Appendix E

THE JOURNEY FROM SAFE YIELD TO SUSTAINABILITY

ground water

Issue Paper/

The Journey from Safe Yield to Sustainability

by William M. Alley[1] and Stanley A. Leake[2]

Abstract

Safe-yield concepts historically focused attention on the economic and legal aspects of ground water development. Sustainability concerns have brought environmental aspects more to the forefront and have resulted in a more integrated outlook. Water resources sustainability is not a purely scientific concept, but rather a perspective that can frame scientific analysis. The evolving concept of sustainability presents a challenge to hydrologists to translate complex, and sometimes vague, socioeconomic and political questions into technical questions that can be quantified systematically. Hydrologists can contribute to sustainable water resources management by presenting the longer-term implications of ground water development as an integral part of their analyses.

Introduction

With increased worldwide attention to the theme of sustainable development and its extension to the sustainability of ground water resources, one might ask how this new concept of sustainability relates to safe yield, and to what extent do the controversies surrounding safe yield carry over to sustainability. Has the term safe yield simply been reinvented as sustainability? To examine these questions, we begin with a brief review of how the two concepts evolved.

The Concept of Safe Yield

The safe-yield concept derives from water supply engineering studies. Originally, the concept focused on the relation between the size (capacity) of a surface water reservoir and its safe yield, defined as the maximum quantity of water that could be supplied from the reservoir during a critical period. With respect to ground water resources, Lee (1915) first defined safe yield as the quantity of water that can be pumped "regularly and permanently without dangerous depletion of the storage reserve." Meinzer (1923) later defined safe yield as "the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible." It is noteworthy that Meinzer's definition used economic factors as a key determinant and, like Lee, focused on depletion of ground water resources. Over time, the concept expanded to include degradation of water quality (Conkling 1946), the contravention of existing water rights (Banks 1953), and other factors. Todd (1959) succinctly and broadly defined the safe yield of a ground water basin as "the amount of water which can be withdrawn from it annually without producing an undesired result."

Various authors have recommended abandoning the term safe yield (Thomas 1951; Kazmann 1956) because of its vagueness, its misinterpretation by laypersons as implying a fixed underground water supply, and its dependence on the particular locations of wells, among other reasons. Nonetheless, the term is still used, and is even found in some state codes. The fundamental idea behind safe yield—quantifying the desirable development of a ground water basin—remains relevant today.

Many suggestions for improving the safe-yield concept have focused on considering the yield concept in a socioeconomic sense within the overall framework of optimization theory. The optimum yield is determined by selecting the optimal management scheme from a set of possible alternative schemes. Of course, within such a framework, consideration of present and future costs and benefits may lead to optimal yields that involve mining ground water, perhaps to exhaustion.

A common misperception has been that the development of a ground water system is "safe" if the average annual rate of ground water withdrawal does not exceed the average annual rate of natural recharge. Bredehoeft et al.

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(1982) and Bredehoeft (2002) give examples of how safe development depends instead on how much of the pumpage can be captured from increased recharge and decreased discharge. Sophocleous (1997) and Bredehoeft (1997) have further discussed this in editorials.

The Concept of Sustainability

The concept of sustainable development, which emerged in the early 1980s, centered on the idea of limiting resource use to levels that could be sustained over the long term. The World Commission on Environment and Development (1987), better known as the Brundtland Commission, defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This report was followed by the United Nations Conference on Environment and Development (Earth Summit) held in Rio de Janeiro, Brazil, in 1992. Several agreements were signed at the conference, the centerpiece of which was a 40-chapter report—*Agenda 21*, an action plan for sustainable development that integrates environmental and developmental concerns. The recent World Summit on Sustainable Development held in Johannesburg, South Africa, highlighted the challenges of achieving the ideals that have been attached to the concept of sustainable development. Water resources sustainability also continues to move into the international spotlight amidst warnings that more than a third of the world's population will not have access to sufficient freshwater by 2025 (Gleick 2001).

Similar to safe yield, ground water sustainability commonly is defined in a broad context, and somewhat ambiguously, as the development and use of ground water resources in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences. Application of the concept of sustainability to water resources requires that the effects of many different human activities on water resources, and on the overall environment, be understood and quantified to the extent possible (Sophocleous 1998; Alley et al. 1999; Sophocleous 2000). In this respect, the importance of managing water at the basin scale, or watershed approach, has emerged along similar lines to the concepts of sustainable development.

Sustainability, like safe yield, is a value-laden concept and one that in many respects is in the eye of the beholder. Defining and measuring sustainability is a major challenge (UNESCO 1999; Loucks 2000). The term sustainability embodies conceptual ambiguities that can be difficult to resolve because they rest on philosophical disagreements (Norton and Toman 1995). For example, ecologists might consider sustainability as use of resources that allows perpetual survival of existing ecosystems, while economists view it more as an allocation of resources that leaves future generations no worse off than present generations. Economists further tend to think about a continuum of sustainability ranging from weak to strong sustainability, with variations in between (Stewart 2003). Weak sustainability requires one generation to hand over to the next a nondeclining total capital stock, which assumes that perfect substitution exists between different types of capital, e.g., new technologies for water treatment or improved water use efficiencies might be developed that somehow substitute for the reduced capital stock of aquifer water. Strong sustainability, on the other hand, assumes that some kinds of natural capital have no substitutes.

In addition to this complexity of values at a given point in time, values relating to the sustainability of ground water resources change with time. For example, in the first comprehensive paper on the effects of withdrawals on aquifer flow components, Theis (1940) indicated no economic loss would be suffered in the capture of ground water that was previously being discharged by nonbeneficial vegetation. In the mid–20th century, native vegetation that consumed ground water was considered, particularly in the American West, to be nonbeneficial. Today, economists recognize a nonmarket value of features such as native vegetation (Brookshire et al. 1986). As values have evolved in the past decades, they are likely to evolve further in the coming decades. These evolutions will continue in various ways in different countries at different stages of development.

Some have argued that humans have advanced at times by a series of unsustainable developments. For example, use of ground water from the Chalk Aquifer of the London Basin in Great Britain during the 19th and early 20th centuries was not sustainable over the long run, but enabled London to develop as a major center of population and manufacturing (Downing 1993). Likewise, Los Angeles, California, relied on ground water in storage even though the supply was being depleted because of the expectation that imported water eventually would take the place of water used from storage. Thus, when talking about sustainability, it may be necessary to stipulate the period over which the use is planned and any assumptions about future sources of water supply (Hiscock et al. 2002).

From Safe Yield to Sustainability

It should be clear the concept of sustainability in relation to ground water resources is far from new and is closely aligned with that of safe yield. The differences represent more of a transition, or to paraphrase a National Research Council (1999) report on sustainability, a journey, in our understanding of the dynamic nature of ground water and its linkages across the biosphere and to human activities (Alley et al. 2002).

Safe yield is almost always defined in terms of an annual water withdrawal, whereas the temporal patterns of withdrawal are more open-ended in definitions of sustainability. Indeed, in many situations, a long-term approach to water resources sustainability may involve withdrawals from ground water storage during dry periods that are balanced by replenishment during intervening wet periods.

The definition of safe yield was developed initially based on a very simple view of how a ground water basin might be developed to maximize the quantity of water withdrawn. The concept expanded with time to include economic, legal, and water quality considerations. Sustainability, on the other hand, emerged around the complex interdependence of society and the environment, and the view that no single environmental issue can be addressed in isolation. Presumably, sustainable development encourages integrated water management approaches such as artificial recharge, conjunctive use of surface water and ground water, and use of recycled or reclaimed water, all of which can profoundly affect the magnitude of development that can be sustained.

Although not originally developed with surface water effects in mind, definitions of safe yield in the United States gradually came to consider the effects of pumping on surface water resources, primarily with respect to water rights in streams. Thus, it became accepted that a yield that is safe with respect to ground water storage might not be so safe with respect to natural discharge areas of aquifers. More recently, concerns about the long-term effects of ground water development have been extended to lakes, wetlands, springs, and estuaries, but these issues seem to have been less tied to determinations of safe yield and more generally related to concepts of sustainability. Today, it is widely recognized that pumping can affect not only surface water supply for human consumption, but also the maintenance of streamflow requirements for fish and other aquatic species, the health of riparian and wetland areas, and other environmental needs. The tradeoff between the water used for consumption and the effects of withdrawals on the environment are increasingly the driving force in determining the sustainability of many ground water systems (Alley et al. 1999). Kendy (2003) emphasizes the importance of distinguishing between water consumption and pumping when assessing sustainability.

