragalus cicer*
Oatgrass, tall	*Arrhenatherum, Danthonia*
Oats (forage)	*Avena sativa*
Orchard grass	*Dactylis glomerata*
Rye (forage)	*Secale cereale*
Sesbania	*Sesbania exaltata*
Siratro	*Macroptilium atropurpureum*
Sphaerophysa	*Sphaerophysa salsula*
Timothy	*Phleum pratense*
Trefoil, big	*Lotus uliginosus*
Vetch, common	*Vicia angustifolia*

Vegetable Crops

Broccoli	*Brassica oleracea botrytis*
Brussels sprouts	*B. oleracea gemmifera*

Table 1. (Continued)

MODERATELY SENSITIVE

Vegetable Crops	
Cabbage	*B. oleracea capitata*
Cauliflower	*B. oleracea botrytis*
Celery	*Apium graveolens*
Corn, sweet	*Zea mays*
Cucumber	*Cucumis sativus*
Eggplant	*Solanum melongena esculentum*
Kale	*Brassica oleracea acephala*
Kohlrabi	*B. oleracea gongylode*
Lettuce	*Latuca sativa*
Muskmelon	*Cucumis melo*
Pepper	*Capsicum annuum*
Potato	*Solanum tuberosum*
Pumpkin	*Cucurbita peop pepo*
Radish	*Raphanus sativus*
Spinach	*Spinacia oleracea*
Squash, scallop	*Cucurbita pepo melopepo*
Sweet potato	*Ipomoea batatas*
Tomato	*Lycopersicon lycopersicum*
Turnip	*Brassica rapa*
Watermelon	*Citrullus lanatus*
Fruit and Nut Crops	
Grape	*Vitis sp.*

SENSITIVE

Fibre, Seed and Sugar Crops	
Bean	*Phaseolus vulgaris*
Guayule	*Parthenium argentatum*
Sesame	*Sesamum indicum*
Vegetable Crops	
Bean	*Phaseolus vulgaris*
Carrot	*Daucus carota*
Okra	*Abelmoschus esculentus*
Onion	*Allium cepa*
Parsnip	*Pastinaca sativa*
Fruit and Nut Crops	
Almond	*Prunus dulois*
Apple	*Malus sylvestris*
Apricot	*Prunus armeniaca*
Avocado	*Persea americana*
Blackberry	*Rubus sp.*
Boysenberry	*Rubus ursinus*
Cherimoya	*Annona cherimola*
Cherry, sweet	*Prunus avium*
Cherry, sand	*Prunus besseyi*
Currant	*Ribes sp.*
Gooseberry	*Ribes sp.*
Grapefruit	*Citrus paradisi*
Lemon	*Citrus limon*
Lime	*Citrus aurantiifolia*
Loquat	*Eriobotrya japonica*
Mango	*Mangifera indica*
Orange	*Citrus sinensis*
Passion Fruit	*Passiflora edulis*
Peach	*Prunus persica*
Pear	*Pyrus communis*
Persimmon	*Diospyros virginiana*
Plum: Prume	*Prunus domestica*
Pummelo	*Citrus maxima*
Raspberry	*Rubus idaeus*
Rose apple	*Syzgium jambos*
Sapote, white	*Casimiroa edulis*
Strawberry	*Fragaria sp.*
Tangerine	*Citrus reticulata*

Table 2: Sequential irrigation of increasingly salt tolerant crops with drainage water from less tolerant crops. Volumes are expressed in arbitrary units.

Crop	**Sensitive**	**Moderately Sensitive**	**Tolerant**	**Very Tolerant**	**Halophyte**
Examples (Ayers and Westcot, 1985)	**peas, beans, strawberries, stone, pome, and citrus fruits**	**lettuce, kale, broccoli, celery, potato**	**wheat, sorghum, rye, beet**	**barley, cotton, sugar beet, bermuda grass, salt cedar, eucalyptus, poplar**	**salicornia**
Irrigation volume	100	25	10	5	2
Salt conc. mg/l	200	800	2,000	4,000	10,000
Efficiency %	75	60	50	60	67
Drainage volume	25	10	5	2	0.67
Salt conc. mg/l	800	2,000	4,000	10,000	30,000

