Research Technical Completion Report

AN ASSESSMENT OF THE ECOLOGICAL IMPACTS OF GROUND WATER OVERDRAFT ON WETLANDS AND RIPARIAN AREAS IN THE UNITED STATES

by

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Abstract

One potential consequence of ground water overdraft which frequently is overlooked in the allocation of ground water resources is the impact of pumping on surface ecosystems which are dependent on ground water. Many researchers have noted the almost anomalous dearth of information on the linkage between hydrogeological factors and ecosystem impacts. As ground water use continues to increase and the health of the remaining wetlands and riparian habitat comes under increasing scrutiny, there is a growing need for an adequate technical understanding of this emerging issue to form the basis of consistent public policy. The purpose of this report is to collect and evaluate information on the location, nature, and extent of ecological effects which have been shown to have occurred in wetlands and riparian areas as a result of ground water pumping.

As transition environments between aquatic and terrestrial ecosystems, wetlands and riparian areas are among the most spatially and temporally complex natural systems on earth. These habitats provide food web support for all trophic levels as well as sites for breeding, nesting, rearing, resting, refuge, feeding, and overwintering. It is estimated that over 70% of the original area of riparian ecosystems in the United States has been cleared and much of the rest has been affected by a myriad of land and water uses during this century.

Ground water overdraft is capable of causing ecological impacts in wetlands and riparian areas in a variety of ways. Because the stage and duration of the natural hydroperiod are among the most crucial aspects affecting the location, composition, and overall health of these ecosystems, ground water drawdown which results in significant hydroperiod perturbation can have a major impact. Examples include ground water level fluctuation in excess of species' limits of tolerance, reduction of ground water discharge on either a seasonal or long-term basis, and induced recharge of underlying saturated zones derived from drainage of surficial aquifers on which ecosystems are

dependent. Overdraft can result in geomorphological changes which impact wetland hydrology such as land subsidence and alteration of river channel morphology and stability. Lastly, changes in the natural geochemical environment in excess of species' tolerance may result from overdraft. Examples include salt water intrusion as well as other modifications of the chemical characteristics of the ground water and the associated solid media.

Literature on ecological impacts from ground water overdraft was found for several countries as well as ten states. The nature and extent of these impacts are described as well as pertinent geological and hydrogeological characteristics of the sites. Some impacts are localized while others have occurred on a regional basis throughout an entire drainage basin or aquifer system.

The extent to which these impacts have been studied varies widely. In a few cases, impacts are reasonably well documented. For the most part the potential for ecological impacts from ground water overdraft is largely overlooked in the context of water allocation as well as ecological assessment. The locations of impacts described in this report are not hydrologically or ecologically unique. Therefore it is probable that the existing body of literature on this subject significantly underestimates the extent of ecological impacts which are the result of ground water overdraft.

To more adequately and accurately address this issue, it is recommended that studies to identify and quantify ecological consequences from overdraft be undertaken more frequently in a broad array of academic and resource management settings including regional water use planning programs, wetland surveys, and regional hydrological studies. A major objective should be an enhanced predictive capability for early identification of "high risk" hydrologic settings and "high risk" wetland and riparian communities and species. Efforts to assess and mitigate impacts from ground water overdraft must be approached with a full understanding of the complexity of hydrologic systems and wetland ecosystems. Many human activities and natural processes can result in ecosystem changes and identification of causal relationships requires detailed, site-specific and usually long-term studies.

With care to avoid erroneous oversimplification, this information should be used to improve planning and policy regarding ground water use and wetland protection. Permitting processes pursuant to applicable federal, state, and local statutes should include an assessment of the potential for impact from subsurface drainage for projects which may affect wetlands and riparian areas. A major objective should be an approach to water management in which there is scientifically valid feedback between the occurrence of ground water overdraft, water stress tolerance limits of affected species, and allowed pumping rates.

Section 1

Introduction

Utilization of ground water resources typically results in increased capture of local recharge and/or withdrawal of ground water from storage. Withdrawal of ground water from storage is commonly called ground water mining or overdraft (Bredehoeft et al., 1982). It is manifested by a decline in the water table, a reduction in artesian pressure or an irreversible compaction of certain fine grained sediments (U.S. Geological Survey, 1984).

There is controversy regarding the definition of overdrafting and whether it should necessarily be avoided (Smith, 1989). One perspective is that overdrafting or ground water mining is "no more unsafe than the mining of any other mineral resource, provided it's recognized and planned" (U.S. Geological Survey, 1984). However, it is frequently the case that the extent of drawdown is not planned and the associated consequences are not accurately anticipated. The impacts of some pumping may not be noticeable until they are irreversible or the consequences may be borne by parties other than those receiving the benefits of the water which was pumped (House Committee on Natural Resources, 1994). At present many of our legal institutions do not adequately address these situations pertaining to ground water pumping (Bredehoeft et al., 1982).

One potential consequence of ground water overdraft which is frequently overlooked in the allocation of ground water resources is the impact of pumping on surface ecosystems which are dependent on ground water. For example, many wetlands are located in ground water discharge zones and many riparian communities are dependent on shallow alluvial aquifers. In arid environments in particular, ground water may be the only perennial water source available to some wetland and riparian communities. In locations throughout the country where water level decline has occurred in the course of ground water development, the potential for large-scale impacts in wetland habitats is great.

In response to a growing body of information on water level decline, the National Water Commission referred to ground water mining as one of the "three principal problems of ground water law, management and administration" (Fort et al., 1993). Predicting and preventing adverse impacts from ground water mining is a complicated task. Habitat impacts are varied and the remedies are often poorly defined and diverse. A broad group of participants is involved in developing public policy including parties with interests in water allocation as well as habitat protection.

Many researchers have noted the almost anomalous dearth of information on the linkage between hydrogeological factors and wetland community functions (for example Fort et al., 1993; Busch et al., 1992; Llamas, 1989). As ground water use continues to increase and the health of the remaining wetlands and riparian habitat come under increasing scrutiny, there is a growing need for an adequate technical understanding of this emerging issue to form the basis of consistent public policy.

Section 2

Methods

The purpose of this report is to collect and evaluate information on the location, nature and extent of ecological impacts which have been shown to have resulted from ground water overdraft. It is hoped that this document will assist those who seek to predict or remedy these impacts in their jurisdictions.

There is considerable controversy over the legal definition of wetlands when used in the context of implementing various statutes. Wetlands as described in this report are broadly and scientifically defined and no attempt has been made to conform to an individual statutory definition. As used herein, a wetland is an area "where saturation with water (either permanent or intermittent) is the dominant factor determining the nature of soil development and the types of plant and animal communities living in the soil, on its surface, and in the overlying water" (U.S. Geological Survey, 1984). As such, wetlands are transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is at least intermittently covered by shallow water. Considerable difficulty in determining the location and extent of some wetlands results from situations in which human activities have either permanently or temporarily created an artificial hydrological regime (Tiner, 1990).

Riparian ecosystems are those floodplain, bottomland and streambank communities which occur along watercourses, both perennial and intermittent. Riparian areas generally occur entirely within the 100-year floodplain of streams and rivers and are characterized by vegetation types which are adapted to and tolerant of relatively high soil moisture conditions (Swift, 1984).

For this report, existing literature was reviewed to collect information on sites at which ecological impacts have occurred as a result of ground water pumping. Locations included in this study are limited to those where pumping of water supplies is known to be the primary causal factor of ecological impacts. Suspected impacts or sites at risk generally were excluded as the determination of causation is a complicated task. As a result of this limitation and the fact that many potential sites have not been investigated by ecological researchers, the number of sites listed in this report undoubtedly underestimates the extent of ecological impacts resulting from ground water pumping.

Sites described in this report are limited further by excluding ecological impacts from intentional water table suppression such as reclamation drainage to make land suitable for agriculture or development. Over the last century many millions of acres have been deliberately drained for cultivation and development. These activities are not the focus of this report. In adddition, wetland and riparian impacts from other sources of hydrological modification such as surface water impoundment and channel modification are excluded where a differentiation can be made. For this study, discussion is confined to impacts incidental to ground water resource development.

This report is organized to give the reader an historical, ecological and hydrogeological context with regard to this issue. This information is found in Sections 3 and 4. For those interested in a predictive capability, hydrogeological mechanisms capable of causing ecological impacts in wetlands and riparian areas are discussed in Section 5. Section 6 contains a summary of documented sites at which impacts have occurred. An evaluation of the adequacy of the existing information as a basis for development of public policy is found in Section 7. Lastly, recommendations for future work are made in Section 8.

Section 3

Historical Background on Wetlands Protection, Ground Water Use, and Ground Water Overdraft

Wetlands Protection

For much of our nation's history, wetlands of all types have been regarded as areas to be converted into some other "more productive use" (Wentz, 1988). Drainage of wetlands has been seen as a progressive, public-spirited enhancement of the natural environment designed to alleviate flood danger and reclaim land for agriculture. Likewise, wetland loss has been viewed as a relatively minor consequence of receiving the benefits of large surface water storage projects (Dugan, 1990).

In arid areas, the close association of phreatophytic plant species with the availability of shallow ground water has been understood since the early part of this century (Meinzer, 1927). Because most phreatophytic species are of low economic value, the water they transpire has been defined as "consumptive waste" for most of this century (Robinson, 1958). The scientific literature on wetlands prior to the early 1970s is filled with water conservation studies describing the advantages of removal of wetland and riparian vegetation for the purpose of "salvaging evapotranspiration" for human needs (Winter, 1988). Replacement of native vegetation with agricultural crops or grasslands for grazing was widely undertaken, particularly in the southwest (for example Culler et al., 1970; Heindl, 1961; van der Leeden, 1991).

It is estimated that more than 70% of the original area of riparian ecosystems in the United States has been cleared and less than 5% of the original riparian vegetation remains in the southwest (Johnson and Haight, 1984). Wetland loss in the midwestern farm belt states of Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin accounts for approximately one-third of all wetland loss in the history of the nation. The highest percentage loss, 91%, has taken place in California and the highest loss of acreage (9,286,713 acres) has occurred in Florida (a 46% loss). All states except for Alaska, Hawaii, and New Hampshire have lost more than 20% of their original wetland acreage. The most significant historical loss of wetlands has resulted from agricultural practices (87%) (National Research Council, 1991).

Wetlands and riparian areas were not widely regarded as ecological systems with essential functions for supporting indigenous flora and fauna until the 1960s (Wentz, 1988). Increasingly, scientific literature has documented the importance of wetlands and riparian areas as integral parts of the surrounding watersheds and stream corridors. Their importance for primary production and nutrient cycling for associated terrestrial and aquatic ecosystems has been demonstrated repeatedly as well as their role in providing spawning, nesting, rearing and refuge habitat for many species (Crance and Ischinger, 1989). Management agencies now also consider the value of riparian areas in providing a vegetated buffer against erosion and flooding as well as irreplaceable recreational and aesthetic values (Harrison and Kellogg, 1989).

Multiple objective water resource planning and management decisions today have replaced the more single-minded objectives of water conservation and land reclamation which predominated earlier in the century (Wentz, 1988). Recent statutes including reauthorized versions of the Water Resources Development Act, the Clean Water Act, and the 1990 Farm Act which established the Agricultural Wetland Reserve Program have provided impetus to achieve a "no net loss" of remaining wetland acreage (National Research Council, 1991). Regulatory efforts have improved in evaluating cumulative impacts on wetland ecosystems. Although wetland restoration is a technically and politically elusive goal, for the most part, efforts have improved in recent years (National Research Council, 1991). However, because wetland preservation and restoration frequently are impediments to development, ongoing controversy surrounds the desirability of protection in some circumstances (Lehr, 1991). For example, recently proposed Congressional bills seek to weaken the wetlands protection provisions currently included in the Clean Water Act. At present, the future direction of wetlands protection is difficult to predict.

Ground Water Use

The United States is fortunate to have a vast ground water resource. By volume it is estimated that over 90% of the fresh water in the United States is in the form of ground water, a volume equivalent to about 35 years of surface runoff nationwide. Of this volume, about half is considered to be extractable if no consideration is given to changes in stream flow, effects on the environment, and the cost of extraction (U.S. Water Resources Council, 1978).

The United States is also a major user of ground water. In an international survey of countries for which data were available, the United States ranked second in terms of volume of ground water used (Llamas et al., 1992). The pumpage of fresh ground water in 1980 was estimated to be about 88 billion gallons per day. This amounted to about 10% of the total natural flow through all of the nation's ground water systems (U.S. Geological Survey, 1984). Ground water supplies drinking water for about half of the country's population and about 35% of the water used for irrigated agriculture (Smith, 1989). It is also a major source of the water used in industrial processes and power generation.

Ground water withdrawals have increased steadily and significantly during most of the twentieth century. As overall water utilization has increased, ground water has supplied an increasingly larger portion of total water needs. Between 1950 and 1975 surface water withdrawals increased annually at a rate of 2% compared to a 4% annual increase in ground water pumped (U.S. Water Resources Council, 1978). Total ground water withdrawals more than doubled between 1950 and 1980 (Solley and Pierce, 1988). Among the factors responsible for the sustained increase in ground water use are significant expansion of irrigation, water supply requirements of growing urban areas, particularly those in arid areas of the west and southwest, water demands associated with energy production, objections to the construction of surface reservoirs, and the fact that ground water usually requires less treatment than surface water as a potable water supply (U.S. Geological Survey, 1984).

Agriculture is the largest consumer of water, acccounting for 83% of the total water consumed in 1975 (U.S. Water Resources Council, 1978). Perhaps the key driving force for the development of ground water resources during this century has been the development of irrigation technology which has permitted a dramatic increase in irrigated acreage nationwide (Smith, 1989). Centrifugal pumps in shallow dug wells were commonly used on small tracts in the 1920s. The more sophisticated turbine pumps, deep well drilling technology and rural electrification which followed by the middle of the century brought many more acres into irrigated agriculture. Development of wheel line and center pivot application systems reduced labor requirements, further encouraging expansion of irrigated acreage (Collins and Cline, 1991). Consequently, ground water useage has increased 5 to 10 fold from 1950 to the present in most heavily irrigated areas of the nation (Smith, 1989). A major exception is the recent reduction in pumpage in some areas of extreme water level decline such as parts of the High Plains states which depend on the depleted Ogallala aquifer. Rising energy costs of greater lifts have provided an economic incentive for water conservation, a return to dryland farming and withdrawal of land from agriculture (Kromm and White, 1986).

Many states are looking to ground water to meet most of their future growth in water use. In a recent survey, the most frequent ground water availability issues identified by states were water level decline in response to intensive pumping (35 states) and legal disputes arising from increasing competition for available ground water supplies (26 states) (U.S. Geological Survey, 1984).

Ground Water Overdraft

Declines in water tables and potentiometric surfaces have occurred in all states to some extent. Areas with declines in excess of 40 feet in at least one aquifer are depicted in Figure 1 (U.S. Geological Survey, 1984).

In terms of volume, the areas of greatest overdraft tend to be relatively localized regions where water availability falls short of water demand. It is estimated that 61% of the overdraft in the western states occurs in Arizona, California, Texas, and Nebraska (U.S. Water Resources Council, 1978). For example, about two-thirds of the ground water withdrawn in Arizona in 1985 was pumped from storage (U.S. Geological Survey, 1990). Similarly about 77% of the ground water pumped in central and coastal Texas was derived from storage. Other areas in which ground water is withdrawn significantly in excess of recharge are parts of Oklahoma, Kansas, New Mexico, Nevada, South Dakota, and eastern Colorado (U.S. Water Resources Council, 1978; U.S. Geological Survey, 1985).

Most regional generalizations about the extent of ground water overdraft and the potential for ecological impacts are inappropriate for several reasons. First it is difficult to summarize the overall extent of water level decline in an area because many areas are underlain by more than one aquifer and declines have not occurred, or have not occurred to the same extent, in all aquifers present. In most areas, the most significant declines have occurred in a semiconfined water bearing zone and not in the overlying unconfined aquifers (U.S. Geological Survey, 1984). Under some circumstances, these instances of overdraft are less likely to result in ecological impacts as the extent of interconnection with surface water bodies may be more limited than with some shallow water table aquifers.