Water resources cannot be developed without altering the natural environment; thus, one should not define basin yields, either as safe or sustainable, without carefully explaining the assumptions that have been made about the acceptable effects of ground water development on the environment. Even with assumptions about acceptable changes, the concept of a static safe, or sustainable, yield may not be realistic in light of potential changes in hydrology from land-use activities and climate change. For example, urbanization and agricultural development in a basin affect infiltration, runoff, evapotranspiration, and recharge, effectively changing the hydrologic cycle through time.

The Role of Hydrologists

An important attribute of the concept of water resources sustainability is that it fosters a long-term view toward management of water resources. The response characteristics of ground water systems and their boundaries often lend themselves to such a long-term view. For example, pumping decisions made today may ultimately affect surface water resources (riverflows, lake levels, discharges to wetlands and springs, etc.), but these effects may not be fully realized for many years. Equilibrium to pumping is reached only when withdrawal is balanced by capture and, in many circumstances, long periods are necessary before even an approximate equilibrium condition can be reached. Some ground water systems do not have boundaries with sufficient potential for capture to match existing or proposed levels of ground water withdrawals, and, thus, new equilibrium is not possible.

Water resources sustainability is not a purely scientific concept, but rather should be viewed as a perspective that can frame scientific analysis. Key to this idea is that the sustainability goal is very much at the heart of current concerns about the long-term effects of ground water development. We briefly illustrate how ground water hydrologists can contribute constructively to sustainability issues, using Paradise Valley in north-central Nevada as an example.

Case Study: Paradise Valley, Nevada

Natural drainage through the basin-fill aquifer within Paradise Valley runs southward toward the Humboldt River (Figure 1). According to a calibrated predevelopment steady-state model, natural inflow to, and outflow from, the Paradise Valley ground water system was 91 hm^3/year (Prudic and Herman 1996). Approximately 88% of the inflow (recharge) occurred through leakage from perennial and ephemeral streams, and the rest occurred through leakage along mountain fronts and ground water inflow across the eastern part of the southern boundary from the adjacent Humboldt River Valley. About 96% of the discharge occurred through evapotranspiration; the rest occurred through outflow across the western part of the southern boundary to the Humboldt River Valley and as seepage to streams.

Analyses of the flow system in Paradise Valley (Figure 1) were carried out using a three-layer numerical ground water flow model (Prudic and Herman 1996). The model was calibrated for a period of historical pumping, and additional simulations were carried out to study possible effects of long-term pumping and recovery. One of the analyses was the simulation of 300 years of pumping using the magnitude and distribution of pumping in 1982, followed by 300 years with no pumping. The pumping rate was 44 hm^3/year, which is almost half the natural inflow to Paradise Valley.

Results of the analysis (Figure 2) show the long-term consequences of ground water withdrawals. Withdrawals of ground water in Paradise Valley have little potential to increase the total rate of surface inflow to the ground water system because almost all of the surface water that flows into the valley already seeps into the ground water system. Pumping, however, can change ground water underflow to and from the adjacent Humboldt River Valley. The source of water withdrawn by wells initially is a decrease of water in storage in the aquifer. With time, storage changes diminish and the sources of water result in a decrease in evapotranspiration in Paradise Valley and an increase in inflow from, and decrease in outflow to, the Humboldt River Valley. After 300 years, the system is approaching a new steady-state condition, with only 4% of the pumped water coming from storage. At that time, 72% of the pumped water is derived from a reduction in evapotranspiration and 21% is derived from an increase in inflow from the Humboldt River Valley.

This analysis of the effects of long-term withdrawals in Paradise Valley illustrates the role that hydrologists can play in providing information related to sustainability (or nonsustainability) of a particular ground water development. Key information in this case includes measures of water level (head) decline, which can help assess consequences of removal of water from storage; information on

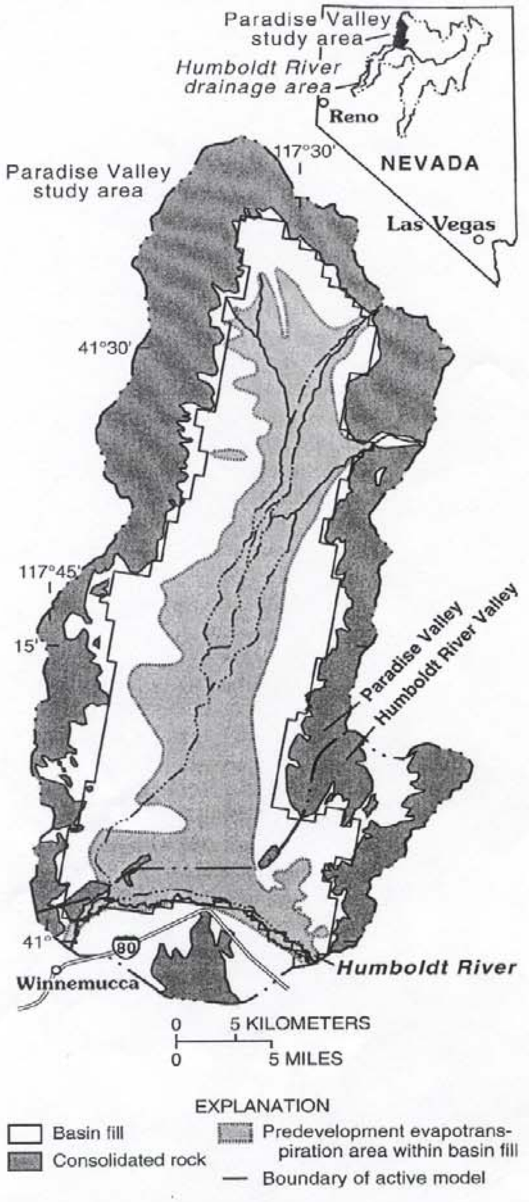

Figure 1. Location of Paradise Valley, Nevada, study area, and select hydrologic and model features. (Modified from Prudic and Herman [1996]).

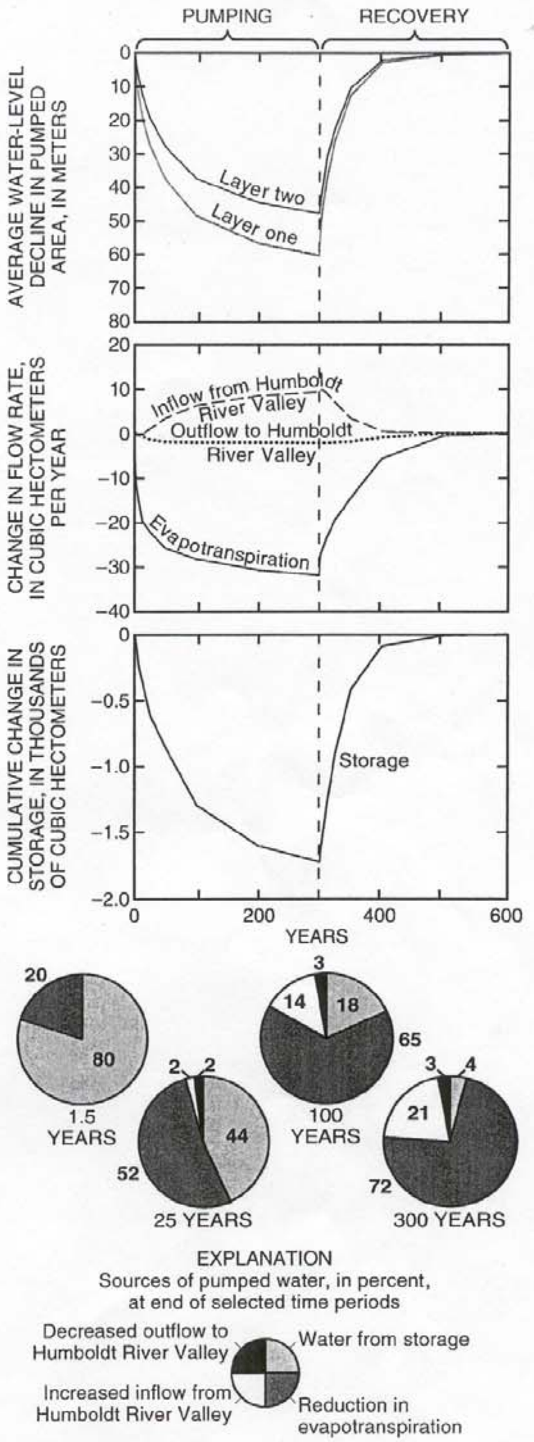

Figure 2. Select results of simulation of ground water withdrawal and recovery for Paradise Valley, Nevada. (Modified from Prudic and Herman [1996]).