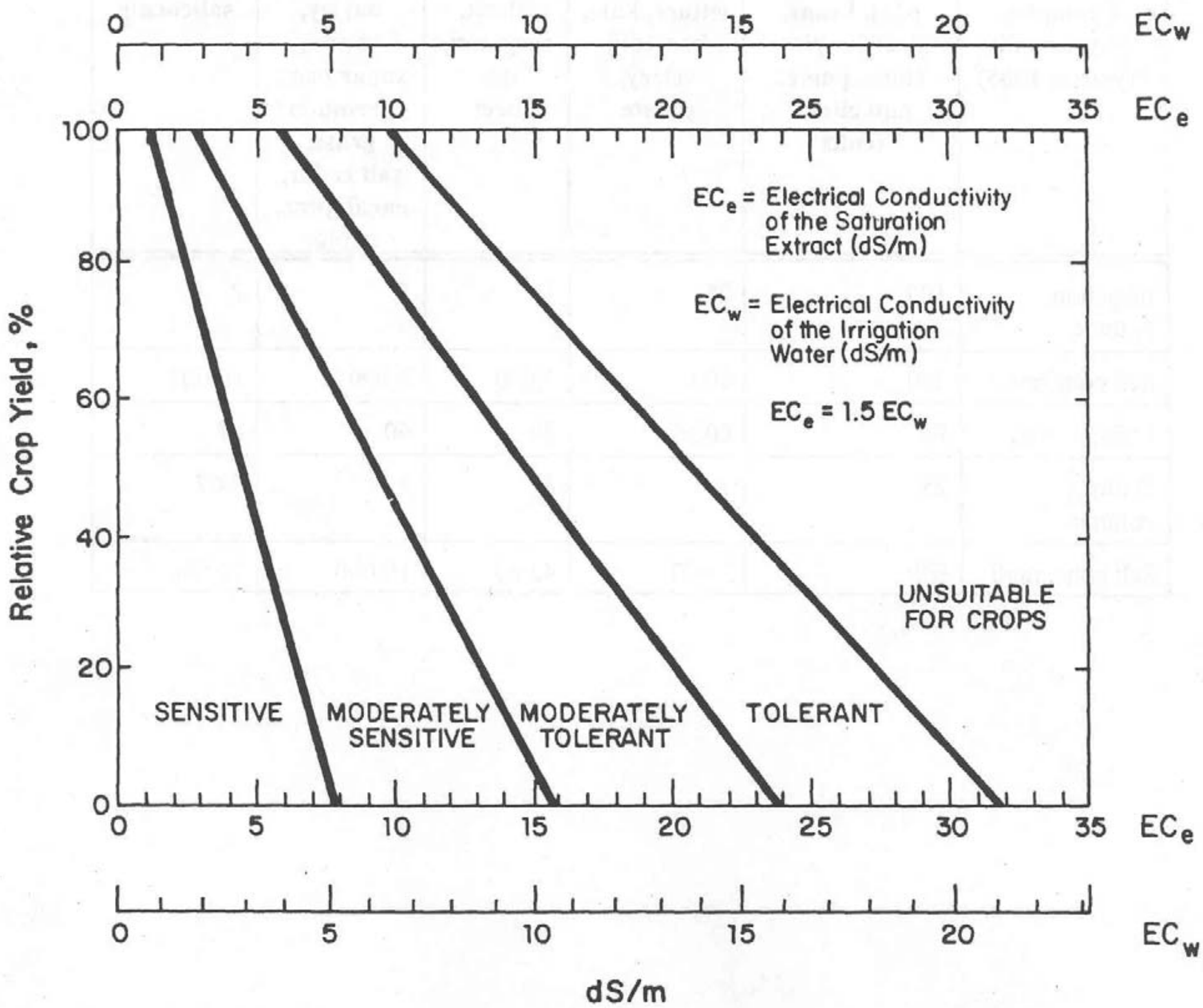

Figure 1. Relative salt tolerance ratings of agricultural crops (E.V. Maas, 1984, as shown by Ayers and Westcott, 1995).