Secondly, extensive water level decline is not necessary for ecological impacts in wetlands and riparian areas. Any perturbation of the natural

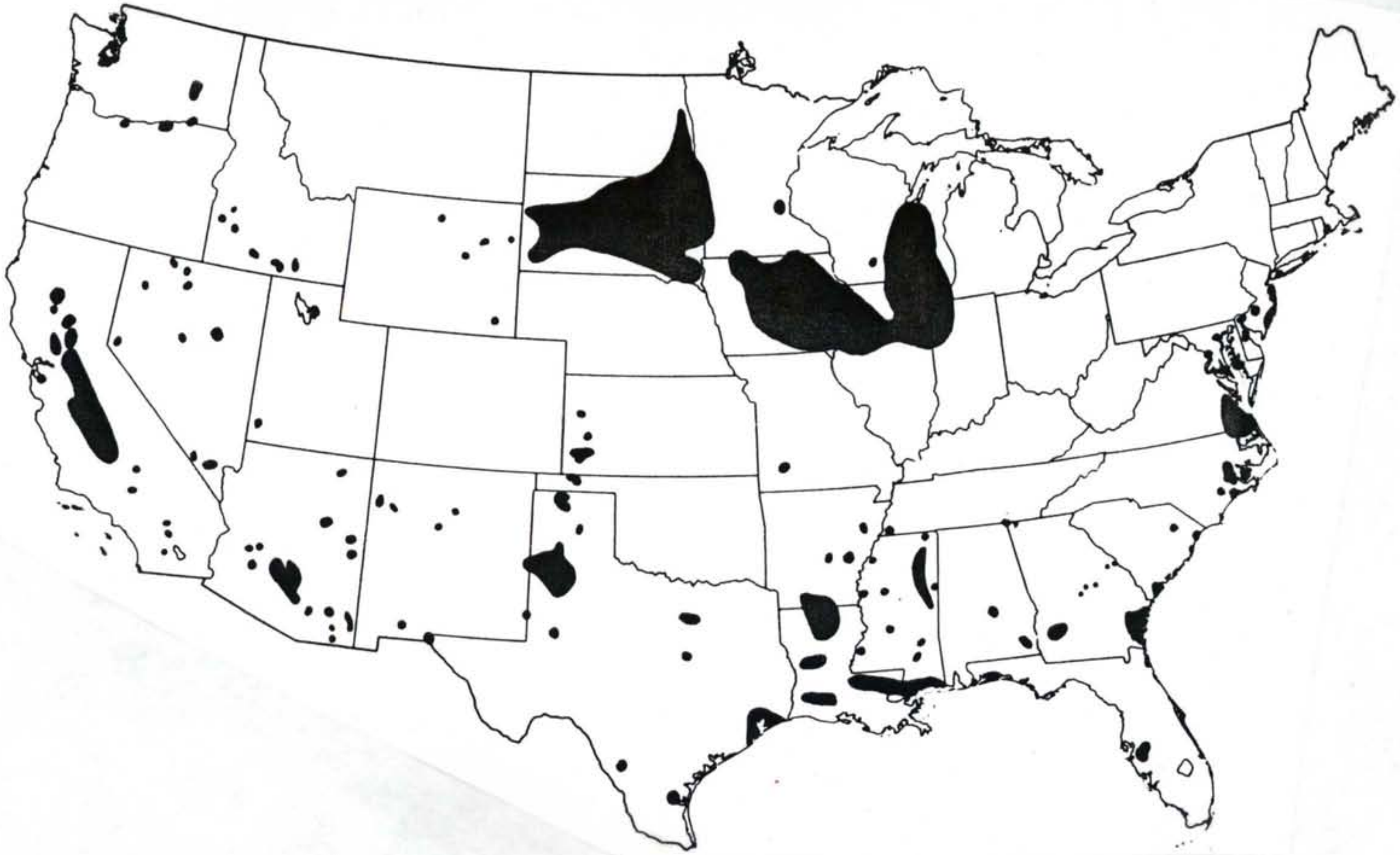

Figure 1. Areas of water table decline or artesian water level decline in excess of 40 feet in at least one aquifer since predevelopment (from U.S. Geological Survey, 1984).

hydroperiod to which a hydric ecosystem is adapted may be sufficient to result in adverse impacts. Three important aspects of a wetland hydroperiod are: 1) the depth or stage of the fluctuating ground and surface water, 2) the duration of the fluctuating water levels, and 3) the periodicity or seasonality of the water level fluctuations (Bacchus, in press). Consequently, determination of the affects of ground water pumping must consider ecosystem sensitivity to alteration of rates of change and duration of the natural hydroperiod as well as the overall magnitude of drawdown.

Thirdly, many of the instances of water level decline depicted in Figure 1 took place many years ago during the initial stages of water development. Today water levels in those areas are stable and associated ecosystems have adapted accordingly. Examples include parts of South Dakota and declines in Iowa and the Chicago-Milwaukee area (U.S. Geological Survey, 1985).

A fourth and extremely important caveat regarding identification of ecological impacts in wetlands and riparian areas resulting from ground water overdraft pertains primarily to the southwest. Interpretation of water level decline data is complicated by a widespread phenomenon called channel incision or arroyo cutting which is believed to be independent of ground water pumping. These dramatic changes in stream channel morphology have had a major impact on wetland and riparian communities throughout the southwest.

Prior to the mid-nineteenth century, many streams in the southwest were associated with wide floodplain aquifers. These shallow water sources supported extensive riparian habitats and numerous headwater wetlands. Frequent floods resulted in adequate seed dispersal and constant replenishment of fertile alluvium. Mature hardwoods forests as well as extensive marsh vegetation were dependent on these shallow alluvial aquifers (Hendrickson and Minckley, 1984).

Between 1865 and 1915, a regional decline in water tables which is thought to be predominantly unrelated to ground water pumping occurred throughout the southwest (Betancourt, 1990). A combination of human impacts including stream ditching and draining, timber harvest from riparian zones and uplands, and excessive cattle grazing is believed to have interacted with drought and floods to cause rapid and widespread channel incision and headward erosion of watercourses throughout the region (Stromberg, 1994). With smaller flows confined to vertical walled channels, alluvial water tables declined many tens of feet in some locations. Many valleys which were previously swampy or which had ground water within 10 feet of the surface were drained (Bryan, 1928). Marshes and grasslands were widely eliminated and ultimately riparian forests were diminished as well (Hendrickson and Minckley, 1984).

In many cases these ecological changes resulting from channel incision were initiated or became evident during periods of development of alluvial ground water resources for agricultural and domestic water supplies. Differentiation of causal factors is difficult in many regions.

In summary, it is clear that in most cases regional generalizations about the impact of ground water overdraft are not advised. The hydrology, water and land use history, and ecological characteristics of each location must be evaluated individually. Many instances of ecological impact are highly localized and result from very minor perturbations of natural ground water levels. On the other hand, some occurrences of water level decline may have little or no impact on wetland and riparian ecosystems. Sections 4 and 5 provide more detail on the hydrological and ecological considerations which contribute to an increased potential for wetland and riparian impacts. Detailed descriptions of the locations and the ecological consequences of ground water overdraft are found in Section 6.

Section 4

Overview of the Ecology of Wetlands and Riparian Areas

Ecological Importance of Wetlands and Riparian Areas

An understanding of the ecological processes and functions that control wetland ecosystems is necessary to provide protection for these critical areas. As transition environments between aquatic and terrestrial ecosystems, wetlands are among the most spatially and temporally complex natural systems on earth (Richter and Richter, 1992). And perhaps most importantly, the ecological importance of an individual wetland is a function of the presence of other wetlands (Swanson, 1988). Therefore, in many regions in which wetlands are naturally limited or in which extensive loss and alteration have taken a toll on predevelopment acreage, the remaining wetland areas are absolutely critical for many plant and animal species.

Freshwater wetlands, although subject to controversy with regard to definition, generally may be divided into three categories. Riverine wetlands include those associated with both perennial and seasonal watercourses. Lacustrine wetlands are associated with permanent and seasonal lakes and ponds. Palustrine wetlands include emergent ecosystems such as marshes, wet meadows, springs, potholes, and fens as well as forested wetland ecosystems (Dugan, 1990). Examples range from small isolated depressional wetlands such as glacial potholes or karst sinkholes to regional features such as poorly drained low relief areas like the Florida Everglades (Brown and Sullivan, 1988).

Recent research on wetland ecology has stressed the importance of understanding the functional values of wetlands. Going beyond traditional areas of interest such as species composition and community structure, emphasis on wetlands functions enables researchers to evaluate impacts if wetlands are eliminated or disturbed (National Research Council, 1991; Brinson, 1993). From an ecological perspective, the most important function is providing "food web support" for associated terrestrial and aquatic ecosystems including primary production and nutrient cycling. Many wetlands are among the most productive of natural ecosystems, exceeding the best agricultural lands and rivaling the production of tropical rain forests (National Research Council, 1991). Other important functions for higher trophic levels include sites for breeding, nesting, rearing, resting, refuge, feeding, and overwintering. Healthy wetlands are important in maintaining regional biodiversity.

Beyond a biological significance, wetlands are important for hydrologic functions including flood conveyance, erosion protection, ground water recharge, and potential water supplies. They also can contribute to improved water quality by removing excess sediment, nutrients and other contaminants from surface runoff and ground water recharge. Lastly, wetlands are of significant economic value for timber harvest, development sites and intrinsic aesthetic characteristics.

It is beyond the scope of this report to provide a thorough review of the broad topic of the ecological importance of wetlands. Instead some of the more crucial roles will be highlighted for the purpose of illustration.

One of the most important types of wetlands is forested areas in regions which otherwise have few trees. Riparian areas are the only native forested environments in the Great Plains (Segelquist et al., 1993) and most desert areas (Walters et al., 1980). Overstory canopies provide perches, nest sites and protection for birds in these locations where they would not otherwise be available. Foliage, flowers, seeds, and fruits support insects, birds, and mammals (England et al., 1984). Therefore, loss of forested riparian areas is significant for all trophic levels.

Waterfowl rely on wetlands for breeding grounds, winter feeding, and feeding and resting sites in migration corridors. Decline of duck populations has been linked directly to drainage and degradation of wetlands (Bellrose and Trudeau, 1988).

In general, the ecology of mammals within wetland ecosystems is poorly known relative to that in other environments. Mammals are less likely to be obligatory inhabitants of wetlands than birds and other vertebrates. However, it is clear that a diversity of mammals engages in opportunistic exploitation of wetlands for diet, cover, and travel corridors (Fritzell, 1988).

Southwestern riparian systems support some of the richest biotas in North America. At the same time, these areas are some of the world's most endangered ecosystems because 70 to 95% have been lost (Johnson and Haight, 1984). Plant species found in these systems are much less drought resistant than surrounding desert flora and as such are vulnerable to hydrological disturbance (Walters et al., 1980). In turn, southwestern riparian habitats support relatively large and diverse populations of mammals, other vertebrates, flowering plants and insects (Johnson and Haight, 1984) as well as the highest density of noncolonial nesting birds in the United States (Carothers et al., 1974). In particular, cottonwood/willow habitat and mesquite bosques (forests) are extremely important for birds and other animals (England et al., 1984). Mesquite bosques were formerly the most abundant riparian type in the southwest and now are reduced to relatively small isolated remnants, virtually none of which remain in pristine condition (Stromberg, 1993b).

One of the most interesting facts which emerges from a review of the literature on the ecological significance of wetlands and riparian areas is their inordinate importance for rare and endangered species. Almost 35% of all rare and endangered animal species either inhabit wetland areas or are dependent on them, although wetlands constitute only about 5% of the nation's lands (National Research Council, 1991). Over 50% of the federally designated animal species are wetland related and 28% of the listed plant species are wetland dependent (Niering, 1988).

Reasons for this relationship between endangered species and wetlands pertain to the nature of wetlands as well as the extensive loss of wetland acreage. Many wetlands are small in size and lack surface water connection to other bodies of flowing water. Thus small populations of endemic species have a high degree of specialization and are vulnerable in the event of wetland disturbance. Second, wetlands in arid areas, particularly in the southwest, are refugia for Tertiary and Recent species which evolved during a much wetter climate. These isolated wetland areas are often remnants of pluvial lakes and support species which are unable to survive elsewhere in current post-pluvial conditions (Hendrickson and Minckley, 1984). As a result, many fish and mollusk species depend entirely on isolated wetlands in the southwest. In addition to development-related habitat loss, this role of wetlands as refugia accounts for the fact that about 60% of the federally listed fish species are found in the desert southwest (Williams and Sada, 1985; Williams et al., 1989).

Types of Ecological Impacts Which May Result from Ground Water Overdraft

Riparian wetlands are now considered to be the most modified land type in the western United States and have undergone major changes in most of the other regions of the country as well (Jackson and Patten, 1988). Historically the most destructive alterations of wetlands have been associated with changes in the hydrologic characteristics which support the wetland ecosystem (National Research Council, 1991). In many wetlands the hydroperiod is the single most important factor which determines species distribution and ecosystem health. Systems supported by ground water for some or all of the year are therefore extremely susceptible to impact from unnatural changes in water level.

A broad array of ecological impacts may result from ground water withdrawals. Generalized examples are discussed here for the purpose of illustration as it is beyond the scope of this report to review this subject in species-specific detail. It is important to remember that ecological changes occur along a continuum (Stromberg, 1994). Some absolute thresholds can be recognized such as maximum ground water depths beyond which a species will not grow. But most changes are gradual such as the ongoing decline of a species or a gradual reduction in disease resistance of individuals experiencing water stress. In addition, there is often a time lag of as much as a decade before the effects of water stress are noticeable. Furthermore, many of the impacts discussed below can be caused by the other sources of anthropogenic disturbance which are common in many wetlands today as well as natural cycles of drought and disease. Consequently it is often far from straightforward to identify impacts from ground water overdraft.

Ground water is a major determinant of riparian vegetation abundance, community structure, species composition, and population health (Stromberg, 1994). Riparian and wetland ecosystems undergo changes in response to water stress in a hierarchical fashion. High levels of stress cause ecosystem and community level changes and less severe stress can evoke reponses in individuals of the least tolerant species (Stromberg, 1992). Among the most common impacts seen in wetland areas in response to hydroperiod perturbation are changes in species composition, species distribution and wetland extent (Stomberg, 1994; Harding, 1993). A typical response may involve the loss of obligate wetland species followed by loss of facultative riparian vegetation species. Hydroriparian and mesoriparian species may be replaced by xeroriparian and upland species. Nuisance species which are more tolerant of abnormal water fluctuations may become established. On the other hand, in some ecosystems water stress results in ongoing impoverishment of the whole community rather than promoting succession to drought tolerant species (Walters et al., 1980).

As the competitive balance is disrupted in water stressed wetlands, native species will frequently be replaced by opportunistic drought tolerant exotic species which may be less desirable with respect to ecosystem function. The extensive proliferation of saltcedar coupled with reduced survivorship of cottonwood and willow seedlings in water stressed riparian areas in the southwest is an example (Stromberg, 1994).

Structural characteristics of most plant species are influenced by water level fluctuations. Tree height and morphology can be altered drastically. When ground water is deeper or not available, trees must invest more resources into root production and therefore are shorter with less dense canopies (Stromberg, 1994). For example, mesquite will occur as a tree if shallow ground water is available but populations will tend toward a shrub morphology if ground water declines below about 5 to 15 m for significant periods of time (Stromberg, 1993b). In fact, most major attributes of plants can be influenced by water availability including total biomass, lifespan, vegetation volume, leaf size, basal area, root mass and depth of penetration, investment in reproductive structures, and susceptibilty to disease. Since many of these parameters are also indicators of insect and avian abundance, impacts from water stress are felt throughout the ecosystem (Stromberg, 1993b).

Other ecosystem responses to anthropogenic ground water level fluctuations result from changes in soil parameters. Of primary importance in some areas is an increased susceptibility to fire (Rochow, 1994; Harding, 1993) Wetland soil which is high in organic matter is very combustible when desiccated. Furthermore, with reduced soil moisture, mineralization of nutrients from decaying organic matter is drastically reduced causing a decline in soil fertility and productivity (Lieurance et al., 1994). In areas where water level decline has resulted in surface soil subsidence, tree roots may become exposed. In the case of pondcypress roots which are adapted to anaerobic conditions characteristic of organic soil and surface saturation, exposure to air can result in death of the tree (Bacchus, 1995).