likely reduction in availability of water for evapotranspiration; and the long-term effects of withdrawals in one area (Paradise Valley) on the flow system in an adjacent area (Humboldt River Valley), which might be managed separately (Figure 2). The possible progression of these changes because of pumping, as well as the dynamics of system recovery if pumping is reduced or ceased, provides a deeper understanding of the consequences of ground water development. A series of such analyses can portray long-term effects caused by alternative scenarios in which the amounts and locations of ground water withdrawals are varied. With this information, society can make better-informed decisions about how to manage their ground water resources in a long-term context. Such analyses also ideally lead to the design and implementation of long-term hydrologic networks to monitor projected outcomes of the ground water development and to improve the ability to predict future system responses. A key challenge is to extend the types of long-term forecasts of changing water budgets presented here to forecasts of other associated potential impacts, such as riparian vegetation decreases.

Summary Remarks

Although many people have expressed concerns about the ambiguity of the term sustainability, the fact remains that prudent development of a ground water basin in today's world is a complicated undertaking. A key challenge for sustained use of ground water resources is to frame the hydrologic implications of various alternative development strategies in such a way that their long-term implications can be properly evaluated. Each hydrologic system and development situation is unique and requires an analysis adjusted to the nature of the water issues faced, including the social, economic, and legal constraints that must be taken into account. The role of hydrologists in addressing issues of sustainability is evolving as technologies, understanding of the long-term effects of ground water consumption, and societal priorities evolve. For example, meeting the challenges of water resources sustainability increasingly involves understanding and predicting long-term ecological and water quality impacts and applying innovative approaches to conjunctive use of ground water and surface water, artificial recharge, and water reuse. Scientists and engineers should continue to play a key role in shaping this transition.

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Appendix F

WATER QUALITY ISSUES

GARY WOODARD

The following sections describe key water quality issues from a regulatory perspective that affect Arizona's future water requirements.

Arsenic

The federal Environmental Protection Agency (EPA) rule lowering the drinking water standard for arsenic from 50 micrograms per liter to 10 micrograms per liter becomes effective on January 23, 2006. This change has an extreme impact in Arizona because arsenic naturally occurs in a large number of groundwater supplies used for drinking water at levels greater than 10 micrograms per liter. Many large systems and an estimated 300 small systems will have to treat, blend or develop alternative sources in order to meet the new standard. Total cost to drinking water systems to comply is estimated at over $100 million. Concern about management of arsenic-laden treatment residuals also has been expressed. Proper management is necessary to ensure that other environmental problems are not created. The Arizona Department of Environmental Quality (ADEQ) has developed an Arsenic Master Plan to assist drinking water system owners in meeting the new arsenic standard in 2006.

See http://www.adeq.state.az.us/environ/water/dw/arsenic.html for additional information.

Perchlorate

Perchlorate, a rocket fuel, munitions and pyrotechnic chemical, is present in Colorado River water from Hoover Dam to the Mexican border at levels of from 4 to 11 micrograms per liter. Perchlorate is an inorganic, soluble salt that is mobile in surface water and groundwater and resistant to degradation. The perchlorate contamination of the Colorado River is due to discharges into Lake Mead that originated from two manufacturing facilities in Henderson, Nevada. Its occurrence in the lower Colorado River is a concern because the river supplies drinking water to millions of people in California and Arizona, including a large population in central Arizona dependent on supplies brought in by the Central Arizona Project (CAP).

No federal drinking water standard has yet been set for perchlorate. The current Arizona Health Based Guidance Level is set at 14 micrograms per liter. California established a Public Health Goal of 6 micrograms per liter as a first step in promulgating a drinking water standard for use there. Standards setting has been highly controversial nationally due to differences of opinion regarding the health impact of perchlorate at low levels. Recent evidence of perchlorate residues in lettuce irrigated by Colorado River water and milk from cows fed on forage irrigated by Colorado River water has heightened concerns.

Governor Janet Napolitano recently formed a task force drawing from four state agencies–the Departments of Environmental Quality, Water Resources, Health Services (ADHS) and Agriculture–to investigate the occurrence levels of perchlorate in Arizona water sources, the risks, if any, it poses to public health, whether Arizona should develop a water quality standard for perchlorate, and to make recommendations for future action, if necessary.

Further information is available at http://www.adeq.state.az.us/function/about/perch.html.

Lead

Lead in drinking water at schools has become a concern nationally because of the discovery of lead in some school systems at levels significantly higher than the EPA action level of 0.015 milligrams per liter in tap water samples. The EPA action level was established to protect public health due to release of lead from lead pipes or soldered copper pipes in water system plumbing and distribution systems serving homes, schools and other places of use. High lead levels are of special concern in schools because of the accumulative nature of lead in human bodies and the disproportionate adverse health consequences for children, who tend to absorb more lead than the average adult. ADHS is gathering data from schools and is working with ADEQ to determine if elevated lead levels are a concern in Arizona.

Mercury

Over the past several years, ADEQ has found increasing evidence of mercury contamination in the lakes and streams throughout Arizona. Based on monitoring results, ADEQ has issued fish consumption advisories on at least 12 water bodies in widely varying locations throughout the state including Alamo Lake, Upper and Lower Lake Mary, Lyman Lake and Parker Canyon Lake. These water bodies will now require development of a total maximum daily load (TMDL) and plan of implementation to improve water quality.

Mercury is a toxic, persistent and bioaccumulative pollutant that is both a public health and an environmental concern. Mercury has a direct affect on the nervous system and has long been known to have toxic effects on humans and wildlife. Since eating fish is the single greatest source of mercury exposure for most people, preventing the entry of mercury into the environment is the best way to reduce mercury exposure that causes health effects.

ADEQ has developed a long-term, multi-media, multi-agency strategy that focuses on preventing new mercury from entering the environment and reducing contributions from existing sources. The strategy involves additional data collection and research to determine actual levels and sources of mercury in Arizona. The strategy also addresses reduction of consumer products containing mercury and encouragement of new technologies that can reduce or replace the use of mercury and facilitate proper disposal of existing products at the end of their useful life.

See http://www.adeq.state.az.us/environ/water/assessment/ongoing.html#merc for additional information.

Sediment

Surface waters of Arizona that do not meet associated water quality standards are considered “impaired.” Under the federal Clean Water Act, which is implemented in Arizona by ADEQ, impaired waters must be listed on a Clean Water Act Section 303(d) list. For each impaired water, a TMDL allocation must be completed and an implementation plan developed to restore the waters to standards. In Arizona, suspended sediment, also measured as turbidity, is a major reason for impairment and is responsible for a large percentage of current or proposed listings on the 303(d) list.

Nitrate

Nitrate is one of the most common pollutants in the state’s groundwater and is almost always caused by anthropogenic activities that result in the transport of nitrogen to groundwater. These activities and sources include agriculture, septic tanks, sewage treatment plants and concentrated animal feeding operations. Large portions of aquifers in Arizona contain groundwater with nitrate concentrations high enough to render the water unfit for potable use. ADEQ water quality permitting requirements limit nitrogen discharges from industrial facilities and sewage treatment plants. Agricultural fertilization practices are regulated through water quality general permits. ADEQ is proposing rules that will limit discharges of nitrogen from animal feeding operations and septic tank concentrations. Proposed regulations would require lined impoundments for wastewater at certain animal feeding operations and allow ADEQ to designate Nitrogen Management Areas to control discharges from concentrations of septic tanks and other nitrogen sources.

Salinity

Salinity, measured by Total Dissolved Solids (TDS), is composed of salts, minerals and metals. A normal component of drinking water, salinity can become undesirable in high concentrations and affect a wide range of water users, including industry, agriculture and municipalities. High TDS levels inhibit agricultural production and also can become a corrosive element, destroying and damaging water delivery systems and water-using appliances. The cost of these combined damages can be extreme. For example, the cost associated with salinity damage for the Colorado River Basin is between approximately $500 million and $750 million per year. Additional costs for many water users could include building or upgrading water treatment facilities and desalting plants in order to remove unwanted salts and improve water quality.

In Arizona, high levels of TDS can occur in groundwater, effluent water and CAP water. Groundwater, usually relatively low in TDS, can increase in salinity as pumping continues to decrease ground water levels. Evaporation from open CAP canals and reservoirs, droughts and seasonal flows of the Colorado River and irrigation practices concentrate and contribute to increase CAP salinity levels. Effluent water from wastewater treatment plants is higher in TDS than groundwater and can add TDS to streams and underground aquifers. As more CAP water reaches wastewater treatment plants, effluent TDS levels will increase. Plans to control the rising salinity levels are being studied by the U.S. Bureau of Reclamation, through the Colorado River Basin Salinity Control Program.

Further information is available at http://www.usbr.gov/dataweb/html/crwq.html.

Endocrine Disrupters

An endocrine disrupter (ED) is a compound that disrupts the endocrine system by mimicking or inhibiting the effects of hormones. EDs can include a wide array of natural and synthetic hormones, steroids, pesticides and other industrial chemicals. Unfortunately, EDs are persistent and can bioaccumulate in the environment, to later be consumed through contaminated water and food supplies. Since the common functions of the endocrine system are reproduction and metabolism, some researchers are concerned that accumulation of EDs in the environment may be the current cause of increased breast cancer, sterility, many other endocrine illness and changes in wildlife populations.

Current concerns have been directed toward effluent dominated water supplies, especially in arid areas, where riparian habitats rely on effluent outfall. The effects of persistent EDs in effluent dependent riparian areas are currently being researched, including the chronic effects of long-term, low-level exposure of EDs on native fish species. Another concern is that recharge of effluent may accumulate EDs and negatively affect the water quality for future generations.

To study the effects of EDs on people and wildlife, the EPA established the Endocrine Disruptors Research Initiative. In 1996, EDs were one of the EPA’s top six research priorities in the Office of Research and Development. The National Research Council and other research groups are studying and monitoring EDs. Much scientific uncertainty remains, as it is difficult to prove that a particular substance or ED is responsible for an endocrine effect.

Further information is available at http://www.epa.gov/endocrine/ for Arizona-specific information, also see http://www.ag.arizona.edu/AZWATER/awr/sep00/feature1.htm.

APPENDIX G

MAJOR STREAMS, RECHARGE AND GROUNDWATER RESOURCES

DAVID A. DE KOK

Basin and Range Lowlands

The major streams of the basin and range lowlands are the Gila River and two of its tributaries, the San Pedro and Santa Cruz Rivers. The Salt, Verde and Agua Fria Rivers flow out of the central highlands and were once important contributors to the Gila River flow, though they are now all diverted for use in the Phoenix area except during flood events. The Salt and Verde Rivers were perennial rivers (those that flow all the time, usually because they are fed by a base flow, or spring, which seeps into the streambed because of a high water table), whereas the Agua Fria was interrupted (its surface flows occurred in some portions of the streambed but not others due to varying underlying geology). Together, they once ensured that the Gila River was perennial all the way to the Colorado River except in years of extreme drought. Downstream from the Granite Reef Diversion Dam, the Salt River is perennial now only because of effluent outflows from sewage treatment plants. The Gila River has perennial effluent flow for a few miles downstream of its junction with the Salt River but is ephemeral (flow in direct response to precipitation events) after that.

Natural recharge to the aquifers in the basin and range region is limited. In the low-lying western portion of the region it is exceedingly limited, occurring mostly in the form of groundwater underflow from neighboring basins and occasionally as streambed infiltration from passing storms. Those basins abutting Lake Mead, Lake Mohave and Lake Havasu have established a hydrologic connection with the lakes, and water tables rise and fall with fluctuations in lake levels. Recharge takes place along the middle reaches of the Gila River from occasional floods that exceed the storage capacity of upstream dams, from underflow of floodwaters captured by the Painted Rock Reservoir, from incidental recharge of urban effluent and irrigation tailwater and from precipitation.

In the Lower Gila and Yuma basins, excessive recharge has created problems. Much like the drain of a bathtub, this area, the state's elevational low point, eventually receives that portion of Arizona's waters that are not lost to evaporation or immediate groundwater recharge. After completion of the canal system that diverts Colorado River water to the fields of the Wellton-Mohawk Irrigation and Drainage District in 1957, water logging (groundwater levels near the surface of the land) threatened crop production in much of the area. In 1961 a network of wells began pumping excess groundwater into drainage canals to lower groundwater levels and relieve water logging. In the adjacent Yuma basin, groundwater levels are controlled by pumping for both irrigation and drainage.

In the eastern portion of the basin and range region, recharge takes place from streambed infiltration of the area's larger rivers (the Gila, San Pedro and Santa Cruz), from mountain-front recharge of precipitation captured by the mountain ranges, from incidental recharge of urban effluent and irrigation tailwater and from direct precipitation. In Cochise County's Sulphur Springs Valley, pumping by large scale irrigated agriculture lowered water tables significantly, eventually resulting in cutbacks in crop production due to high pumping costs and an accompanying leveling off of water table declines. However, unlike those basins adjacent to the Colorado or Gila Rivers or along the path of the Central Arizona Project (CAP) system, there is no recharge of water from outside of the immediate drainage basins. This means that the net recharge into the valley is limited to only that which naturally occurs.

Recharge patterns throughout the basin and range region have been altered considerably by human use. Storage and diversion dams have decreased the natural recharge resulting from flood flows that in the past reached the alluvial valleys. Entrenchment of watercourses such as the San Simon and Santa Cruz Rivers lowered water tables, reduced local infiltration rates and sped floodwaters downstream at faster rates. Effluent outflows from sewage treatment plants in Nogales, Tucson and Phoenix have brought perennial flows to new reaches of river and have caused incidental recharge to occur in areas removed from the river's former natural recharge sites.

Many of the basins in the basin and range lowlands experienced severe declines of their water tables between the 1940s and the late 1970s. In the Harquahala Plain, the depth to groundwater in one location went from 202 feet in 1955 to 532 in 1985. In the Salt River Valley, the depth to groundwater dropped from 181 feet in 1945 to 373 feet in 1980. In the Avra Valley, the water table depth went from 251 feet in 1955 to 346 feet in 1975, before rising again to 310 feet in 1990. Since the early 1980s many of the lowland basins have achieved a leveling off or even a rebound in their water tables as irrigated agriculture has reduced production and utilitzed CAP supplies.

Central Highlands

The principal streams of the central highlands are the Salt and Verde Rivers and their tributaries. The highlands account for 30 percent of the total drainage of the two rivers but produce 65 percent of their combined streamflow. The chief runoff producing area of the Verde River is the Mogollon Rim-San Francisco Mountain region. Significant drainages feeding the Verde River are Sycamore, Oak, Beaver, West Clear, Fossil and East Verde Creeks. This drainage area of 1,900 square miles produces an average annual runoff of 300,000 acre-feet. (The entire Verde watershed of 6,600 square miles has an annual average runoff of 468,100 acre-feet). The Salt River's chief runoff producing area consists of the drainage areas of the White and Black Rivers whose headwaters are on, respectively, the north and south slopes of Mount Baldy. Their combined drainage area of 1,860 square miles produces an average annual runoff of 380,000 acre-feet. (The entire Salt River watershed of 6,300 square miles has an annual average runoff of 666,800 acre-feet.) Other significant tributaries of the Salt River are Carrizo, Cibecue, Cherry and Tonto Creeks.