One of the key parameters which is indicative of the health of an ecosystem is the age class diversity. Seed germination and seedling survival are often indicators of the ability of populations to sustain themselves. In some areas, seedlings will not germinate without alluvial ground water as rainfall alone is insufficient (Segelquist et al., 1993). Frequently, seedlings of riparian species are more sensitive to water level decline than mature individuals with well developed root systems. Alternatively, some streamside seedlings have been shown to utilize surface water while mature individuals have evolved to use a presumably more seasonally dependable ground water supply (Dawson and Ehleringer, 1991). Thus perturbations in ground water levels can be differentially detrimental at various stages of development for certain species. Knowledge of these variables is necessary to interpret observed impacts.

The seasonal cycle of anthropogenic ground water fluctuations can have a great influence on the extent of ecological impacts. Spring drawdown can be detrimental to seed germination as well as populations of macroinvertebrates and their associated predator species (Riley and Bookhout, 1990). Summer drawdown can be harmful as alternative water sources such as surface water or precipitation are least available to compensate for the loss of ground water during the summer months (McKnight, 1992; Lewis and Burgy, 1964).

Much of the preceding discussion has focused on impacts to plant species. Impacts of water level decline are found at all trophic levels (Loftus et al., 1992). Often the elimination or degradation of one plant species will have an impact on the entire floral and faunal assemblages.

Section 5

Hydrogeologic Mechanisms Capable of Causing Ecological Impacts from Ground Water Overdraft

Introduction

Wetlands occur in geologic and hydrologic settings which enhance the accumulation or retention of water. Water sources may include surface water, ground water, precipitation or anthropogenic sources such as irrigation or wastewater disposal. Two key aspects of a landscape need to be considered to understand wetland hydrology: 1) the shape and hydraulic characteristics of the land surface which affect movement of water across it and 2) the geologic boundaries and hydraulic characteristics of the subsurface which affect ground water flow systems (Winter, 1988). Ground water dependent wetlands result from the interaction of these two sets of surfaces. Examples include locations were the water table intersects the land surface such as at breaks in surface slope, surface watercourses and water table mounds as well as artesian discharge at springs and seeps.

The natural hydroperiod is among the most important factors which determine the location, composition and health of wetlands and riparian ecosystems. To preserve the natural hydroperiod, the sustainable yield for allowable pumping must be based on the season, rate, and location of pumping as well as the magnitude of the withdrawal (Dingman, 1994). Ground water pumping which results in changes in excess of species' limits of tolerance in any of these parameters will result in some degree of ecological impact.

In this section the various hydrogeological changes which result from pumping will be described in terms of the ways in which they may cause in ecological impacts in wetlands and riparian areas. Hydroperiod perturbations may result from changes in the seasonality, rate, and extent of natural fluctuations in the following: 1) the water table and capillary rise in the vadose zone, 2) surface water flow, and 3) artesian discharge. In addition, alteration of natural hydrologic conditions by ground water pumping may cause or be accompanied by other changes in the physical environment. Overdraft can result in geomorphological changes which impact wetland hydrology such as land subsidence and alteration of river channel morphology and stability. Lastly, changes in the natural geochemical environment in excess of species' tolerance may occur including alteration of equilibria between the ground water and the associated solid media as well as salt water intrusion.

Ground Water Level Fluctuation

In riparian settings, alluvial soil moisture is determined by a complex interaction of channel geometry, river stage and discharge, precipitation and alluvial ground water dynamics (Segelquist et al., 1993). A growing body of evidence suggests that riparian ground water is a primary source of water for many riparian plant and tree species (Busch et al., 1992). Ground water pumping may lower the water level beneath the depth of root penetration either temporarily or permanently, thereby subjecting riparian vegetation to lethal or sublethal water stress.

Riparian vegetation may be particularly vulnerable to impact from water level decline for several reasons pertaining to the hydrologic variability characteristic of riparian settings. In arid and mesic environments, alluvial ground water may be the only water supply available during summer periods of base flow. Consequently, even a small change in riparian water availability can have a pronounced impact on riparian ecosystems (Stromberg, 1993a). Similarly, periodic flood flows deposit seeds of some riparian species such as Fremont cottonwood and Goodding willow in high floodplain settings distant from the active river channel. Seedling survival may thus become entirely dependent on shallow riparian ground water (Stromberg, 1993c). In addition, the coarse alluvium which is common in many riparian environments has a low water retention capacity and reduced capillarity, predisposing these environments to water stress (Mahoney and Rood, 1992).

The rate, duration, seasonality and magnitude of hydroperiod perturbations are all important in determining the effect of ground water withdrawal on riparian and wetland ecosystems. Frequently, ground water pumping is greatest during the dry summer months, particularly if ground water withdrawal is needed for agricultural supplies. When pumping ceases or declines after the growing season, water levels may recover. This seasonal pattern can be detrimental to riparian ecosystems because recharge from base flow and precipitation are at an annual low and plant water requirements are highest during periods of greatest pumping.

Many phreatophytic species are capable of rapid root growth in response to a seasonally declining water table. Water level decline within these species-specific limits may not be harmful and in fact, may promote extensive root growth. For example, seedling survival of plains cottonwoods was shown to be highest at a drawdown rate of 0.4 cm/day and decreased with increasing rates of water level decline (Segelquist et al., 1993). Likewise, the maximum depth of root penetration varies by species and is a major factor in determining the ability of a species to withstand a declining water table. A related variable in determining riparian survivorship is the soil texture. Coarse alluvial soils enhance root penetration but are also readily drained (Mahoney and Rood, 1992).

Time lags on the order of years to decades may occur as impacted riparian ecosystems adjust to reduced soil moisture conditions. This is because mortality often occurs episodically and because individuals within a population may vary in their tolerance to water stress (Stromberg, 1993a). Thus the effects of water level decline may be unnoticed until considerable impact has occurred.

Numerous examples of riparian and wetland impacts from ground water level fluctuation are described in Section 6. One brief example will be mentioned here as an illustration. Portions of the alluvial aquifer of the Carmel River Valley (California) have experienced as much as 10 m of drawdown resulting from pumping for municipal water supplies. When combined with a two year drought which virtually eliminated annual recharge from river flow, phreatophyte mortality in the vicinity of the well fields was extensive. Downstream of the well fields, aquifer drawdown was minimal and vegetation experiencing the same weather-related conditions remained healthy (Kondolf and Curry, 1986).

Adverse impacts also may occur when ecosystems have successfully adapted to anthropogenic ground water level decline and pumping is then stopped or reduced. As the water level recovers, surface or subsurface inundation may be injurious to root tissue adapted to an aerobic, lower moisture regime. Groeneveld (1989) identified root tissue damage resulting from rapid water table fluctuations associated with changes in ground water pumping rates. Likewise, when pumping ceases in dewatered mining and construction pits, recovery of water levels has the potential for similar adverse impacts on any wetlands in the impacted area.

Reduction of Ground Water Discharge

Ground water discharges to the land surface as a result of gravity, artesian pressure, topography, and structural and stratigraphic geologic features. Ground water discharge zones typically support important ecosystems such as gaining reaches of rivers and their associated riparian areas. Other more localized discharge features include a wide variety of wetlands, marshes, springs, and seeps. Ground water discharge may be the sole means of sustenance for some of these settings, particularly in arid environments where precipitation and surface discharge may be intermittent or nonexistent during much of the growing season.

Anthropogenic withdrawal of ground water may reduce natural discharge to these types of ecosystems in several ways. Excess pumping of ground water in floodplain aquifers may reduce the baseflow in rivers to the detriment of aquatic and riparian ecosystems. (Baseflow is that portion of the annual discharge of a watercourse which is derived from ground water storage or other delayed sources (Hall, 1968)). The hydraulic gradient may even be reversed resulting in a previously gaining reach becoming a losing reach.

Such is the case in portions of the lower Carmel River in California. After spring runoff discharge events, the river is sustained primarily by bank storage from the alluvial aquifer. Timing of baseflow contributions is critical to downstream migration of steelhead trout smolt and success of willow seedlings. In recent years, localized pumping of the alluvial aquifer for municipal water supplies has been shown to reverse the hydraulic gradient in some reaches and deprive the river of a volume of baseflow which was directly proportional to the rate of pumping (Kondolf et al., 1987). Furthermore, in late summer in 1982 when pumping was coupled with prolonged drought, the river dried up completely in the pumped reach and re-emerged downstream.

Ground water pumping also may reduce or eliminate discharge at springs, seeps, and wetlands. This has occurred on a widespread basis throughout the southwest at localized headwater wetlands called cienegas (Stromberg, 1994) and at many former sites of artesian springs. Reduction of spring flow is a serious concern at the major springs fed by the Edwards Aquifer in Texas (Longley, 1992) and at springs in similar settings in the southeast (House Committee on Natural Resources, 1994). Likewise, seeps, springs and marshes in the Humboldt River Basin (Nevada) are threatened by ground water pumping for dewatering gold mining pits (Bureau of Land Management, 1993a).

As was mentioned in the previous section, the extent of ecological impacts from a reduction of ground water discharge is determined by the rate, duration, seasonality and magnitude of the reduced flow as well as various ecological characteristics of the wetland and riparian communities. In many cases, hydrophytic vegetation is rapidly replaced by species which are more tolerant of water stress, resulting in a loss of food sources, shelter and nesting sites for animals which rely on wetland areas.

Induced Recharge

In many areas ground water in confined or semiconfined aquifers is under sufficient artesian pressure to discharge vertically to an overlying unconfined aquifer or to discharge to the surface in the form of springs, wetlands or a surface water body. If pumping of the confined aquifer exceeds recharge, the hydraulic pressure in the confined system may be reduced to the point that surface discharge ceases. Further pumping may reverse the vertical gradient causing the unconfined aquifer to recharge the underlying pumped aquifer. If recharge to the unconfined aquifer is insufficient, the water table will decline. This sequence is called induced recharge (Fetter, 1988). Clearly any riparian or wetland ecosystems which are dependent on the artesian discharge or the unconfined shallow ground water will be adversely impacted if induced recharge is significant.

Certain geologic settings predispose wetlands to being vulnerable to hydroperiod alteration from induced recharge. In general, any discontinuity in a confining layer will convey downward recharge in the event of excess pumping of the confined aquifer. Examples include lenses of highly permeable materials such as glacial or alluvial sand and gravel. Structural discontinuities such as fractures, faults or karst features such as sinkholes also serve as conduits for downward recharge. Geophysical methods such as ground penetrating radar can be used to identify structural features which present a risk to wetlands in the event of excess pumping (Bacchus, 1994; Bacchus, 1995).

Documented examples of wetland impacts from induced recharge are not abundant although the phenomenon is not uncommon. Pondcypress in depressional wetlands in the vicinity of municipal well fields in southwest Florida have been adversely impacted by induced recharge derived from surficial saturated zones. Other ecological impacts identified in wetlands in this area include succession to upland plant species, soil subsidence and increased susceptiblilty to fire (Rochow and Rhinesmith, 1991).

Las Vegas Valley (Nevada) provides another example. Development of ground water resouces has resulted in over 300 ft of water level decline. Artesian springs which were abundant in the nineteenth century have been eliminated and the vertical hydraulic gradient has been reversed in some areas. As a result, the shallow aquifer which previously had supported marsh vegetation in portions of the valley now recharges the underlying semiconfined aquifer (Katzer and Brothers, 1988).

Land Subsidence

Ground water decline can result in land subsidence which may adversely affect riparian and wetland ecosystems in several ways. Subsidence can occur either surficially or in the subsurface. Surface subsidence typically occurs when moist highly organic soils are subjected to drying conditions such as would result from water table decline or loss of artesian flow. With exposure to the atmosphere, the organic matter is oxidized and surface compaction may result. Wetland tree species such as pondcypress are particularly vulnerable to damage from surface subsidence. Tree bases and roots which are adapted to an anaerobic soil environment become exposed to air and susceptible to fungal pathogens. The resulting decay may result in the death of the tree (Bacchus, 1995). Loss of organic soils at rates of up to 15 cm within the first year of ground water withdrawal is not uncommon from this type of subsidence in the Southeastern Coastal Plain (Bacchus, 1994).

Subsurface subsidence is by far more areally extensive. It occurs when ground water is withdrawn from unconsolidated or poorly consolidated fine grained sediments, typically clay. Collapse of the molecular structure of the clay minerals results in permanent compaction of the dewatered materials. Although irreversible once it has occurred, compaction will cease when further ground water decline is halted (Freeze and Cherry, 1979). Another type of subsurface subsidence occurs in the form of collapse from dissolution of karst features (Bacchus, 1995).

The areal extent and elevation loss resulting from land subsidence can be considerable. The maximum subsidence recorded in the United States is 29 ft measured on the west side of the San Joaquin Valley (California). California also ranks first in terms of statewide total area affected by subsidence induced by ground water withdrawal with over 6,200 mi^2. Texas and Arizona follow with 4,600 mi^2 and 1,000 mi^2 respectively (Poland, 1981). For perspective, it is interesting to note that the total volume of aquifer storage lost as a result of aquifer compaction in California's Central

Valley alone is half the man-made surface storage capacity statewide (Conniff, 1993). Management of this source of impact is difficult because laws governing liability for subsidence are not settled in most jurisdictions (Kopper and Finlayson, 1981).

Many areas of subsidence are in coastal regions where ground water is derived from alluvial and shallow marine sediments (Johnson, 1981). As a result, coastal wetland ecosystems are at increased risk due to salt water intrusion and erosion and inundation from tides and storms (U.S. Water Resources Council, 1978). For example, since 1943, several thousand acres of bayfront property have been submerged into tidal reaches of Galveston Bay, Texas (Neighbors, 1981) and similar impacts have been observed around southern San Francisco Bay, California (Fowler, 1981). Subsidence of about 450 mi^2 in the Delta area formed at the confluence of the San Joaquin and Sacramento Rivers (California) has resulted in submergence of islands to a depth of 10 to 20 ft below sea level (Bertoldi, 1992). Specially adapted intertidal communities such as salt marsh vegetation can be eliminated when subsidence alters tidal elevations (National Research Council, 1991).

Subsidence also can alter or reverse surface water drainage patterns, adversely affecting riparian and wetland ecosystems which are adapted to the characteristics of a particular watercourse. Examples have been cited in Galveston Bay (U.S. Water Resources Council, 1978) and the San Joaquin River basin (Kopper and Finlayson, 1981). Subsidence can lead to reduction of the gradient of a drainage basin. Riparian ecosystems are then exposed to repeated flooding such as has occurred in the lower Santa Cruz River basin in Arizona (Schumann et al., 1986). Where drainages cross the periphery of a subsiding basin, the river channel gradient is increased resulting in accelerated erosion. Removal of topsoil and deepening of the stream channel may also adversely affect riparian ecosystems (Schumann et al., 1986).

Lastly, subsidence can result in surface features such as earth fissures and sinkholes. These depressions can accelerate erosion and capture surface flow and thereby alter the hydrologic characteristics to which riparian ecosystems are adapted (Newton, 1981).

Changes in River Channel Morphology and Stability

River channel morphology and stability are determined by a complex and dynamic equilibrium between many aspects of a drainage basin including the soil and bedrock characteristics, the slope of the watercourse, and seasonal discharge patterns including flooding cycles (Bloom, 1978). Riparian vegetation is adapted to these factors and changes outside species' specific ranges of tolerance can adversely impact entire riparian ecosystems.

Ground water flow in shallow riparian aquifers plays an important role in riverine hydrology and geomorphology. Excess pumping of alluvial aquifers can deprive riparian vegetation of an adequate water supply, particularly in the hot summer months during periods of low river flow. Loss of the stabilizing effect of plant roots can greatly increase erosion of river banks resulting in temporary or permanant loss of riparian habitat. Subsequently eroded sediment can be redeposited farther downstream with adverse effect on plant species which may not be adapted to depositional environments. In general, the relative importance of vegetation for bank stability is greater for smaller streams but can be critical for all watercourses (Kondolf and Curry, 1986).