The other major watercourses of the central highlands are the Bill Williams, Hassayampa, Agua Fria and San Carlos Rivers. The two major tributaries of the Bill Williams are the Santa Maria and Big Sandy Rivers. The Santa Maria River drains mountains to the west of Prescott. The Big Sandy's drainage area is to the northwest of the Santa Maria's and includes portions of the basin and range lowlands to the southeast of Kingman. The Hassayampa River has its headwaters in the Bradshaw Mountains and drains the area south of Prescott. The Agua Fria River's 2,700 square mile drainage basin is immediately east of the Hassayampa's. The San Carlos River drains the area east of Globe and empties into the San Carlos Reservoir above Coolidge Dam.

Groundwater resources are much more variable in the central highlands region of Arizona than in the basin and range lowlands. In the eastern central highlands water for the Pinetop-Lakeside-Show Low area is pumped from the Pinetop-Lakeside aquifer. This aquifer has exhibited no significant decline in storage. Well production rates there can exceed 300 gallons per minute. Some wells in the central part of Payson have experienced water-level declines of four to five and one-half feet per year. This aquifer appears to be drought sensitive.

The depth to groundwater in the Verde Valley is generally less than 800 feet and wells produce at rates of 30 to 150 gallons per minute, but yields in some areas may exceed 1,000 gallons per minute. Water levels here have shown no appreciable change. Depths to water in Sedona range from 180 to 1,000 feet. Wells produce an average of about 70 to 80 gallons per minute. Groundwater levels in the area appear to be declining at a rate of less than one foot per year.

The Prescott area straddles two sub-basins, the Little Chino Valley and the Upper Agua Fria basin. The depth to groundwater ranges from 60 feet in the northwestern part of the valley to 580 feet near Granite Dells. Pumping for irrigation water near the Town of Chino Valley dropped water levels as much as 75 feet between 1940 and 1982. A decline in irrigated acreage and a switch to less water consumptive crops has reduced the rate of decline and even allowed water levels to rise in some portions of the valley, however water levels are generally continuing to decline. In the Upper Agua Fria basin depth to groundwater ranges from 25 feet near Humbolt to 530 feet in Prescott Valley. Highly localized water-level declines in the Prescott Valley of over 100 feet have been recorded, however generally the declines, while ongoing, are considerably less than that.

Because of its many small, fragmented and fairly shallow basins, quantities of water stored in the central highlands are small relative to the amounts in storage in the basin and range lowlands. The limited storage capacity of some of the region's aquifers makes them particularly dependent on regular, frequent precipitation in order to remain productive while being pumped at high volume. The climatic sensitivity of some aquifers has already proven troublesome to a few communities in the central uplands and could prove to be an even more difficult problem for these burgeoning towns to address in the future. The limited amounts of irrigated agriculture, chiefly in the Verde and Chino Valleys, have never played as big a role in the region's groundwater development as the farming in the basin and range lowlands. This has saved the central highland's groundwater resources from the tremendous overdrafts that depleted some of the lowland basins, but it also has given the highlands very limited amounts of agricultural land to retire in order to offset the rising water needs of its many fast growing communities. Annual groundwater withdrawals in the central highlands are generally increasing, having reached a high of 92,000 acre-feet in 1989, and probably considerably more than that since estimates were last made in 1990.

Plateau Uplands

The Little Colorado River is the major drainage for the plateau uplands. The river's headwaters drain the northeastern part of the White Mountains. Irrigation diversions near Springerville, Snowflake and St. Johns, along with considerable channel losses, prevent surface flow from reaching the Colorado River in all but the wettest years. Major tributaries of the Little Colorado River are the Puerco River, Silver Creek, Chevelon Creek, Clear Creek and Moenkopi Wash. About 360,000 acre-feet of water are discharged out of the Little Colorado River Basin annually. Most of this is discharged into the Colorado River, including 160,000 acre-feet of highly saline water that issues from springs along the lower 13 miles of the Little Colorado River.

Chinle Creek drains water from the northern third of the Little Colorado River Plateau basin and delivers 18,100 acre-feet of water annually to the San Juan River in Utah. The Paria River, which originates in south-central Utah, is perennial for its entire 25-mile length from the Utah border until it enters the Colorado River near Lees Ferry. It discharges an average of 21,450 acre-feet of water per year. Kanab Creek and the Virgin River are the major streams of the Arizona Strip, that portion of the state to the north and west of the Grand Canyon. The Virgin River has an average annual discharge of 174,6000 acre-feet. Nearly all of the streams on the Coconino Plateau flow only in response to rainfall or snowmelt. Waters from the eastern third of the plateau empty into the Little Colorado River. The central and western third of the plateau is drained by the ephemeral Cataract Creek, which then empties into Havasu Creek. The Colorado River receives an average of 47,000 acre-feet of water annually from Havasu Creek.

Arizona's upland plateau region is far larger than the central highland region, but groundwater resource development is only slightly greater than it is in the highlands. Approximately 112,000 acre-feet of groundwater were withdrawn from the plateau region in 1989. Some portions of the upland plateau have virtually no economically retrievable groundwater. Major population centers are few and widely dispersed. Due to short growing seasons, among other reasons, agriculture has only a limited presence in the region. Groundwater developments on the Navajo and Hopi Reservations are for the most part limited to small wells for domestic and livestock use, although the Black Mesa Coal Mine is a significant industrial user of groundwater from one regional aquifer.

The Arizona Strip is composed of five groundwater basins: the Paria basin, the Kanab basin, the Shivwits Plateau basin, the Virgin River basin and the Grand Wash basin. Because they are virtually empty of people, there has been almost no groundwater development in the Paria, Shivwits Plateau and Grand Wash basins. About 2,000 acre-feet of groundwater were withdrawn from the Kanab Plateau basin in 1985 to support the communities of Colorado City, Moccasin and Fredonia and to irrigate a few hundred acres of crops and pasture. This amount almost certainly has climbed with Colorado City's explosive growth. Alluvium along the washes in the Short Creek-Cane Beds area proved to be the most productive aquifer, with yields of up to 200 gallons per minute. In the Arizona portion of the Virgin River basin 6,000 acre-feet of groundwater were withdrawn for irrigation in 1990.

The Coconino Plateau basin lies in north-central Arizona, south of the Grand Canyon and to the north and west of Flagstaff. The basin's two major settlements are the City of Williams and the Grand Canyon-Tusayan area. Groundwater development has been negligible because of the great depth to and the limited yields of wells in the basin. However, in the summer of 2003 the City of Williams began drilling a 4,000-foot well, the deepest municipal well in the Southwest, in response to the droughts effects on its surface reservoirs. A 3,000-foot well near Tusayan yields only 80 gallons per minute. In general, springs such as Blue Springs and Havasu Springs that drain into the Little Colorado and Colorado Rivers drain the basin's potential aquifers. The Little Colorado River Plateau basin, at 27,300 square miles, is the state's largest groundwater basin. The basin's groundwater is contained by numerous, small local aquifers as well as three large regional aquifers. Streambed deposits of the Little Colorado River and its tributaries are important sources for domestic water supplies. However, the quality of water from these aquifers varies considerably. The alluvial aquifer along the Puerco River has radiochemical contamination from the 1979 Church Rock uranium mine tailings pond spill. Downstream movement of these radionuclides continues due to discharges from the sewage treatment plant in Gallup, New Mexico.

The three regional aquifers in the Little Colorado River Basin are known as the D-, N- and C- aquifers. The uppermost aquifer, the D-aquifer, extends for 3,125 square miles. Water from this aquifer is used for domestic supplies in the north central parts of the basin where the other two regional aquifers are too deep. Because of its high concentrations of dissolved solids, water from this source is used only where no other water is available. The intermediate-lying N-aquifer covers an area of 6,250 square miles. Water from this aquifer is suitable for most uses. The N-aquifer is a source of water for the Navajo and Hopi Reservations as well as the Black Mesa Coal Mine. The C-aquifer, at 21,655 square miles, is by far the most extensive aquifer and it underlies most of the Little Colorado River Basin. It is for the most part utilized only south of the Little Colorado River, as it is either too deeply buried or has too high a concentration of dissolved solids north of the river. Flagstaff, Heber, Overgaard, Show Low, Snowflake and Concho use the C-aquifer. Although a few cones of depression are developing in areas of heavy pumpage in the D- and C-aquifers, they are still largely in a state of hydraulic equilibrium. Portions of the N-aquifer are showing decline due to heavy pumping for the contentious Black Mesa Coal Mine slurry pipeline, which carries coal to Southern California Edison Company's Mohave Generating Station near Bullhead City. Some opponents of the slurry pipeline expect that the Station will close in 2005 when it must be retrofitted to meet more stringent clean-air standards.

Appendix H

AGRICULTURE'S DIMINISHING ROLE IN ARIZONA

DAVID A. DE KOK

Agriculture has long been the primary developer and user of Arizona's water resources. It was agriculture that instigated the construction of the Salt, Gila and Colorado River storage and diversion dams and it was agriculture that first used large numbers of high capacity pumps to irrigate fields that were beyond the reach of canal-distributed river water. Groundwater use shot up from about one and a quarter million acre-feet per year in 1940, to about four and a half million acre-feet a year in 1960, before eventually reaching nearly six million acre-feet per year in the mid-1970s. The tremendous increase in groundwater pumpage after World War II occurred as a direct result of the rapid spread of irrigated fields throughout Arizona's farm belt, which was made possible by widely available turbine pump technology.

Despite the feverish post-war expansion of irrigated agriculture in Arizona, the industry was losing its economic prominance as other economic sectors far outpaced it. Agriculture's share of personal income fell from 12.5 percent in 1940, to 7.3 percent in 1961, to 2.7 percent in 1970, to 1.9 percent in 1980, to 1.0 percent in 1990 and finally to 0.5 percent in 2000. However, agriculture continues to be an important component of the economy in many of the state's more rural areas. Farm income constitutes 9.7 percent of personal income in Yuma County, 6.9 percent of personal income in La Paz County and 5.3 percent of personal income in Pinal County. In booming Maricopa County, where farm income is second only to that of Yuma County, agriculture makes up only a quarter of one percent of all personal income.

Over the last two decades Arizona's agricultural economy has not only been battling the nationwide phenomenon of shrinking agricultural profit margins but also has been losing ground, literally, to urban encroachment, particularly in Maricopa County where crop acreage has fallen by some 50 percent, more than a quarter million acres. The post-war growth and decline of the state's cropped acreage can be tracked in Table H.1. Irrigated agriculture reached its greatest extent in Pima County in 1958 and in Maricopa County in 1960. Farming continued to expand throughout the rest of the state for another decade and a half, reaching a statewide zenith of 1,429,210 harvested acres in 1976. Arizona's harvested acreage dropped rapidly in the late 1970s and early 1980s as high-energy prices and falling water tables and purchase and retirement of farm lands by cities combined to rein in groundwater-irrigated fields.

Although crop agriculture has exhibited a fairly steady statewide decline since the mid-1970s, the pattern has not been consistent across all counties. In Cochise County, where the combination of falling water tables, high energy costs and low commodity hit farmers particularly hard, crop acreage plummeted from 133,150 acres in 1976 to just 32,000 acres by 1990. Crop acreage there has since rebounded modestly to 42,500 acres in 2000. Crop acreage in Yuma County fell from nearly 300,000 acres in 1980 to just over 175,000 acres in 1985. It has been steadily growing since then and reached nearly 225,000 acres by 2000.

Crop acreage in Pinal County has yo-yoed from 284,270 acres in 1980, to 192,405 acres in 1985, to 227,970 acres in 1995 before dropping to 181,175 acres in 2000. Urban encroachment is beginning to claim an increasing share of Pinal County farmlands as fields near Casa Grande, Florence and Eloy are being readied for future subdivisions. There is little reason to think that this pattern of urban encroachment, which began in the vicinity of Phoenix in the 1960s, will not continue to claim farm fields throughout Pinal County and perhaps eventually down the Gila Valley towards Yuma. In a reversal of the old rural fears that city dwellers would buy up water rights and ship water to the cities, urbanization is in many areas migrating to the farm fields. Although this conversion from farm to suburb usually lessens the total water demand appurtenant to that land, it also hardens that demand, as urban water use cannot be allowed to go "fallow" during a drought. This loss of water management elasticity is one of the growing perils of our state's burgeoning population.

Table H.1

ARIZONA CROP ACREAGE: 1940-2000

Year	Pima County		Maricopa County		Other Arizona Counties		Arizona	
	Total	%Change	Total	%Change	Total	%Change	Total	%Change
1940	14,500		370,000		280,500		665,000	
1945	25,000	*72.4*	400,000	*8.1*	350,000	*24.8*	775,000	*16.5*
1950	24,000	*-4.0*	435,000	*8.8*	456,000	*30.3*	915,000	*18.1*
1955	55,000	*129.2*	485,000	*11.5*	660,000	*44.7*	1,200,000	*31.1*
1960	52,105	*-5.3*	523,863	*8.0*	687.705	*4.2*	1,263,673	*5.3*
1965	49,715	*-4.6*	481,120	*-8.2*	629,165	*-8.5*	1,160,000	*-8.2*
1970	55,500	*11.6*	462,710	*-10.1*	700,820	*11.4*	1,219,030	*5.1*
1975	52,880	*-4.7*	471,740	*2.0*	852,200	*21.6*	1,376,820	*12.9*
1980	36,800	*-30.4*	474,560	*0.6*	785,320	*-7.8*	1,296,680	*-5.8*
1985	26,690	*-27.5*	330,680	*-30.3*	604,947	*-23.0*	962,317	*-25.8*
1990	22,550	*-15.5*	309,345	*-6.5*	647,890	*7.1*	979,785	*1.8*
1995	19,600	*-12.9*	299,650	*-3.1*	611,800	*-5.6*	931,050	*-5.0*
2000	17,100	*-12.8*	231,800	*-22.6*	585,290	*-4.3*	834,190	*-10.4*

Source: Derived from Arizona Agricultural Statistics Service.

Appendix I

WATERS ALONG THE BORDER WITH MEXICO

DAVID A. DE KOK

The San Pedro River

The San Pedro River, which has its headwaters near the Sonoran mining city of Cananea, flows northward and, after crossing the international border just south of Palominas, continues another 140 miles northwestward before it joins the Gila River. The river is ephemeral along most of its reach, flowing only in response to local rainfall. The San Pedro has a perennial stretch of about 18 miles between Hereford and a point just south of Fairbank.

The Upper San Pedro Basin, which is bounded to the west by the Huachuca, Mustang, Whetstone and Rincon Mountains and to the east by the Mule, Dragoon, Little Dragoon and Winchester Mountains, has two interconnected aquifers: a regional aquifer composed of alluvial basin-fill and a floodplain aquifer of alluvium from the San Pedro Rivers channel. The total amount of water stored in these two aquifers of the Upper San Pedro Basin is estimated to be 59 million acre-feet. The regional aquifer is the main source of supply for Sierra Vista and Fort Huachuca. Precipitation that occurs along the mountain fronts is the most significant source of recharge of the regional aquifer.

The floodplain aquifer, which spans the San Pedro's floodplain, ranges in depth from 40 to 150 feet and is very permeable, with well yields of 200 to 1,800 gallons per minute. It is this aquifer that is the main source of supply for most of the irrigated fields in the region. The streambed alluvium is primarily recharged from surface-water infiltration; however, it also receives water from the regional aquifer, underflow from Mexico and percolation from irrigation return flows and runoff water. Because of the floodplain aquifers reliance on surface-water flows, water levels fluctuate seasonally, rising slightly in the spring and summer and declining in the fall and winter.