The Lower Carmel River (California) is an example of the scenario described above. Extensive pumping from the alluvial aquifer in recent decades has resulted in massive death of riparian vegetation. Subsequently, several relatively minor discharge events widened the river channel from 60 to over 400 ft in just 6 years (Groeneveld and Griepentrog, 1985). The overall character of the river in the affected reach has changed from a narrow, stable meandering channel to a wide shifting channel with braided reaches, with obvious effects on the success with which the previous riparian community can re-establish itself. Downstream reaches unaffected by pumping have maintained healthy bank vegetation and have experienced no major erosion (Kondolf and Curry, 1986).

Channel stability and morphology also can be affected when ground water discharge to a watercourse is anthropogenically increased. In the case of Las Vegas Wash (Nevada), ground water pumped from a deep aquifer is used extensively to irrigate lawns and golf courses in the area. This has caused a considerable increase in recharge to the shallow aquifer system. The resulting increased discharge from the shallow subsurface to Las Vegas Wash has been partially responsible for changing the wash from an ephemeral to a perennial stream. As a consequence of this increased discharge, erosion and headcutting have had a major impact on the riparian vegetation. As the channel has been lowered by about 15 ft, water levels have declined in the riparian communities. Plant communities have changed from swamp and marsh vegetation to saltgrass and salt cedar. Headcutting has resulted in the upgradient migration of the hydrophytic species (Burbey, 1993).

Salt Water Intrusion

When ground water is pumped from fresh water aquifers that are in hydraulic connection with saline water, the resulting gradient may induce a flow of salt water toward the well. Overpumping of a well or well field in close proximity to the salt water/fresh water interface can result in the interface being drawn toward the well to the extent that salt water intrudes into the fresh aquifer (Freeze and Cherry, 1979). This can occur under several conditions. In coastal areas, sea water of greater density frequently underlies surficial fresh water aquifers. In addition, an estimated two thirds of the continental United States is underlain at some depth by saline ground water, with the majority of the shallowest located in the Central Plains and Midwestern states (Atkinson et al., 1986). Excess pumping in these areas can draw underlying salt water upward toward or into a fresh water zone, a phenomenon known as upconing (Fetter, 1988).

Salt water intrusion is a widespread problem in many parts of the country. Atkinson et al. (1986) provide a comprehensive summary of the locations where salt water intrusion is threatening or contaminating fresh water supplies. As an overview, salt water intrusion has occurred in each of the 21 coastal states and has the potential to worsen as water demand increases in coastal urban areas. Among the more critical problem areas are Long Island (New York), the Biscayne Aquifer (Florida), and several basins in California and Georgia. In total, only 8 states throughout the country have not reported any instances of salt water intrusion (Atkinson et al., 1986).

Riparian areas and wetlands which are supported by fresh ground water discharge can be impacted when overpumping results in intrusion of highly mineralized water. Riparian and wetland communities are adapted to specific ranges of salt tolerance. Increasingly saline conditions interfere with water and nutrient uptake by plants (Bolen, 1964). As salinity increases, plant growth usually is reduced and succession to more halophytic species may occur. Such changes will typically be accompanied by impacts to native animal species, particularly waterfowl, which depend on wetland vegetation (Bolen, 1964). Evaporation and evapotranspiration accelerate salt accumulation in the soil surface, exacerbating salinity impacts during the growing season. In contrast, one potentially beneficial but relatively minor effect of increased salinity has been noted in fine grained wetland soils. Increased salinity enhances the internal cohesiveness of clay particles and results in reduced erodibility of these soils (Jenkins and Moore, 1984).

Although salt water intrusion is geographically widespread, and the potential for ecological impacts is great, research on the nature and extent of such impacts is very limited. Attention is focused more frequently on the impacts on drinking water supplies, water quality for irrigated agricultural supplies, and costly impacts borne by industrial users (Atkinson et al., 1986).

One comparatively well documented example of potential ecological impact from salt water intrusion is occurring in portions of the Edwards Aquifer (Texas). Overpumping for public water supply draws highly saline water toward freshwater springs which threatens several endangered species of amphibians (Longley, 1992).

Changes in Ground Water Geochemistry

Studies on the interaction between ground water and surface water have more commonly focused on the hydrologic balance in the system. As noted above, alteration of the rate and direction of ground water flow can result in ecological impacts to ecosystems. However, many geochemical aspects of the surface water/ground water system and the associated solid media can profoundly affect the biological communities which inhabit them. In general, geochemical effects associated with changes in ground water discharge have received relatively little attention compared to the ecological significance of surface water chemical parameters (Hagerthey and Kerfoot, 1992).

Nutrient availability can be influenced significantly by ground water discharge in a wetland. Reduction of ground water discharge can reduce the rate of mineralization of detrital organic matter, resulting in decreased delivery of essential nutrients such as carbon, nitrogen and phosphorus to the root zone. Alternatively, reduced ground water discharge may result in increased nutrient availability if ground water discharge is not available to dilute nutrient concentrations and transport nutrients from the root zone (Harding, 1993). Overall nutrient ratios as well as nutrient availability are important in determining species composition and health in many wetlands. Selective removal of the more soluble nutrients will alter optimal ratios to which species are adapted.

Reduction of ground water discharge to wetlands can alter several other important geochemical parameters of ecological significance including the dissolved oxygen concentration, pH, redox potential, salinity and alkalinity of the soil/water environment. Redox potential controls the solubility and bioavailability of redox sensitive elements such as iron, manganese, nitrogen, sulfur, and chromium (Stumm and Morgan, 1981). Reduction of ground water discharge to a wetland also can affect physical features of the soil such as the temperature and the degree of aeration of the soil (Grootjans and Ten Klooster, 1980). Furthermore, without ground water input to certain wetlands, surface outflow may be eliminated and evapotranspiration may become the major hydrologic output, thereby promoting solute buildup in the soil (Davis, 1993).

Wetland ecosystems generally are adapted to a specific range with respect to each of these parameters. Changes that exceed the tolerance of the individual species will result in a loss of species and succession to more tolerant species. For example, calcium-rich ground water discharge traditionally has supported many rare and endangered plant species in a nature reserve in the Netherlands. Increased ground water pumping for drainage and drinking water supply over a period of 40 years has reduced the ground water discharge. As a result, the extent of the calciphilous marsh species has been reduced and succession to woody species such as *Alnus* has been promoted (Wassen et al., 1989). Another example is provided by changes in salinity in Las Vegas Wash (Nevada). Increased land application of pumped ground water has resulted in greater flow through the salt-laden shallow alluvial deposits along the banks of the wash. The resulting increase in salinity has adversely affected riparian vegetation in this area (Burbey, 1993).

Section 6

Locations of Ecological Impacts of Ground Water Overdraft on Wetlands and Riparian Areas

Introduction

The following section is a compilation of the literature which was found on the location and extent of impacts on wetlands and riparian areas. The majority of the information is from the United States although some international examples have been included where documentation is sufficient. Most of the locations are confined to an individual drainage basin or aquifer system. However, several instances of more regional impacts were identified.

This compilation is intended to be as comprehensive as possible. Because many sites are not well researched or well documented, it clearly is not indicative of the magnitude of this issue in the United States. In some cases, extensive hydrological modifications resulting from ground water drawdown are described in the literature but no followup investigations regarding the potential for impacts in associated wetland ecosystems have been conducted.

Discussions of some locations of impacts have been developed into case studies because detailed information was available. In some cases, considerable information on geological settings and local hydrogeology has been included. It is hoped that this information will be of use in a predictive sense for other as yet unrecognized locations with similar characteristics.

INTERNATIONAL STUDIES

ENGLAND

Redgrave and Lopham Fens, East Anglia

Botanical and zoological data document ecological changes occurring over the past 30 years in several valley wetlands in a national nature reserve in East Anglia, England (Harding, 1993). Beginning in 1957, nearby pumping of ground water for public water supplies was determined to be the primary cause of impacts occuring at the species, community and ecosystem levels. Because East Anglia has the highest concentration of such wetlands in Britain and also has a substantial water supply deficit, there is the potential for widespread and long term impacts (Harding, 1993).

Prior to the late 1950s, calcium-rich, nutrient-poor water discharged under artesian pressure from a semiconfined aquifer and supported largely herbaceous wetlands in the Redgrave and Lopham fens in East Anglia. With the onset of pumping in 1957, artesian pressure was reduced to the point that surface discharge was eliminated and plant communities were sustained exclusively by precipitation. This change in hydrology resulted in a drastic alteration of the competitive balance of the dominant plant species. By the 1970s, herbaceous species rapidly were being replaced by scrub species such as *Salix cinerea* and *Betula pubescens*. The loss of ground water discharge eliminated the specialized environmental conditions required by semiaquatic and surface rooted species which can be sensitive to reductions in water levels of as little as 2 to 3 cm.

Invertebrate species dependent on spring-fed and calcareous wetlands also have declined. Seventy seven percent of the fen and bog species have been lost. The spider *Dolomedes plantarius* currently faces extinction in this area. An associated impact of the loss of ground water discharge is that the wetlands are now susceptible to frequent damage from fires.

NORTHWESTERN EUROPEAN LOWLANDS INCLUDING THE NETHERLANDS

The hydrology of the vast northwestern European lowlands has been altered drastically by drainage, primarily for land development and agriculture. Wet meadows have become rare as they have been converted to highly productive pastures. Remnants of native types of meadows are under protection as nature reserves (Grootjans and Ten Klooster, 1980).

Vegetation changes associated with altered hydrology were investigated in Germany as early as the 1930s. However, the objective of these studies was to measure changes in agricultural productivity to estimate compensation payments to farmers (Jalink, 1994). Beginning in the 1970s, considerable research has been undertaken by Dutch scientists but studies limited to the impacts of ground water pumping have not been performed because of the widespread alteration of the natural hydrology for drainage. Currently, research is directed increasingly toward identifying ways in which changes in surface water management and land use can minimize the ecological impacts of ground water pumping (Jalink, 1994). Regulations for well siting and ground water allocation in the Netherlands currently do address the importance of conservation of the remaining natural wetlands (Jansen and Maas, 1993).

In very low relief landscapes such as are typical in the Netherlands, ground water discharge zones called seepage faces are common (Jansen and Maas, 1993). Natural vegetation around these zones may be dependent entirely on the soil chemistry and water availability resulting from the ground water discharge. Excess pumping of ground water readily can threaten or eliminate vegetation adapted to these conditions as was shown by Grootjans and Ten Klooster (1980) for three Dutch wetland reserves and by Jansen and Maas (1993) for the Punthuizen wetland sanctuary.

Similarly, Wassen et al. (1989) have investigated the impacts of ground water decline in the Naardermeer nature reserve in the Netherlands over the past 40 years. The seepage areas have long supported *Thelyperis*-reedlands and many rare and endangered plant species. During the last 40 years ground water has been pumped for drainage and drinking water. This has reduced ground water discharge in many seepage areas. Because the regional ground water is calcium-rich, the distribution of endangered calciphilous plant species including *Caricion davallianae* has been restricted severely. Diminished fresh seepage flow also has resulted in the acidification, salination, and eutrophication of the studied marshes. Succession to woody species such as *Alnus* is widespread and has resulted in accelerated loss of additional marsh species.

SPAIN

Spain is the most arid country in Europe. Ground water demand for various uses is large and has increased rapidly during the last two decades. Similarly, the great ecological value of the wetlands in Spain did not become appreciated widely until the 1970s. This growth of water demand already has led to some serious conflicts between wetland conservation and ground water development (Llamas, 1989). The problem is excerbated by a lack of knowledge of the hydrology of many wetland ecosystems (Suso and Llamas, 1993).

Douro River Basin

Among the more systematically studied ecological impacts resulting from ground water extraction are the ecosystem changes occurring in the Douro River Basin in central Spain (Bernaldez et al., 1993). Because the basin is a somewhat geographically isolated semiarid enclave, many species including several endangered species of birds of prey, depend almost entirely on the dispersed wetlands. Several different types of wetlands occur in the basin including wet meadows, sedge meadows, marshes, phreatophytic woodlands, ponds and sloughs. They include ground water discharge and recharge sites and have differing degrees of interconnection with the regional and shallow aquifers.

Over 40 years of declining water table levels are the result of ground water pumping, primarily for crop irrigation. The average decline from 1970 to 1987 was 1 m/year. In the four subareas studied in detail by Bernaldez et al., 39 to 82% of the wetland area has been lost (i.e. is now area which is no longer classified as a wetland).

The following impacts were noted. 1) Non-phreatophytic annual species such as *Trisetaria panicea*, *Bromus tectorum* and *Vulpia* spp. have increased, indicating dryness and increasing nitrification due to the mineralization of labile soil organic matter in the reduced moisture regime. 2) Perennial plants such as *Festuca rothmaleri*, *Phleum pratense* and others have disappeared. Mosaics of xerohalophytes have proliferated. 3) Desiccation of slightly sandy soils has resulted in wind erosion of the A soil horizon and enhanced surface salination which further impedes growth of vegetation.

Because many of the wetlands in this basin are interspersed in vast expanses of irrigated cropland, they are reserves for a diverse flora and fauna which may be dependent entirely on an individual isolated locality. Food webs of plants, insects, aquatic invertebrates, reptiles, waterbirds and mammals are being impacted by the loss of relatively small wetland areas (Bernaldez et al., 1993).

Donana National Park

The Donana National Park (DNP) is recognized as one of the most important natural environments of the European Community (Llamas, 1989; Suso and Llamas, 1993). The area first received legal protection in 1969 and has been designated a Reserve of the Biosphere by the United Nations.

Donana National Park is situated in a tectonic basin filled with Plio-Quaternary sediments in the Lower Guadalquivir Valley. Three ecosystems can be distinguished in the DNP: stabilized eolian sands and moving coastal dunes on the periphery and the central marshlands. An extensive partially confined aquifer is located beneath thick clay deposits in the central area. Ground water is recharged by rainfall on the sands and discharges at the ecotone between the sands and marshes as well as contributing base flow to surface streams. The permanent wetness of the ecotone renders it the most productive and fertile zone of the DNP.

In 1979 the Spanish government approved and principally subsidized a massive irrigation project utilizing ground water from this aquifer (Llamas, 1988). Since then the drinking water demands in the area have increased as well, primarily due to expansion of the tourist industry. The ground water models used to project allowable pumping rates were developed primarily from the perspective of technological feasibility with little or no consideration of ecological suitability (Suso and Llamas, 1993). More recent modelling by leading Spanish researchers predicts the following ecological impacts from the approved pumping scheme: 1) desiccation of the ecotone wetlands in some locations leaving the abundant soil organic matter vulnerable to fire, 2) considerable reduction of surface water influent to the park as gaining reaches of streams become losing reaches, and 3) degraded ground water quality, primarily by nitrate (Suso and Llamas, 1993).

As a result of international public protest, the size of the originally approved irrigation project has been reduced. However, the researchers cited above continue to predict that ecological impacts to the park's wetlands are inevitable with the timeframe being dependent only on the amount of natural precipitation available in the interim.

Tablas de Daimiel National Park

One of the most extreme examples of ecological impacts from ground water pumping is found in the Tablas de Daimiel National Park. The internationally recognized park is located on the Central Plateau of Spain. Prior to ground water development, the park consisted of an approximately 20 km^2 marshy area around the confluence of the Guardiana and Giguela Rivers. The area was the natural discharge zone for the extensive underlying aquifer system which is composed of calcareous and detrital material of continental origin (Llamas, 1988). Prior to development, the swamps of the Tablas were covered by about 1 m of water except during extremely dry periods in the summer.

The major land use in the surrounding region was dryland farming until the hydrogeology of the extensive La Mancha aquifer became understood more widely about 20 years ago. From 1974 to 1987, ground water irrigated acreage increased from 30,000 to 130,000 ha and annual ground water pumping increased from 200 hm^3 to 600 hm^3 (Llamas, 1989). The average annual recharge rate is only about 260 hm^3 from a combination of sources including ground water, surface water and rainfall.

As result of prolonged overpumping, the water table has fallen to as much as 20 m beneath the land surface. This depletion has caused the total disappearance in this area of the Guardiana River since 1984 in addition to the progressive desiccation of the Tablas. Phreatophytic vegetation has been lost totally and the highly organic soil is undergoing a slow process of spontaneous combustion. In 1986 and 1987, two large fires burned over one third of the national park (Llamas et al., 1992).

In 1987, under pressure from Spanish and international ecological groups, the aquifer officially was declared "overexploited" in accordance with the 1985 Spanish Water Law. This required the preparation of a management plan and the creation of a local Users Committee to attempt to mitigate these impacts. About $10 million (US) from the Spanish government was used to attempt to regenerate the wetland. The primary approach was to supply water from other sources including land applying pumped ground water, importation of surface water via aqueduct and impoundment of surface water to retain it for the park (Llamas et al., 1992). However, the reallocation of water resources for regeneration was met with considerable local opposition and ultimately only 10% of the water deficit was made available during the first three year trial period.

According to some researchers, the changes in the vegetation and fauna are so significant that the area appears to be an "ecological desert" even though there sometimes is water on the land surface. It has been suggested that the government's investment in regeneration would be spent more wisely by promoting reconversion to crops requiring less water (Llamas et al., 1992).

UNITED STATES

ARIZONA

Introduction

In many areas in Arizona, particularly in the southern part of the state, ground water pumping has increased dramatically since the 1940s to meet the needs of irrigated agriculture, industry and rapid population growth. Ground water supplied 48% of Arizona's large water demand in 1985 and agriculture accounted for 87% of the total water use (U.S. Geological Survey, 1990).

The imbalance between the quantity of water consumed in Arizona and the long-term dependable suppy is a major problem. Overall about two thirds of the ground water pumped in recent years was withdrawn from storage (U.S. Geological Survey, 1990). Annual pumpage rates may exceed natural recharge rates by more than 500 times in some areas (Schumann et al., 1986). Ground water levels have declined by 50 to 300 ft in several basins throughout the state including the Gila, San Simon, Avra Valley, and others and by 400 ft or more in several additional basins such as the Santa Cruz and Salt (Schumann et al., 1986).

As transition zones between aquatic habitat and surrounding terrestrial habitat, riparian and wetland ecosystems are the most biologically productive areas in the arid Southwest. Over 85% of wildlife species are dependent upon wetland and riparian areas for some aspect of their existence. These areas serve as important breeding areas, refuges from the desert heat, important corridors for animal movement through the surrounding desert, and critical sites for forage production (Davis, 1993). The highest known breeding bird densities in the United States have been recorded in the desert riparian habitat (Carothers et al., 1974).

Historically many of Arizona's rivers and streams were perennial and supported large expanses of wet meadows, marshes, swamps, and dense mesquite bosques (woodlands) (Davis, 1993). These wetlands and riparian areas have been impacted extensively and severely in the last century. Only about 15% of the riparian areas which were present in the early 1800s still remain and the percentage is even lower when only Sonoran Desert riparian areas are considered (McNatt et al., 1980). Impacts result from ground water pumping as well as other causes such as arroyo cutting, livestock grazing, land clearing for agricultural and urban development, and hydrological modification of surface flows (Stromberg, 1994). It is frequently difficult to identify which factors are responsible for riparian damage or loss.

Gallery forests of Fremont cottonwood (*Populus fremontii*) and Goodding willow (*Salix gooddingii*) historically covered hundreds of kilometers along the floodplains of many of Arizona's rivers and similar low-elevation rivers in California, Utah, and northern Mexico (Stromberg, 1993c). Today these Sonoran riparian cottonwood-willow forests are among the most threatened forest types in the United States (Swift, 1984). Excessive ground water pumping is one of several causes for the decline of these forests.

Similarly, mesquite (*Prosopis velutina*) woodlands were the most abundant riparian type in the southwestern United States (Klopatek et al., 1979). In locations where ground water is less than 50 ft such as the alluvial floodplain aquifers which were historically common in Arizona, mesquite can grow to tall dense canopy forests called bosques. Deep root systems and symbiotic associations with nitrogen-fixing bacteria contribute to the high productivity of this species. In turn, bosques support diverse and abundant ecosystems including one of the highest densities of breeding birds of any southwestern habitat. Again, as a result of ground water decline and several other land uses such as those listed above, these bosques now are reduced to relatively small isolated remnants, virtually none of which remain in pristine condition. Attempts to restore degraded mesquite bosques have had limited success (Stromberg, 1993b).

Other ecosystem impacts which commonly occur with the loss of mesquite flowers and fruits include fewer insects and insectivores. Avian abundance and diversity decline with reduced canopy volume. The activity of nitrogen-fixing bacteria is decreased thereby reducing the soil nutrient pool (Stromberg et al., 1992). Furthermore, as has been observed in many other drainages, death of riparian vegetation results in increased flood flows and increased erosion and channel widening (Groeneveld and Griepentrog, 1985).

Another ramification of the extensive ground water depletion is widespread land subsidence which is manifested as generally lowered land elevation as well as sink holes and earth fissures. Subsidence has affected more than 3,000 mi^2 in southern Arizona alone (Schumann et al., 1986). Subsidence was detected initially in 1948 in the lower Santa Cruz basin and since then subsidence of up to 12.5 ft has been measured in many southern drainage basins.

In addition to the economic costs of impacts to man-made structures, subsidence and fissures can result in costly environmental impacts as well. Fissures transect natural drainage patterns and can capture large volumes of surface runoff which may deprive downstream alluvial aquifers of recharge vital to riparian communities. Accelerated erosion along fissures forms gullies which exacerbates the impact on natural drainage channels over time. Accelerated erosion also occurs in natural drainages along the periphery of subsiding basins where the gradient between the basin floor and the surrounding mountains is increased. In constrast, subsidence decreases the gradient of streams and rivers which traverse subsiding basins, thereby reducing surface water flow rates and increasing sediment deposition and flooding. The combination of these effects can have major impacts on the natural hydrology and ecology of an area. These effects are most pronounced in the Salt River and lower Santa Cruz River basins (Schumann et al., 1986).

Santa Cruz River Basin

The 13,790 mi^2 watershed of the Santa Cruz River is located in southern Arizona and northern Mexico. The Santa Cruz River rises in the mountains of southeastern Arizona and after a short loop south into Sonora, Mexico, it flows generally northwest. It is an intermittent desert drainage containing interrupted perennial and effluent dominated reaches and regions of subsurface flow. Perennial flow is absent except in short reaches. Primary drainage is to the Gila River near Phoenix in south central Arizona.

The floodplain of the Santa Cruz is alluviated deeply. These sands and gravels generally are unconsolidated and are major water bearing units. Some wells drawing from these deposits yield over 1,000 gpm (Stromberg, 1994). At the time of early settlement, this unconfined alluvial aquifer supported extensive riparian communities including many gallery forests. Numerous marshes and springs were present where structural features forced underflow to the surface and these areas also supported wetland ecosystems. A combination of factors primarily including ground water pumpage and arroyo cutting have eliminated or drastically reduced most of these wetland features (Hendrickson and Minckley, 1984).

The natural vegetation of the low floodplain of the Santa Cruz River is dominated by Fremont cottonwood (*Populus fremontii*) and Goodding willow (*Salix gooddingii*) and dense bosques (woodlands) of velvet mesquite (*Prosopis velutina*), netleaf hackberry (*Celtis reticulata*) and Mexican elder (*Sambucus mexicana*) on the river terraces. Other riparian vegetation associations include cienegas (marshes), sacaton grasslands, and shrublands of seepwillow (*Baccharis salicifolia*), rabbit brush (*Chrysothamnus nauseosus*), and burro brush (*Hymenoclea spp.*) (Stromberg, 1994).

The Santa Cruz basin has been inhabited and cultivated continuously since the seventeenth century which has resulted in extensive hydrological and ecological changes (Hendrickson and Minckley, 1984). Early irrigation required diversion of surface flows from the river. For the last few decades most of the water needs of the extensive irrigated croplands, the mining industry, and the rapidly growing population have been met by ground water (Stromberg, 1994). Total pumpage in this hydrologic basin has increased greatly and often has exceeded that of any other basin in southern Arizona by nearly an order of magnitude (Hendrickson and Minckley, 1984). Ground water levels have declined throughout the basin with the maximum decline of 460 ft measured in the lower Santa Cruz basin and 150 ft in the upper Santa Cruz basin (Schumann et al., 1986).

The following examples of the impacts in riparian ecosystems in the Santa Cruz basin serve to illustrate the effects of ground water decline. In general, the extent and severity of ecological impacts increases downstream in the drainage. In many cases, impacts are regional in extent and native riparian vegetation has been eliminated totally.

In the lower Santa Cruz basin, ground water is the only source of water for municipal, industrial, and agricultural use (Schumann et al., 1986). Water and land uses in the relatively recent past practically have elimated riparian vegetation from the lower reaches of the river (Stromberg, 1994).

In the upper Santa Cruz basin irrigation and mining consume the first and second largest quantities of ground water respectively. During the past several decades, ground water pumping by mines and pecan growers has caused massive ground water declines in Pima County. This has resulted in total elimination of riparian habitat from central portions of the river (Stromberg, 1994). Obligate phreatophytic species have been replaced by scrub species such as desert broom, burro weed and burro brush. Mesquite bosques and sacaton grasslands historically supported by subflows essentially are no longer present.

Ground water pumpage in the Avra Valley, a major tributary to the Santa Cruz, has been extensive and water tables have undergone major declines (White et al., 1966). Farther upstream, recent ground water withdrawals from the floodplain aquifer in Santa Cruz County have caused localized water table declines and reduced abundance of cottonwood-willow forests.

Ground water pumping from the floodplain aquifer for the growing populations of Nogales, Arizona (population 20,000) and Nogales, Sonora (population 250,000) is creating cones of depression which have caused low growth rate, low tree density and low canopy cover of Fremont cottonwoods and other riparian populations (Stromberg et al., 1993a). In areas where ground water depths are greater than about 25 ft, cottonwoods and willows have been lost. Effluent released into the Santa Cruz channel from the Nogales International Wastewater Treatment Plant is increasing recharge to the alluvial aquifer to the benefit of riparian vegetation.

In comparison, where ground water levels remain shallow, riparian communities are healthy. At a site near the Mexican border where a shallow bedrock layer serves to minimize ground water level deline (7 to 10 ft), populations of cottonwoods and willows are in relatively good ecological condition and survival of seedlings is high. Similar geological conditions exist farther downstream at the Guevavi Narrows and again riparian communities are able to thrive (Stromberg, 1994).

Tanque Verde Creek

Tanque Verde Creek is an ephemeral river in the Sonoran Desert near Tucson. It flows for 16 miles from its headwaters in the Rincon Mountains to its confluence with Pantano Wash in south central Arizona. In some areas, the alluvial floodplain aquifer supports large mesquite (*Prosopis velutina*) bosques. Increased ground water pumping in this area has had a severe impact on these ground water dependent riparian woodlands (Stromberg et al., 1992).

Regional ground water decline in this area already had resulted in sublethal stress to mesquite bosques in the early 1980s as measured by low stem water potential, reduced leaflet size, and canopy mortality of over 45% (Stromberg et al., 1992). Depth to ground water ranged from 1 to 46 ft in 1986. When the City of Tucson activated several new large capacity wells in

1988, ground water began declining at an unprecedented rate of 12 to 21 ft/year, reaching depths of up to 105 ft in 1990 (Stromberg et al., 1992). Water depths of this range are typically lethal to mesquite, particularly in coarse alluvium with low water retention capacity. Trees farther upstream in areas where ground water levels remained at about 10 to 16 ft were in good ecological condition with tall stature and no canopy dieback (Stromberg, 1994).

San Pedro River Basin

Roughly parallel to, and 40 to 70 miles to the east of, the Santa Cruz River, the San Pedro River flows northwest from Sonora, Mexico for about 150 miles to join the Gila River at Winkelman. The 16,635 km^2 drainage basin is similar to others in the Basin and Range province. Thick floodplain alluvium of gravel, sand, and silt overlays basin fill materials throughout the drainage. Irrigation and municipal wells in the valley obtain water from both the basin fill aquifer and the overlying alluvial floodplain aquifer (McGlothlin et al., 1988; Stromberg, 1994).

The San Pedro River is largely perennial in the upper portion of the basin and intermittent in most other reaches. Baseflow in the river and the water table beneath the riparian zone are maintained almost entirely by inflow from the regional basin fill aquifer. At times of low flow, the entire flow is diverted in lower reaches (Stromberg, 1994).

Irrigated agriculture began in the latter part of the nineteenth century and increased steadily until the late 1960s. Ground water pumpage roughly parallels growth in irrigated acreage (Hendrickson and Minckley, 1984).

As recently as a century ago, the San Pedro River was unincised and marshy along much of its length (Hendrickson and Minckley, 1984). Ground water withdrawal for agriculture, mining and municipal supplies, as well as dam construction, overgrazing and clearing of riparian vegetation for pasture drastically have altered the hydrology of this area (Richter and Richter, 1992). Surface flows have been reduced or eliminated in some areas. Ground water levels have declined and springs, wetlands, and cienegas have been reduced to isolated remnants, several of which are located in the headwaters of tributary valleys such as the Aravaipa and Babocomari. Cienega vegetation has been replaced widely by riparian scrub species (Stromberg, 1994).

The most severe water level declines in the upper San Pedro basin have occurred in wells near the expanding population and agricultural centers of Sierra Vista and Hauchuca City. Water levels in this area declined approximately 1.4 ft/year between 1966 and 1986 (Stromberg, 1994). Ground water pumping in this area also has reduced the baseflow in the river (McGlothlin et al., 1988). Riparian mesquite bosques along the river have experienced sublethal stress as a result of ground water decline (Stromberg, 1993b).

Portions of the upper San Pedro River in the far southeast corner of the state contain some of the healthiest remaining desert riparian ecosystems in the southwest United States. Included are cienega plant associations, mesquite bosques, and cottonwood-willow forests as well as the most extensive remaining sacaton grasslands in Arizona. Also indicative of the health of this ecosystem is the low abundance of the exotic saltcedar (Stromberg, 1994).

About 40 perennial miles of the river in this area and its associated riparian zone were acquired in 1986 by the Bureau of Land Management to be managed as the San Pedro Riparian National Conservation Area. The primary management objective is the protection of the remaining riparian habitats. Cattle grazing and sand and gravel mining are restricted and agricultural lands have been retired from farming.

Although ground water pumping is not allowed in the Riparian Conservation Area itself, there is concern that the cone of depression from increased ground water overdraft in the vicinity of nearby Sierra Vista may extend to the Riparian Conservation Area to the detriment of native vegetation (Richter and Richter, 1992). Also there is high potential for future development elsewhere within this portion of the basin (Stromberg, 1994). Ecological modelling predicts that ground water decline of only 3 ft would result in the loss of many marsh species including the Huachuca water umbel (*Lilaeopsis schaffneriana* var. *recurva*) which is a Federal Endangered Species Category 1 listing candidate and only recently has been rediscovered along the San Pedro River (Stromberg, 1994). In some areas in the Conservation Area, seasonal ground water fluxes of this magnitude already have eliminated obligate wetland species and threaten facultative wetland plants. Other impacts which have been noted in some areas are low survivorship of cottonwood and willow seedlings, increased establishment of saltcedar and riparian scrub species such as burro brush and rabbit brush, and sublethal stress in sacaton grasslands and mesquite bosques (Stromberg, 1994).

Gila River Basin

The Gila River is the major drainage of southern Arizona. The basin extends eastward into the mountains of New Mexico, crosses the full width of the state and joins the Colorado at the western state border. Topographically the basin is typical of those in the Basin and Range physiographic province. It is a comparatively flat, wide, sediment filled valley between narrow rugged mountain ranges. Basin fill materials and terrace and floodplain alluvium have been significant ground water bearing units in the past (Culler et al., 1970).

Prior to the twentieth century, there were extensive marshes, swamps, and floodplains along much of the river. Dominant vegetation included cattail (*Typha domingensis*), bulrush (*Scirpus olneyi*), giant reed (*Arundo donax*), commonreed (*Phragmites communis*), arrowweed (*Pluchea sericea*), and many cottonwood and willow trees. The dense vegetation of these well-developed riparian communities often reached 10 to 15 ft in height and supported large and diverse wildlife populations. The river gradient was shallow and the floodplain was so level that marshy lagoons formed in places along the main channel (Rea, 1983).