The amount of groundwater recharged into the Upper San Pedro Basin aquifer is thought to total about 30,000 acre-feet per year. Of this total, approximately 75 percent comes from Mexico as underflow and surface flow. Mexico is not bound by treaty to deliver any set amount of water from the San Pedro River to the United States. Agricultural water use in the Mexican portion of the Upper San Pedro amounts to about 14,000 acre-feet annually. Cananea, a city of about 35,000, uses nearly 6,300 acre-feet of water a year. The copper mine at Cananea was pumping 12,500 acre-feet a year in 1999. Although Cananea and Naco have not grown at the same pace as other northern Sonoran towns, there is little likelihood that they will maintain their current size and water demand. The mines at Cananea pump groundwater for use in several mining processes and then discharge the resulting wastewater outside the San Pedro River Basin and into the south-flowing Rio de Sonora River Basin. This unquantified regional outflow obviously lessens the amount of water flowing north into Arizona.

Not all of the water reaching Arizona from Mexico in the San Pedro River Basin is of high quality. In 1977 and 1978 tailing pond spillages at the Cananea copper mine repeatedly contaminated San Pedro River surface water with concentrations of copper, iron, manganese and zinc. There were smaller reoccurrences of these spillages in the 1980s. Since the mid-1980s there also have been repeated instances of spillage from sewage ponds at Naco, Sonora, dumping raw sewage into Greenbush Draw that empties into the San Pedro. Livestock and other farming operations also have led to increased nitrate levels in the San Pedro River.

The population of Sierra Vista, which was 32,983 in 1990, was estimated to have grown to 40,430 in 2003. Pumping from the regional aquifer to supply Sierra Vista and Fort Huachuca has created a cone of depression, or a lowering of the water table, in the location of the main well fields. There were approximately 12,700 acres of irrigated land in the Upper San Pedro in 1990, but these fields were primarily irrigated by wells in the floodplain aquifer. The amount of irrigated land in the Upper San Pedro Basin has since dropped due to the 1988 creation of the San Pedro Riparian National Conservation Area (RNCA). The Act creating the Conservation Area also created an explicit federal reserved right to enough water to fulfill the purposes of the Area. The San Pedro RNCA, which was the first RNCA, was created to protect and enhance the riparian areas and associated resources, and the aquatic, wildlife, archaeological, paleontological, scientific, cultural, recreational, educational, scenic and other resources and values.

The difficulty for Sierra Vista and Fort Huachuca was that the growing cone of depression beneath their well fields was threatening to eventually intersect the floodplain aquifer. This could potentially begin to drain this aquifer, which would likely dewater a portion of the San Pedro River's perennial flow. To counter this threat to the San Pedro RNCA the City of Sierra Vista has constructed the Sierra Vista Wastewater Recharge Project. The intent is to create an underground wall of water between the RNCA floodplain aquifer and the City well field's cone of depression.

An additional concern beyond the overdraft of groundwater (which was just over 10,000 acre-feet in 1990) is the Gila River Indian Community's claims to the San Pedro Sub-basin water. Because the Community draws its water from the Gila River downstream from the Upper San Pedro River Basin, they contend that the Basin's waters are part of the supply for their reservation. This matter should be clarified through the Arizona Water Settlement Act now under consideration in Congress.

Concern about the overdraft of groundwater in the Upper San Pedro River Basin has been growing for decades. In the 1960s, the Central Arizona Project (CAP) was envisioned to bring Colorado River water to the San Pedro via a pipeline from Tucson. Water was to be stored in a reservoir created by a dam to be built on the river at Charleston. The CAP pipeline idea was revived in 1994, when Interior Secretary Bruce Babbitt ordered a study on building a pipeline from the end of the CAP aqueduct in Tucson to Sierra Vista. The idea again surfaced in November 2003 in an editorial in the *Arizona Daily Star*, where Mr. Babbitt championed the idea of delivering 15,000 acre-feet of CAP water to Sierra Vista. The cost of the proposed $71 million to $95 million pipeline would be bourn, at least in part, by the federal government to assure the continued existence of Fort Huachuca.

At about the same time as the most recent appearance of the CAP pipeline concept, another idea to save the San Pedro's surface flows came to light. This would involve pumping water from the abandoned mines under Tombstone and using it to help the San Pedro River. The total quantity of water available and the effects of mine pumping on the City of Tombstone's water wells are unknown. Additional questions about the efficacy of the mine pumping proposal include the extent that the mine water would have to be treated to bring it up to federal standards, the cost of pumping from the 400 to 500 foot depth of the mines, the effect that dewatering of the mines would have on the structural integrity of the timber support posts in the mines once they were exposed to air, the possibility of subsidence caused by the pumping and the possibility of an existing hydrologic connection between the mine's aquifer and the River, which might make the pumping counterproductive.

Although the Upper San Pedro River Basin has enormous groundwater reserves that could sustain the current overdraft for centuries, continued overpumping poses a very real threat to the river's perennial flow and the tremendous biodiversity, especially bird-life, which relies upon it. To meet this threat the Upper San Pedro Partnership was formed to bring together the region's various stakeholders to suggest ways in which water resources can be managed. The group has set a goal of ending the groundwater overdraft by 2011. Given that nearly 23,000 acre-feet of the surface and groundwater that replenishes the Upper San Pedro comes from Mexico, which has no legal obligation to maintain that continuing supply, and given that some proponents are pushing for Fort Huachuca to double its size with the addition of new operations drawn from the next round of base closures, the Partnership faces a great challenge in achieving its goals. A new organization, the San Pedro Binational Watershed Alliance, which is composed of the Partnership and several municipal, Sonoran and federal entities from Mexico, may ease concerns about the continuing flow of the San Pedro. The Alliance hopes to establish a binational, holistic, ecosystem-based approach to natural resources conservation and environmental planning.

The Santa Cruz River

The Santa Cruz River crosses the international border twice, first flowing into Mexico from Arizona's San Raphael Valley two miles east of Lochiel and then flowing into the United States five and a half miles east of

Nogales. Between the two crossing points the river flows for 32 miles through Mexico. The permeable portion of the basin near the border is only about 300 feet thick at its greatest extent, greatly limiting the aquifer that supplies Ambos Nogales with water.

The basin-fill sediments near Nogales are divided into three aquifers: the younger alluvium, the older alluvium and the Nogales formation. The younger alluvium is the most widely used and productive of the aquifers, with well yields up to a thousand gallons per minute. There is a hydraulic connection between surface flows and this aquifer. Groundwater levels decline and recover in association with river flows or their absence. The surface water flows of the Santa Cruz River are extremely variable, ranging from just a few hundred acre-feet some years to 88,000 acre-feet in 1979. The mean surface flow near the international border since 1935 is 19,110 acre-feet and the median is 14,283 acre-feet. The recent drought has greatly limited the replenishing surface flows, to just 628 acre-feet in 2002 and 936 acre-feet in 2003.

The older alluvium stores a considerable amount of water, but is a poor transmitter of water to wells. Well yields in the older alluvium seldom surpass 30 gallons per minute and, consequently, this aquifer has not been widely tapped. The far deeper Nogales formation has poor water bearing characteristics and has not been widely developed. The few productive wells generally yield less than 30 gallons per minute.

Although the two communities of Ambos Nogales share a common watershed and a wastewater collection and treatment system, their water supply and distribution systems are nearly independent of each other. The shared groundwater basin and the topographical gradient have guided the development of the fresh water and wastewater systems, but the international line separating the communities has repeatedly complicated the building and maintenance of this infrastructure. A shared distribution system existed until 1911, when the City of Nogales, Arizona purchased the system and used public funds to install a well in the Santa Cruz River and expand the Arizona side of the distribution system. Thereafter, Nogales, Sonora was left to eventually develop its own water supply system, which it did in 1940.

Nogales, Arizona also led the way in the development of a sewer system. By the end of World War II virtually all of the City's residents and businesses were served by this system. However, Nogales, Sonora still did not have a sewer system in place and instead relied on cesspools and outhouses. The Mexican health department began developing plans for a sewer system in the early 1940s, but the Nogales Wash topography dictated that a treatment plant and its sewage outfall line would have to be located across the border in the United States. Eventually, the International Boundary and Water Commission (IBWC) persuaded the U.S. Congress to fund a joint treatment plant. The first international wastewater treatment facility for Ambos Nogales was completed in 1951.