By the end of the nineteenth century the perennial flow of surface water was reduced drastically and only in a few locations did surface flow continue until the 1950s. Deprivation of surface water recharge coupled with channel incision and ground water exploitation caused the floodplain water table to decline. As a result, the entire riparian community of willows and cottonwoods was eliminated and replaced in many areas by exotic saltcedars (*Tamarix spp.*) (Rea, 1983).

One locality in this drainage provides an example of the extent of ecological impacts which have resulted from the major hydrological alterations which have occurred in this drainage. As late as 1940 an extensive bosque known as the New York Thicket existed at the confluence of the Santa Cruz and Gila Rivers and three major washes (Vekol, Green and Santa Rosa). The bosque was up to 6 miles wide in areas with mesquite and screwbean mesquite (*Prosopis pubescens*) reaching heights up to 40 ft. By the late 1970s ground water pumping had caused the water table to decline to about 100 ft below the land surface resulting in the death of 90% of the mesquite (Rea, 1983). Although mesquite have deep roots and tolerate moderate water stress, lowering the ground water level below about 50 ft results in death of riparian mesquite trees or in conversion of mesquite from a dense tree community to a sparse shrub community (Stromberg, 1994).

Regional habitat loss such as that described above has had a major impact on wildlife in this area. Twenty-nine species of birds have been completely extirpated from the middle Gila and lower Santa Cruz Rivers and several other avian species have declined noticeably in population size because of habitat deterioration. Loss of nesting sites and food sources are major factors affecting species numbers (Rea, 1983).

Casa Grande National Monument

Casa Grande National Monument is situated 1.5 miles south of the Gila River and approximately 50 miles west of its confluence with the Salt River in south central Arizona. The 480 acre site is located in the floodplain of the Gila in Pinal County. Designated a national monument in 1918, it has had restricted access to people and livestock for over 70 years (Judd et al., 1971).

Ground water withdrawal for nearby agricultural development began in the early twentieth century and increased in the 1940s, causing the water table to decline from about 6 ft to about 43 ft (Stromberg, 1993b). An extensive bosque of large mesquite trees which utilized alluvial ground water survived during this initial period of decline. However, all of the trees died when pumping increased and the water table dropped about 3 ft per year to depths of 40 to 150 ft below the land surface (Judd et al., 1971). Continued increases in pumping in the latter half of this century had lowered the water table to as much as 650 ft as of 1970 and the site now is dominated by upland desert shrubs (Stromberg, 1994). The area is littered with large deformed stumps of dead mesquite trees (Judd et al., 1971).

Verde River Basin

The Verde River watershed lies in the Central Mountains physiographic province in central Arizona and drains 17,218 km^2. The river rises in the mountains to the west of Flagstaff and flows south to join the Salt River east of Phoenix. The watershed is semiarid and has an average annual rainfall of 30 cm (Stromberg, 1993a).

The floodplain of the lower Verde River contains thick deposits of alluvial silt, sand, and gravel that support stands of mesquite (*Prosopis juliflora*), interspersed with arrow-weed (*Pluchea sericea*), seepwillow (*Baccharis glutinosa*), and saltcedar (*Tamarix pentandra*). Fremont cottonwoods (*Populus fremontii*) and Goodding willow (*Salix gooddingii*) are common in the floodplain and occur in stands along the existing channel or along sections of old river channels (McNatt et al., 1980).

Where it is healthy, this riparian habitat supports a large and diverse fauna including big game (mule deer and javelina), waterfowl and wading birds, and small mammals including beaver, muskrat, and rabbits. Higher than average densities of coyotes, bobcats, skunks, and raccoons utilize this area. Over 160 species of birds are known to frequent this riparian habitat including two endangered species, the bald eagle and the Yuma clapper rail. A portion of the Verde River riparian area has been identified as having the highest bird population density in North America (McNatt et al., 1980).

The riparian ecosystems in the Verde River floodplain are experiencing considerable impacts due to water table decline. In central Arizona, ground water pumping for agriculture reduces water available to the Verde River riparian zone and its tributaries (Stromberg, 1994). Pumpage from the Big Chino Valley aquifer also could pose a threat to the upper Verde River riparian ecosystems (Stromberg, 1994).

In the lower Verde drainage the riparian community is "on the verge of collapse" as a result of a combination of natural and anthropogenic factors (McNatt et al., 1980). Prior to 1977 less than 4% of the cottonwood trees were dead along the Fort McDowell reach of the lower Verde. Since 1977, 46 to 84% have died. In addition, many of the remaining trees are approaching maturity and very few seedlings are regenerating successfully in the floodplain.

The cause of this mortality is a combination of hydrological factors. Limited water releases from Bartlett Dam, located upstream of this reach, have deprived the alluvial aquifer of recharge needed to maintain the floodplain water table. Further, natural floods which assist in cottonwood regeneration have been eliminated. Lastly, as of 1983, the City of Phoenix operated an infiltration gallery and 14 wells in the area of greatest mortality. These well fields withdraw 20,000 acre-ft of alluvial ground water per year for municipal use and are capable of lowering the water table over 10 ft. In 1977, the year of greatest cottonwood loss, drought conditions resulted in almost no releases from Bartlett Dam and considerable water table decline.

In comparison, Sycamore Creek, a nearby tributary to the Verde, is not controlled or pumped but did experience similar drought conditions in 1977. Riparian vegetation including cottonwoods in this drainage does not exhibit increased mortality or impaired seedling regeneration (McNatt et al., 1980).

Loss of cottonwoods is very detrimental to populations of nesting birds in this area. Reduction of cottonwood densities from 46 trees/acre to 10 trees/acre resulted in over a 50% reduction in the number of nesting bird pairs per 100 acres (McNatt et al., 1980). These data are derived from a study of intentional phreatophyte removal for water conservation but are a reasonable estimate of avian impacts from cottonwood mortality due to water level decline as well.

Salt River Basin

The Salt River drainage is a major tributary to the Gila and passes through the growing metropolitan area of Phoenix. Ground water pumping in the basin has increased steadily over the past 50 years. About two-thirds of the total ground water withdrawal in Arizona occurred in the combined areas of the Salt and lower Santa Cruz basins (Schumann et al., 1986). Ground water level decline has exceeded 300 ft in many parts of the Phoenix, Tempe, Mesa and Scottsdale areas. Subsidence of 3 to 5 ft has been measured in an area of over 500 mi^2. Fissures resulting from this subsidence capture surface water flow in some locations (Schumann et al., 1986), creating the potential for detrimental ecological impacts associated with surface dewatering.

From the time of earliest record of European explorers until the 1920s, the Salt River was a perennial stream lined with cottonwoods and willows. Large sections of the channel consisted of sand bars which were exposed at low water flow and were colonized by seepwillow and arrowweed. By the 1950s the river was a conduit only for flood flow as upstream irrigation dams impounded all of the normal discharge. Native vegetation was eliminated and many miles of impenetrable thickets of exotic saltcedar (*Tamarix chinensis*) overgrew the dry channel banks. The saltcedar was sustained by a sufficiently shallow water table of approximately 23 ft (Graf, 1982). Without river recharge, intensified ground water pumping by Tempe, Scotttsdale and Mesa in south central Arizona caused ground water levels to decline to over 220 ft in the 1960s. This resulted in the elimination of the saltcedar thickets. Despite ground water level rises of more than 115 ft after recent floods, the ground water remains too deep and fluctuates too erratically to sustain riparian vegetation except for a few ribbons of tamarisk growth supported by irrigation return flows and sewage effluent in some locations (Graf, 1982).

CALIFORNIA

Introduction

California consistently leads all states in volume of surface and ground water withdrawals. The state has retained this position for 40 years primarily because of the large volume used by irrigated agriculture (U.S. Geological Survey, 1990). During the past 100 years, the population and the associated industrial and agricultural demand increasingly have gravitated toward the more arid areas in the southern portion of the state. Massive projects have been undertaken to export surface and ground water from areas of relative abundance to areas were it is needed. However, available water supplies are insufficient to meet current needs without substantial depletion of ground water from storage. Furthermore, population projections predict an average annual increase of more than 330,000 people for the remainder of this century (U.S. Geological Survey, 1990). Periodic drought further exacerbates this water shortfall.

Ground water overdraft is an increasingly critical problem in many areas of the state. Statewide, ground water pumping exceeds recharge by an average of 2.0 million acre-ft/year. Eleven basins in California have been identified by the Department of Water Resources as being subject to critical conditions of overdraft, based on problems of salt water intrusion, deterioration in quality, land subsidence, and prohibitive pumping costs (Fort et al., 1993).

California has a wide range of water rights laws. Ground water regulation is undertaken primarily at the local level and overdraft generally is permitted unless curtailed through adjudication of a basin or administration by a local management entity (Fort et al., 1993). Prevention or minimization of overdraft is difficult under this system.

Owens Valley

Owens Valley is a long narrow closed basin located in east-central California. The 3,300 mi^2 valley is bounded longitudinally by the Sierra Nevada on the west and the White and Inyo Mountains on the east. One major river, the Owens River, flows south through the valley. Numerous tributaries drain the east face of the Sierra Nevada and have formed extensive alluvial fans along the west side of the valley (Hollet et al., 1991). Historically, springs and wetlands were found throughout the valley (Rogers et al., 1987).

The valley is filled with unconsolidated to moderately consolidated sedimentary deposits and intercalated volcanic flows and ash. Nearly all the recoverable ground water in the valley is found in these valley-fill materials (Rogers et al., 1987). An unconfined aquifer is present throughout the valley. Depth to water ranges from the land surface to more than 15 ft below the surface of the valley (Sorenson et al., 1989). The saturated thickness of this unit ranges from 30 to 100 ft. An underlying confined water bearing unit also is present throughout most of the valley. The degree of confinement is negligible in many areas as the clay beds of the intermediate confining layer are discontinuous. Virtually all of the ground water in the Owens Valley aquifer system is derived from precipitation that falls in the Sierra Nevada and infiltrates through the alluvial fans (Hollet et al., 1991).

As a result of the rain shadow effect caused by the Sierra Nevada, the climate in the Owens Valley is semiarid to arid. Most of the land in the valley is covered by native vegetation. The communities which occupy the greatest land area are 1) shallow ground water alkaline meadow, 2) shallow ground water alkaline scrub, 3) dryland alkaline scrub, and 4) dryland nonalkaline scrub (Sorenson et al., 1991). The three shrubs Nevada saltbush (*Atriplex torreyi*), greasewood (*Sarcobatus vermiculatus*), and rabbitbrush (*Chrysothamnus nauseosus* ssp. *viridulus*) in combination with two grass species saltgrass (*Distichlis spicata* ssp. *stricta*) and alkali sacaton (*Sporobolus airoides*) comprise more than 90% of the vegetation growing on shallow ground water zones of the Owens Valley floor (Groeneveld, 1989). Because of the availability of shallow ground water, the valley floor supports about 73,000 acres of phreatophytic vegetation (Dileanis and Groeneveld, 1989).

In the early 1900s the City of Los Angeles recognized the value of the relatively abundant surface and ground water supplies in the Owens Valley and acquired much of the land. A 233 mile aqueduct was completed in 1913 to divert water from the Owens River and modest quantities of ground water (generally less than 10,000 acre-ft/year). Prior to this diversion the Owens River flowed into the 100 mi^2 Owens Lake. Evaporation now exceeds inflow and, except in very wet years, the lake is dry (Hollet et al., 1991).

In 1970 a second aqueduct was completed which increased the average capacity for exporting water by 50% (Rogers et al., 1987). The majority of the additional export has been ground water. Ground water export accounts for over 50% of the discharge from the valley's aquifer system (Hollet et al., 1991) and evapotranspiration by phreatophytic vegetation accounts for the majority of the remainder (Duell, 1990).

Extensive export of surface and ground water from this arid region has resulted in widespread impacts to the shallow ground water vegetation (Rogers et al., 1987). In the early 1970s, phreatophytic plants covered about the same acreage and conditions were similar to those observed between 1912 and 1921. In 1981, a loss of 20 to 100% of the plant cover on about 26,000 acres was noted. This reduction was postulated to be a response to the increased pumpage of ground water and changes in surface water use. Considerable public concern was expressed regarding these environmental impacts and the related loss of recreational activities and wildlife habitats (Hollet et al., 1991).

Historically, springs between the communities of Big Pine and Independence in central Owens Valley discharged the largest quantities of water. Included are Fish, Big Seeley, Little Seeley, Hines, Little Black Rock and Big Black Rock Springs. A direct and immediate effect was measured in the quantity of spring flow when nearby deep wells were pumped for export. Springs ceased to flow with continued pumping and flowed again when pumping stopped or was minimal (Rogers et al., 1987). As this occurred, aquatic and riparian habitat was lost. Effects were particularly severe on the four native fish species in the Owens River system. Two species, the Owens pupfish (*Cyprinodon radiosus*) and the Owens chub (*Gila bicolor snyderi*), are listed as endangered and one, the Owens dace (*Rinichthys osculus*), is threatened.

Fish Slough is a remnant of a once widespread shallow aquatic/riparian wetland in central Owens Valley. It supports a variety of rare plant species and the endangered Owens pupfish (Pister and Kerbavaz, 1984). Three springs provide the flow in this slough. Declining ground water levels have reduced spring flow since 1971 and resulted in a reduction of riparian wetland acreage. The area currently is designated as the Owens Valley Native Fish Sanctuary which protects the refuge under an interagency management plan. However, further agreements to avoid additional ground water drawdown are needed (Pister and Kerbavaz, 1984).

Little Black Rock Spring also is located in central Owens Valley about 9 miles north of Independence and is used to support a local fish hatchery. In 1971, when the discharge from the spring began declining, a nearby well was pumped to replenish the water supply for the hatchery. Soon after pumping began, the spring ceased to flow. Additional surface water was used to meet the needs of hatchery (Perkins et al., 1984). Not only was the attempt to mitigate the loss of spring flow unsuccessful in terms of supplying adequate volume to sustain phreatophytic vegetation, the surface water was lower in alkalinity, salinity and nutrients. The result was a significant loss in marsh area as well as a change in species composition. The area once inhabited by marsh vegetation has been invaded by more drought tolerant perennials (Perkins et al., 1984).

Fish Springs Lake and the Springfield are two other wetland environments which have undergone similar changes as a result of ground water pumping. The lake is now ephemeral and artesian flow at the springs has ceased. Marsh vegetation has been lost entirely from these areas and plant diversity ultimately has been reduced to include only those annuals which can survive on infrequent precipitation.

As part of ongoing litigation between the City of Los Angeles and the local Inyo County government, a ground water monitoring program has been designed to curtail pumping when potential ecological impacts are predicted. Provisions for well shutdown have been included as the basis for a permanent agreement for ground water management to preserve the existing vegetation cover (Groeneveld, 1989). It is essential to prevent further vegetation loss because attempts at revegetation have been unsuccessful. Poor soil aeration limits the invasion of xeric shrub species from the nearby alluvial fans (Groeneveld, 1989).

Carmel River Valley

The Carmel River drains an area of 255 mi^2 in the northern Santa Lucia Mountains of the central California coast range. The upper 21 miles flow through steep canyons with little alluvium and the lower 15 miles flow through an alluvial valley known as the Carmel Valley. The alluvial fill is typically 15 to 30 m thick and consists of sand and gravel with some silt and clay interbeds. Stream flow in the Carmel River is in response to precipitation with high flows during the rainy season from November to April. The river stage declines in late spring and summer. In its upper reaches the Carmel River is perennial but in the alluvial valley flow is intermittent, typically drying up in late summer (Kondolf and Curry, 1986).

The alluvial valley fill is a generally unconfined aquifer, although localized areas of confinement exist. Seasonal fluctuations of the water table result from recharge of the aquifer by winter stream flow and subsequent decline of the water table by drainage of bank storage and, more importantly, by ground water withdrawals primarily during the dry season (Kondolf et al., 1987).

Because of the low water retention capacity of the poorly developed and coarse textured floodplain soils, plants in the riparian zone are either xeric or phreatophytic in habit due to the long summer dry period. In undisturbed locations, the mature riparian forest is composed of approximately 60% red willow (*Salix laevigata*), 30% black cottonwood (*Populus trichocarpa*), and 10% California sycamore (*Platanus racemosa*) and white alder (*Alnus rhombifolia*) combined (Groeneveld and Griepentrog, 1985).

The upper watershed is settled sparsely. Extensive commercial and residential development has occurred in the last three decades in the lower Carmel Valley, especially near the river mouth on the Monterey Peninsula. Prior to the 1960s, the Carmel River supplied most of the water for the peninsula. Because little surface water storage capacity is available, the increasing demand for municipal water supply has been met by ground water withdrawn from the alluvial aquifer. Production from the aquifer reached a relative peak in 1976 and then decreased in 1977 because the aquifer was depleted locally (Kondolf and Curry, 1986). However, throughout the 1980s, additional wells have been drilled in the Carmel Valley for increased export of ground water to the Monterey Peninsula downstream (Kondolf et al., 1987).

This extensive ground water withdrawal has altered the riparian ecosystems as well as the general hydrology and geomorphology of the Carmel River itself (Groeneveld and Griepentrog, 1985). Beginning in the late 1960s residents noticed that trees in the vicinity of the municipal wells were dying. Analysis of aerial photographs taken at intervals between 1956 and 1980 confirmed progressive loss of riparian forest cover over that period (Groeneveld and Griepentrog, 1985). Downstream of the reach which was impacted by ground water pumping phreatophytes remained healthy (Kondolf and Curry, 1986).

During two years of drought in 1976 and 1977, the alluvial aquifer received almost none of its usual annual recharge from river flow. Water table drawdown of over 10 m was measured along 4 km of the river in the vicinity of the well fields. Downstream of the pumped reaches, drawdown was minimal. The low water retention capacity of the coarse alluvium resulted in a rapid decline of the water table. This prevented phreatophytes from extending their root systems to follow the declining water table even though poplars, of which the black cottonwood is a member, have been observed to achieve daily root growth rates of up to 5 cm (Groeneveld and Griepentrog, 1985). Coupled with negligible summer precipitation, the riparian vegetation was eliminated rapidly.

Pumping of the municipal wells was sufficient to have a major effect on several other aspects of the regional hydrology. Drawdown in the pumped reach reversed the hydraulic gradient in the upstream direction in this area. Stream flow became influent to the banks in the reach of major pumping which had previously been a gaining reach of the river. In fact by mid-August 1982, the Carmel River entirely dried up in the pumped area but re-emerged downstream of the pumped reach (Kondolf et al., 1987). The loss of bank storage to sustain the base flow in the summer months was extremely detrimental to the summer downstream migration of steelhead trout smolts (*Salmo gairdneri*) as well as the rest of the riverine aquatic life (Kondolf et al., 1987).

Channel geomorphology has also been impacted by the loss of the stabilizing effect of the roots of riparian vegetation. The channel of the Lower Carmel River had been essentially stable from 1939 to 1977. Since 1978 the reach in which the majority of the phreatophyte dieoff occurred has experienced extensive bank erosion. Aerial photographs depict the channel widening from 60 ft in 1976 to over 400 ft in 1982 (Groeneveld and Griepentrog, 1985). The flows that produced this erosion were not unusual events (two five year recurrence interval flows) but the impact on the river channel was equivalent to that of the 100 year recurrence interval event which occurred in 1911. Downstream reaches unaffected by pumping maintained healthy bank vegetation and experienced no major erosion (Kondolf and Curry, 1986). Recent bank erosion along the Carmel River has caused property losses in excess of $1.5 million. Further losses can be expected because the present channel is near the threshold of meandering and braided characteristics rendering it inherently unstable (Kondolf and Curry, 1986).

Lower Colorado River (Needles and Blythe)

Indirect documentation was found on the impact of anthropogenic lowering of the riparian water table in the vicinity of Needles and Blythe. These two communities are near the Arizona - California border on the lower Colorado River. The climate is extremely arid. The river supports a shallow alluvial aquifer with depths to ground water ranging from 2 to 4 m throughout the growing season (Busch et al., 1992). The natural riparian vegetation is phreatophytic forest species including Fremont cottonwood (*Populus fremontii*), Goodding willow (*Salix gooddingii*) and the Eurasian native saltcedar (*Tamarix ramosissima*). The first two species are obligate phreatophytes and as such are highly vulnerable to impact if ground water pumping severs their connection to their water supply. This has been observed in the lower Colorado floodplain. With the reduction or elimination of the mature canopy species, saltcedar can competitively exclude native species and dominate the plant community. Similarly, understory shrubs such as screwbean mesquite (*Prosopis pubescens*) and arroweed (*Tessaria sericea*) have become dominant (Busch et al., 1992).

Central Valley

The Central Valley of California occupies about 12% of the total land area of the state. In the past century, it has become one of the most hydrologically and ecologically altered regions in the country. Ground water pumping has played a major although not exclusive role in these changes.

Central Valley is a long alluvium-filled structural trough occupying approximately 20,000 mi^2 of relatively flat land lying between the Coast Ranges on the west and the Sierra Nevada to the east. The climate is arid to semiarid with precipitation decreasing to the south. The northern half of the basin is drained by the Sacramento River and the southern portion is the drainage basin of the San Joaquin River. The area surrounding the confluence of the two rivers is called the Delta. The most southern portion of the valley, the Tulare Basin, has no perennial surface outlet. However, there is considerable underflow of ground water from the Tulare Basin to the San Joaquin drainage basin (Katibah, 1984).

Lenses of gravel, sand, silt, and clay of predominantly fluvial origin fill the entire valley. Most lenses are not widespread with the exception of the Corcoran Clay Member which forms an extensive confining bed between the overlying semiconfined aquifer and the underlying confined water bearing zone. The degree of vertical leakage is highly variable (Bertoldi, 1992).

In 1850 the Central Valley contained an estimated 4 million acres of wetlands (Peters, 1989). Prior to the construction of over 100 dams on the two main rivers and their tributaries, seasonal flooding formed vast flood basins and large shallow seasonal lakes which supported marsh vegetation. Dense riparian forests of Fremont cottonwood, California sycamore, and willow and associated intermediate and undergrowth species utilized the riverine silt of the natural levees. Along the Sacramento River, the levees frequently prevented mountain streams from reaching the main river resulting in a network of distributaries ending in sinks of tule marshes. Because of the lack of surface drainage in the Tulare Basin, seasonal lakes with abundant marsh vegetation were common (Katibah, 1984). The Delta was an area of convoluted inlets and islands supporting wetland ecosystems (Conniff, 1993).

Because these wetlands occurred in an otherwise arid area, they long have been important wintering areas for Pacific Flyway waterfowl. About 60% of the ducks, geese, and swans of this flyway use the valley wetlands during the winter (Peters, 1989).

Beginning around 1850, fertile soil, flat land, and abundant surface water provided the incentive for the development of one of the nation's most productive agricultural areas. Today more than $15 billion worth of crops are produced annually on the approximately 7.3 million acres of irrigated agricultural land in the valley (Bertoldi, 1992).

To support this lucrative industry, massive flood control and water diversion projects have been constructed and hundreds of thousands of acres of wetlands have been drained in the past 100 years. Two large aqueduct projects were built in the middle of this century to convey water from the northern part of the basin to the San Joaquin Valley.

Ground water resources have been developed simultaneously with the peak of development occurring in the 1960s and 1970s. Over 100,000 irrigation wells have been constructed. Pumpage increased from 362,000 acre-ft in 1912 to about 15 million acre-ft in 1977 (Bertoldi, 1992). Ground water levels have been altered significantly throughout the valley. Most long-term declines have been less than 100 ft except in the southern part of the San Joaquin Valley were heads have declined from 100 to 400 ft (Bertoldi, 1992). In many areas horizontal hydraulic gradients have been reversed and downward gradients have been created as the deeper aquifer is frequently the most heavily pumped. As a result of increased pumping costs, ground water withdrawals have leveled off or declined since 1967 and additional water needs are being met with increased surface water delivery. The recovery of the potentiometric surface from 1967 to 1984 in the most heavily pumped areas averages approximately one half of the previous drawdown (Llamas et al., 1992).

Of the 4 million predevelopment acres of wetlands in the valley, less than 400,000 remain today. It is difficult to determine the role which ground water pumping has played in this 90% decline because other hydrologic modifications such as surface water impoundment for flood control and irrigation also have been extensive. Today the majority of the remaining wetlands in the Central Valley are managed for waterfowl habitat and sport hunting (Peters, 1989). Recent inventories of remaining riparian vegetation indicate that most of the acreage is in a disturbed or degraded condition (Katibah, 1984).

Ground water pumping in the Central Valley also has resulted in the largest volume of anthropogenically induced land subsidence in the world (Bertoldi, 1992). Subsidence has been most extreme in the heavily pumped San Joaquin Valley with about 5,200 mi^2 having subsided more than 1 ft and localized regions of 20 to 30 ft. The loss of 20 million acre-ft of aquifer storage is about half of all the manmade surface water storage capacity in the state (Conniff, 1993). Islands in the Delta area which were originally at or slightly above sea level are now 10 to 20 ft below sea level (Bertoldi, 1992), undoubtedly resulting in impacts to all levels of the wetland ecosystems.

FLORIDA

Introduction

Wetland vegetation throughout extensive portions of Florida has died or is in a state of premature decline due to excessive ground water withdrawals (Bacchus, 1994). Many of Florida's freshwater wetlands are associated with shallow unconfined aquifers perched above confined regional aquifers. Ground water withdrawal from shallow saturated zones can cause extensive impacts in these wetlands. In addition, where confinement is intermittent, pumping of underlying aquifers has resulted in increased downward recharge, thus draining wetland ecosystems of the water which sustains them. Prevalent fractures in the extensive karst regions in Florida promote this induced recharge (Bacchus, 1995).

Many land use activities have the potential to alter the hydrology of wetlands in Florida. Included are ditching for drainage for agriculture or other development, cattle grazing, silviculture, mining, dredging and filling operations, and other land uses. Occasionally it may be difficult to separate the impacts of these activities from the impacts of ground water withdrawal for consumptive uses. However, numerous instances of ecological impacts from ground water withdrawal are sufficiently well documented around the state for this activity to be considered a significant threat to wetlands in Florida. Furthermore, population growth in many areas of the state continues to increase the demand for ground water. Maximum pumping for irrigation of crops, lawns and golf courses often occurs during the summer, the season of greatest vulnerability for wetlands (Ormiston et al., 1994).

Dade County

Municipal well fields in Dade County in southern Florida are increasingly susceptible to contamination from salt water intrusion and urban land uses in the Miami metropolitan area. To minimize the risk of contamination, the Northwest Well Field was developed in 1983 in an inland well field protection zone. This 65 mi^2 site is comprised primarily of undeveloped wetlands and rock pits. The hydrologic effects of this well field are of major interest because of the increasing preference for siting municipal supply wells in such inland areas (Sonenshein and Hofstetter, 1990).

The Northwest Well Field is located in the Everglades, a large wetland area which covers most of southern Florida. The hydrology of the Everglades has been altered drastically throughout this century for flood protection and land development. Many canals and levees have been constructed.

The Northwest Well Field is operated by the Metro-Dade Water and Sewer Authority. The system consists of 15 supply wells with a total capacity of 165 mgd and an average production of 132 mgd for the period 1984 through 1987. Water is withdrawn from the Biscayne aquifer, which is an unconfined aquifer composed primarily of a very porous sandy limestone with interbedded sandstone (Sonenshein and Hofstetter, 1990).

Continuous water level data beginning in 1960 are available at five observation wells. Two additional observation wells were installed, one in 1970 and another in 1982. Monitoring data show that water levels in the center of the well field have declined 6 to 7 ft during both the wet and dry seasons since pumping began. Water levels in a 10 mi^2 wetland area surrounding the well field have been below the land surface 100% of the time since pumping began. Sonenshein and Hofstetter (1990) concluded that this dewatered area was no longer considered a wetland. In another 10 mi^2 wetland area surrounding this core area, water levels have been below the land surface as much as 99% of the time since pumping began. Water levels at four monitoring wells outside the cone of depression of the well field showed no effect from pumping. While no references describing the nature and extent of ecological changes in this area were found, impacts undoubtedly are extreme given the extensive alteration of the hydrology.

Jensen Beach Peninsula, Martin County

Jensen Beach Peninsula is a long narrow spit along the southeastern coast of Florida. The North Martin County well field is located on the peninsula in the vicinity of significant wetland areas. Average daily withdrawal is 1.65 mgd.

A long-term ground water monitoring network has been established primarily to monitor salt water intrusion. Data from inland locations show a gradual decline in water levels resulting from a variety of possible causes including increasing well field withdrawals, surface drainage modifications or below average precipitation over the monitoring period. Ecological investigations in the area have shown cause for concern that increased pumping may adversely affect wetland vegetation (Shupe and Gleason, 1989).

Loxahatchee River Basin, Palm Beach and Martin Counties

The Loxahatchee River Basin is an area of considerable wetlands near the southeast coast of Florida. Historically, water was retained in the wetlands throughout the basin during the wet season. During the dry season, this water provided fresh water discharge to the Northwest Fork Loxahatchee River (Birkitt and Gray, 1989). These ecosystems have undergone extensive hydrological alteration as a result of several factors, the individual effects of which are difficult to distinguish. Channelization and drainage for development and ground water pumping in municipal well fields have reduced water storage in the basin. This has resulted in excessive flows in the wet season and very low to non-existent flows in the dry season.

The reduced dry season flows have resulted in severe alteration of the natural hydroperiod of the basin wetlands. Water levels in surface water bodies have been lowered as well. Of particular concern is the fact that decreased discharge in the Northwest Fork Loxahatchee River has allowed salt water to intrude farther into the drainage, damaging wetland vegetation. Cypress trees increasingly are being replaced by mangroves in a significant portion of the river basin including the reach which has been designated a federal Wild and Scenic River and in Jonathan Dickinson State Park (Birkitt and Gray, 1989).

As of 1989, the Northern Palm Beach County Water Control District was developing a major Water Resources Plan to reallocate water in the basin in an attempt to restore a more natural hydrologic regime. Specific objectives were to enhance the quality of the wetlands, to restore historic hydroperiods and water flow patterns, and to increase ground water recharge to provide a sustainable long-term municipal water supply.

When fully implemented, the Water Resources Plan was designed to create 30,000 acre-ft of surface water storage capacity to store water during the wet season and redistribute it during the dry season. The creation of these reservoirs was expected to destroy 2,358 acres of wet prairie or marsh habitat and 330 acres of low pine flatwoods. However 4,855 acres of open water habitat and 650 acres of newly created wet prairie and freshwater marsh habitat were expected to replace formerly degraded wetland areas. In addition, 4,200 acres of wetlands were expected to be restored (Birkitt and Gray, 1989).

Pasco, Pinellas, and Hillsborough Counties:
Tampa - St. Petersburg Area

Wetlands such as marshes, wet prairies, pondcypress domes (*Taxodium ascendens*), and swamps are common in southwest Florida and typically comprise 20 to 30% of the landscape (Rochow, 1993). They serve as nesting and feeding sites for Florida sandhill cranes, bald eagles, wood storks (a federal endangered species), and an array of amphibians, as well as provide habitat for other wildlife (Bacchus, 1995).

Throughout most of southwest Florida ground water is the primary source of drinking water as well as water for agricultural and for industrial uses. To meet the needs of the rapidly growing Tampa - St. Petersburg area, ground water pumping has increased extensively in recent years (Rochow and Rhinesmith, 1991). At least 75% of the public water supply is derived from concentrated regional well fields (Southwest Florida Water Management District, 1996).

The Southwest Florida Water Management District has maintained an extensive program of hydrological and biological monitoring in regional well fields for approximately twenty years (Rochow, 1994). Observed impacts from pumping include lowering of lake levels, reduction in stream flow, and destruction of wetland habitat. In some areas along the coast, lowered ground water levels have caused water quality degradation as a result of saline intrusion (Southwest Florida Water Management District, 1996). Rochow and Rhinesmith (1991) report that detrimental impacts observed in wetlands include replacement of aquatic plant species by upland species, decreased abundance of wetland-dependent wildlife, increased wetland susceptibility to fire damage, increased soil subsidence, and excess wetland tree mortality.