Flooding is another problem common to the two communities of Ambos Nogales. Major floods swept Ambos Nogales in 1905, 1909, 1914, 1915, 1926 and 1930. The 1930 flood took five lives, caused much property damage and spurred Arizona's Senator Carl Hayden to get the two federal governments to design and build a joint flood control project. The IBWC built the system in the 1930s and the 1940s. The flood control system currently consists of two covered channels and additional lined open canals.

Nogales, Arizona is entirely dependent upon groundwater for its fresh water needs. The water supply and distribution system is owned and operated by the City of Nogales. Two main well fields, the Potrero Wash and Santa Cruz fields, feed the system and provide an adequate supply of fresh water for the City's current needs; however each field's future productivity is to some extent threatened. A cone of depression has developed around the Potrero Wash well field and water table levels there fell over 20 feet below the level of the surrounding water table between 1982 and 1995. Additionally, a small plume of poor quality water developed in northern Nogales, which curtailed the City's pumpage from one of its major production wells. Plans are under way to clean the contaminated water to potable water quality standards and deliver the treated water to the nearby Palo Duro Golf Course. The threats to the Santa Cruz well field may occur over a longer time period but be more consequential. Nogales, Sonora is undertaking an upgrade of its water system, which is likely to reduce inflows to Nogales, Arizona's well fields.

The water pumped from the Potrero and Santa Cruz well fields is chlorinated on-site and then moved through the delivery system to the City's four main storage reservoirs whose combined capacity is nearly five million gallons. The City supplied 4,290 acre-feet of water to 18,975 people in 1995. The water usage rate was 202 gallons per capita per day (GPCD). This high rate of per capita usage stems from several causes. On a daily basis 30,000 people cross the international border from Nogales, Sonora into the City of Nogales. Additional visitors arrive from the north via Interstate 19. None of these daily visitors are counted as part of the service area population when calculating Nogales GPCD. Additionally, the City's water system suffers from a high volume of unaccounted water losses. It was estimated that in 1990, ten percent of water usage was lost through leakage in the delivery system, and an additional ten percent went unrecorded either through unmetered or under-metered deliveries.

Almost 50 percent of the City's water is delivered to single-family residences, 24 percent of the water goes to commercial users and about 13 percent is used by apartment dwellers. The Nogales Water Department also still supplies some water to Nogales, Sonora customers through four separate water mains, two of which are among the water department's 50 largest customers. Because the level of water consumption by these account owners is larger than would be expected given the nature of their businesses, it is assumed that some of the water is being used for other purposes or by other users.

Aside from the four above-mentioned water lines, the Nogales, Sonora fresh water delivery system is entirely separate from the Nogales, Arizona system. However, because of the shared watershed and topography, the maintenance, operation and plans for the Sonoran water system have a direct effect on the Nogales, Arizona system. The underlying water problem in Nogales, Sonora is the lack of a sound distribution system. The Nogales, Sonora water system gets 15 percent of its water from wells in the Nogales Wash, 45 percent from wells in the Santa Cruz River and 40 percent from wells in the Los Alisos River watershed.

About 36 percent of the Nogales, Sonora population is not connected to the water supply system. These residents must haul their own water or buy it from large water trucks, or *pipas*. The *pipas* are usually filled from wells within Nogales Wash, which are very drought sensitive and frequently run low in the early summer. In the summers of both 2002 and 2003, Nogales, Arizona provided a temporary water line to help keep the *pipas* on their appointed rounds. Connection to the water supply system, however does not guarantee a steady supply of water. In the summertime, even some affluent neighborhoods must put up with water shortages, which means water is rationed and available only a few hours a day. It is estimated that average water usage in Nogales, Sonora only amounts to between 40 and 60 GPCD. The relatively wide range of the estimate is due to the uncertainty about the Nogales, Sonora population. The official population estimate for the year 2000 was 213,784, but many knowledgeable observers think 350,000 might be closer to the reality. Nogales, Sonora currently consumes 18,500 acre-feet of water a year.

In order to deal with this water crisis, Nogales, Sonora has embarked on a $39 million plan to meet the shortfall and prepare for the continued rapid rate of growth. The plan proposes to increase pumpage along the Santa Cruz River from 6,300 acre-feet per year to 15,200 acre-feet per year. The projected Mexican pumpage would then represent about 75 percent of the long-term annual flow in the Santa Cruz River at the international border. This could have a severe impact on Nogales, Arizona's Santa Cruz well field, both increasing pumping costs from a much-lowered water table and exposing the well field to greater susceptibility to drought. Mexican dewatering of the Upper Santa Cruz River basin could limit the ability of Nogales, Arizona to accommodate future growth. There currently is no international agreement to guarantee that there is water in the Santa Cruz River when it reaches Arizona. However, the Arizona Department of Water Resources and the IBWC are engaged in a hydrologic modeling effort so as to understand the relationship between pumpage and flows in the binational Upper Santa Cruz basin.

As has been discussed, Nogales, Arizona and Nogales, Sonora share a single wastewater treatment plant. The first joint facility went into operation in September 1951, sixteen years after it was authorized. The plant quickly became overwhelmed, with raw sewage being bypassed during 1960.

After considerable negotiation, the Mexican government agreed in 1967 to join with the United States in constructing a new, larger Nogales International Wastewater Treatment Plant (NIWWTP) nine miles north of the border near Rio Rico at the confluence of the Nogales Wash and the Santa Cruz River. The new plant began operating in 1972. By 1982 the plants daily capacity was once again being regularly exceeded and about 60 percent of its influent was coming from Sonora. After more negotiations an expansion of the plant was begun in 1989. The constant struggle to keep the capacity of the NIWWTP ahead of, or at least not too far behind, the areas population growth has been just one of the difficulties facing the Ambos Nogales wastewater system.

The specter of disease outbreaks has been the driving force behind the communities' improvements to their wastewater systems. In the summer of 1990, monsoon rains broke numerous sewer lines all over Nogales, Sonora. The resulting contamination of Nogales Wash was linked to 42 cases of hepatitis A among residents clustered around the Wash. Cholera has been found in the Wash and a February 1991 test turned up the polio virus. It is estimated that 14 to 21 percent of the Nogales, Sonora population faces health risks due to sewer line breaks.

Despite a large operating budget and expanded capacity, the NIWWTP has repeatedly had difficulty meeting water quality standards. High inflow into the plant has occasionally forced the release of wastewater before treatment has been completed. This has caused the plant to be cited for excessive levels of suspended sediments in its effluent. In addition, the NIWWTP has been cited for excessive levels of phenols, cyanide and mercury. The plant is not designed to remove these chemicals that most likely come from the Mexican maquiladoras. The only way to remove these chemicals from the effluent is to prevent them from entering the sewage system in the first place. The lack of an industrial pretreatment program in Nogales, Sonora is another of the systems inadequacies.

The treated outflow from the NIWWTP flows through the Santa Cruz River channel for about 14 miles before it completely infiltrates into the riverbed near Tubac. Despite the intermittently high pollution levels of the river at its confluence with Nogales Wash, the river manages to cleanse itself as it flows to Tubac and is periodically diluted with fresh rainwater runoff. The effluent discharges from the NIWWTP have stabilized the water table along this section of the Santa Cruz River and have helped to maintain one of the few healthy riparian gallery forests left in Arizona.

Nogales, Sonora has rights to a portion of the NIWWTP effluent equal to its influent contribution, which is now about two-thirds of the total output. The international treaty between the United States and Mexico allows Sonora to retain or reduce the amount of influent at any time and also allows it to transport the treated effluent back to Mexico at any time. Although Nogales, Sonora currently has no means to make use of its share of effluent, it has developed a plan to construct a wastewater treatment plant of its own in Los Alisos, as well as pump stations to convey sewage to the new plant. To address its water supply shortfall, the Mexican government plans to recharge effluent into its own well fields. The current expectation is that Mexico would continue to send the same amount of influent to the NIWWTP as it now does, and that the new Los Alisos Plant would serve the portion of the Nogales, Sonora metropolitan area south of the Nogales Wash Basin boundary. However, if the Los Alisos plant were to treat some of the effluent from the Nogales Wash Basin and recharge into the Los Alisos Basin, it would be lost to the Santa Cruz River system forever, since the Los Alisos Basin is a tributary to the Magdalena River in Mexico.