Based on this monitoring, the District has found that water table drawdowns ranging from 0.5 to 3.0 ft can be expected within a distance of approximately one mile from most production wells (Rochow, 1993). The District also has determined that any ground water development which lowers the water table in the surficial aquifer by as little as 1 ft can adversely impact wetlands. Consequently, in 1989 the District enacted a rule requiring detailed environmental review for any water use permits where drawdown was predicted to exceed 1 ft (Rochow and Rhinesmith, 1991). Long-term site-specific ecological monitoring is required of permitees as the full impact of ground water decline may not become evident for one to two decades after pumping begins (Rochow, 1994).

Studies conducted at specific well fields under the jurisdiction of the Southwest Florida Water Management District provide examples of the wetland impacts which result from excessive ground water withdrawal (Southwest Florida Water Management District, 1996). The Starkey well field consists of 14 production wells located about 30 miles north of St. Petersburg in Pasco County. The well field boundaries encompass abut 8,200 acres of predominantly natural and undisturbed pine flatwoods, cypress domes, marshes, wet prairies, and sandhills (Rochow and Rhinesmith, 1991). Pumping began in the 1970s at a rate of 1 to 3 mgd and increased beginning in 1983 to an average of 13 mgd in 1989. At this rate of withdrawal, the water table was predicted to decline at least 1 ft in an area of about 4 mi^2 in the central part of the well field.

Beginning shortly after the increase in pumping in the mid-1980s, the following impacts were observed at several sites in the Starkey well field: 1) extensive invasion of upland weedy species including dog fennel and broomsedge, 2) destructive fires, 3) abnormally high tree fall, and 4) excessive soil subsidence/fissuring (Rochow, 1994). Subsidence results primarily from the oxidation of the highly organic soil. This contributes to the loss of tree species, particularly cypress, by reducing root support. Abnormal hydroperiods also render trees more susceptible to pathogens. Although present at nearby unaltered control wetlands, fish were absent and amphibians were absent or in very low abundance at sites associated with the well field. The limited food resources at these lower trophic levels was thought to curtail the utilization of these sites by wetland reptiles and wading birds (Rochow and Rhinesmith, 1991).

Impacts of pumping at the the Eldridge-Wilde well field also have been extensively studied. This well field is located about 26 miles north of St. Petersburg in Pinellas and Hillsborough Counties and consists of 3,500 acres of pine flatwoods, cypress domes, and marshes as well as improved pastures and citrus groves. Production began in 1956 and averaged about 16 mgd in 1965, after which it increased steadily to an average of 29 mgd since 1972. Water table decline of up to 3 ft is predicted for about 50% of the area of the well field. Vegetation changes indicative of severely altered hydroperiods were observed on aerial photographs beginning in the mid-1970s (Rochow and Rhinesmith, 1991). Cypress have been almost completely eliminated from some monitoring sites. Recent assessments estimate that 85% of the wetlands on well field land have been moderately to severely affected in terms of subsidence, loss of canopy species, and invasion of upland species (Rochow, 1994).

Similar impacts have been documented at the Cypress Creek well field in Pasco County. Pumping began in 1976 and reached an annual rate of 30 mgd which has been sustained since 1979. A water table decline of 3 ft has been modelled for about 60% of the site (about 6 mi^2) and the 1 ft drawdown contour encompasses about 12 mi^2. Biological monitoring since 1975 has documented minor to severe impacts to wetlands in this area. Although some hydrologic modifications undoubtedly have occurred as a result of agricultural and residential development in this area, detailed long-term monitoring has documented that some of the observed ecological impacts result from ground water pumping. Wetlands with a predicted water table drawdown of 1 ft or greater have hydroperiods about 50% shorter than control sites outside the area of water table drawdown. This coincided with 12 to 28% mortality of tree species such as pop ash and cypress within the 1 ft drawdown area as well as other impacts similar to those mentioned above at other well fields (Rochow, 1994).

Other nearby well field sites monitored by the Southwest Florida Water Management District and its permitees show similar results. At the Cross Bar well field the remains of 400 dead gopher tortoises were found at Big Fish Lake which was dry during 1991 in spite of above average local rainfall for that year. Extensive replacement of wetland plant species such as floating hearts and waterlily by drought tolerant species such as dog fennel and maidencane was also noted. Trends of wetland alteration beginning in the late 1970s at the Morris Bridge well field were found to have stabilized when pumpage was reduced by 40% from 1986 to 1993 (Rochow, 1994). Lastly, in addition to several tens of thousands of acres of wetlands which have been irreversibly altered in this area, ground water pumping has contributed to the failure of more than 1,000 private wells which have been repaired or redrilled at a cost of \$3.5 to \$4 million, has drained lakes and streams, and has increased the rate of sinkhole formation in the area (House Committee on Natural Resources, 1994).

Because these types of wetlands and hydrologic conditions are not confined to southwest Florida, but extend throughout the Southeastern Coastal Plain physiographic province, it is likely that wetland impacts such as those which have been documented carefully by the Southwest Florida Water Management District and its permitees are occurring elsewhere, either on a local or potentially regional scale (Bacchus, 1994; Bacchus, 1995). For example, depressional wetlands typical of southwest Florida occur throughout Florida, southern Georgia, North and South Carolina, Alabama, Mississippi and a portion of Louisiana. The range of pondcypress wetlands, which are extremely vulnerable to alteration of hydroperiod, is approximately coincident with the limits of the Floridan aquifer in Alabama, Georgia and South Carolina and continues throughout North Carolina, Mississippi and the southeastern portion of Louisiana (Bacchus, 1995).

IDAHO

Bruneau River, Owyhee County

Geothermal discharge at Hot Creek and 128 small flowing thermal springs and seeps along a 5.3 mile length of the Bruneau River in southwestern Idaho has decreased significantly over the last 25 years threatening the organisms which inhabit the springs and the outflow (Federal Register, 1993). Ground water in this area flows northward through volcanic rocks from areas of recharge along the Jarbidge and Owyhee Mountains and is discharged as spring flow or leaves the area as underflow. Prior to development, natural recharge and discharge from the regional geothermal aquifer underlying the 600 mi^2 Bruneau area were estimated to be approximately in balance at 22,800 acre-ft/year.

Ground water development began in the late 19th century and discharge to wells increased throughout this century, primarily to meet the growing demand from irrigated agriculture. Maximum discharge was reached in the early 1980s at 49,900 acre-ft resulting in annual deficit pumping of over 26,000 acre-ft. In large part due to the Conservation Reserve Program administered by the U.S. Soil Conservation Service, pumping has declined to the 1991 level of withdrawal of 34,700 acre-ft in spite of a prolonged drought throughout the late 1980s. Pumping has caused water levels in the volcanic portion of the geothermal aquifer to decline more than 30 ft in much of the Bruneau area (Federal Register, 1993).

As a result, geothermal spring discharge also has declined. For example, in 1965 spring discharge at the Indian Bathtub spring was 2,400 gpm and declined to about 130 to 162 gpm during the summer of 1978 (Young et al., 1979). By 1985 the spring had ceased to flow during the irrigation season. A similar trend of reduction of discharge was noted at other springs in the area (Federal Register, 1993).

The Bruneau Hot Springsnail (*Pyrgulopsis bruneauensis*) is found only in the springflow of Hot Creek and the springs and seeps of this area. Most of the springs are small and highly vulnerable to impacts from water level decline. As a result of habitat threats from declining spring flow, the springsnail was determined by the U.S. Fish and Wildlife Service to meet the criteria of an endangered species in 1993. Population estimates made in 1982 and 1992 show a 50% reduction in the number of individuals in many springs. In some local areas such as the Indian Bathtub spring the species has been totally eliminated as a result of spring flow decline and sedimentation. Common aquatic associates of the springsnail which are also at risk include three mollusks, the creeping water bug (*Ambrysus mormon minor*) (also endemic to the Hot Creek thermal spring complex), and the skiff beetle (Federal Register, 1993).

If water levels in the geothermal aquifer continue to decline, the U.S. Fish and Wildlife Service anticipates that all remaining thermal springs containing Bruneau Hot Springsnails eventually could cease to flow, causing the extinction of the endemic species (Federal Register, 1993).

INDIANA

Indiana Dunes National Lakeshore

The Indiana Dunes National Lakeshore is a federally protected natural area managed by the National Park Service. It is a 12 mile segment of lakeshore and dunes located on Lake Michigan in northwest Indiana. In the middle 1970s the Bailly Nuclear Generator was constructed on a 7 acre site about 800 ft west of the Lakeshore boundary. During construction, ground water levels under the nuclear site were drawn down 20 to 30 ft for about 18 months. With this drawdown, the westernmost ponds in the Lakeshore were predicted to dry up almost completely. Less than 0.5 ft of water was expected to remain in about 1% of the pond under average conditions. Sustained dewatering would obviously be damaging to the aquatic and surrounding riparian ecosystems (Marie, 1976).

NEVADA

Introduction

Nevada is one of the nation's fastest growing states. Its population increased 50% from 1980 to 1990. Nevada is also the most arid state in the nation (U.S. Geological Survey, 1995a). Because surface water resources are scarce to nonexistent in many areas and most often fully appropriated, new development frequently relies on ground water.

The combination of these factors creates an ongoing need to balance the allocation of scarce water resources between humans and aquatic and wetland ecosystems. These isolated habitats are typically critical refuges for the plant and animal species which are entirely dependent upon them.

Ash Meadows and Devils Hole, Nye County

Ash Meadows is a unique and biologically rich hydric ecosystem in the Amargosa Desert in southwestern Nevada. Within the 162 km^2 area, over 30 springs and seeps discharge a total of 17,000 to 20,000 acre-ft of water annually, sustaining an oasis in the otherwise arid region. Many of the springs are large with headwater pools of 6 to 10 m in diameter. The area is a discharge point for several thousand square miles of a regional flow system developed in carbonate rocks (Westenburg, 1993).

Like much of the Great Basin, the Ash Meadows area was much wetter during the late Pleistocene, supporting Lake Ash Meadows as an ephemeral feature. As the climate of the post-pluvial period became drier, Ash Meadows developed as an isolated remnant environment. For this reason, the flora and fauna of Ash Meadows represent a unique and threatened biota, including two extinct and over 25 endemic species. The eight plants, two insects, ten mollusks, five fishes and one mammal species constitute the highest amount of biological endemism of any area in the United States (Williams, 1984). As of 1984, eight species were candidates for listing as federal endangered species and two others officially had been designated as endangered species, the Devils Hole pupfish (*Cyprinodon diabolis*) and the Amargosa pupfish (*Cyprinodon nevadensis pectoralis*) (Williams, 1984).

Dense to moderate growths of mesquite and saltbush occur at the springs and along the outlet channels. Extensive saltgrass marshes cover the poorly drained flatlands which receive the spring discharge (Dudley and Larson, 1976). The large spring discharge supports waterfowl and other migratory birds.

Several factors have contributed to extensive alteration of this ecosystem. Carson Slough, the major discharge channel for the region was drained for mining peat and clay from 1910 to 1930. During the mid-1940s several exotic predators were introduced to the detriment of the native fish species. Most recently, further alteration of the natural hydrology has occurred. Prior to 1960, the small number of local residents used natural spring flow for irrigation downslope. Beginning in 1961, development of the ground water resource increased steadily and about 40 wells had been drilled as of 1976. In 1967, a large ranching corporation began acquiring extensive acreage and water rights to develop about 12,000 irrigated acres in crops for cattle feed (Dudley and Larson, 1976). Pumping for the ranching operation began in May 1969.

Beginning in 1969, spring discharge throughout the area began to decline and reached a record low in 1972. Annual overdraft in 1971 was estimated to be 1,500 acre-ft. Discharge was reduced by as much as 50% in some springs (Dudley and Larson, 1976).

Of particular concern was the 2.5 ft decline in water level in Devils Hole, a warm pool in a collapsed depression in the limestone hills of a 40 acre disjunct part of Death Valley National Monument. This pool is the sole known natural habitat of the Devils Hole pupfish (*Cyprinodon diabolis*), a federally designated endangered species (Williams, 1984). The pupfish feeds and reproduces on a slightly submerged rock ledge which is highly susceptible to exposure under conditions of ground water decline. In light of declining spring discharge, in 1976 the United States Supreme Court established a minimum water level to ensure the survival of the pupfish. Pumping rates were reduced and eventually all pumping for irrigation ceased in 1982. Water levels recovered quickly (Westenburg, 1993). In 1984, the Ash Meadows National Wildlife Refuge was created to protect remaining endemic species (Graham, 1992).

Subsequent to the termination of pumping for irrigation for the ranching operation, a large tract was sold to a developer. In the mid-1980s plans were completed for development of over 33,000 homes in the area, requiring additional ground water withdrawal (Williams, 1984). It is clear that the feasibility of this development must be assessed carefully to avoid future impacts on the spring ecosystems.

Las Vegas Valley and Las Vegas Wash, Clark County

Increased ground water pumping to meet the demand of the burgeoning population of the Las Vegas valley as well as for crop and landscape irrigation needs has contributed to a complex alteration of the hydrology of this region in the last fifty years. This frequently has been to the detriment of the wetland ecosystems for which this city in the Mojave Desert was named. Ironically, Las Vegas means "the meadows" (Graham, 1992).

Water use in Las Vegas is about 350 gallons per day per person, about twice the national average and almost three times that of other arid cities such as Los Angeles and Tucson (Egan, 1994). While undoubtedly inflated by the large tourist population, water consumption is still high in this city which receives only 4 inches of precipitation per year. The majority of the water usage is for irrigation of urban landscapes (Katzer and Brothers, 1988).

The demand for water in Las Vegas Valley has increased from that obtained from a few domestic wells in the early part of the century to an annual use of more than 200,000 acre-ft. About one third of the demand is supplied by ground water and the rest is delivered from Lake Mead in the Lower Colorado River system (Burbey, 1993). Fine to coarse grained alluvial fan and floodplain deposits comprise the principal aquifers within the valley. In many areas the water table is within 1 to 10 ft below the land surface (Emme and Prudic, 1991). Along principal drainage courses such as Las Vegas Wash, hydrophytic vegetation such as reeds and cattails abound. Phreatophytic species such as mesquite, saltgrass, and saltcedar are also abundant in these areas.

Pumping of ground water has led to water level decline of up to 300 ft in parts of the valley (Katzer and Brothers, 1988). Artesian springs which were scattered throughout the valley around the turn of the century have ceased flowing and their associated marsh ecosystems have been lost. In addition to wetland impacts, induced recharge from the overlying shallow aquifer, which is high in natural and anthropogenically introduced solutes, threatens the quality of the drinking water supply. Dewatering of fine-grained sediments has caused subsidence over 400 mi^2 in the valley (Katzer and Brothers, 1988).

When used to irrigate lawns, golf courses and crops, ground water withdrawn from the deeper aquifer typically recharges the shallow aquifer in the central part of the valley. This water ultimately discharges into ephemeral channels, primarily Las Vegas Wash. Excess irrigation recharge and treated sewage effluent have combined to change the previously ephemeral wash into a perennial stream. As a result, the wash has experienced considerable erosion and headcutting in recent years. The channel level has been lowered as much as 15 ft, isolating adjacent wetlands dependent on bank storage. As a result of headcutting, hydrophyte-dominated vegetation has been eliminated in lower reaches and has re-established in areas farther upstream where ground water levels are sufficiently shallow. Continued headcutting will ultimately threaten these riparian areas as well (Burbey, 1993).

Other impacts from the loss of wetland vegetation along the major washes include diminished habitat for bird species such as phainopeplas, cactus wrens and crissal thrashers (Graham, 1992). These species depended primarily on the dense mesquite stands the washes previously supported. In addition, the endemic fish species, the Las Vegas dace (*Rhinichthys deaconi*), became extinct when a creek in what is now downtown Las Vegas was dewatered by declining ground water levels (Graham, 1992).

As the population of Las Vegas continues to increase at a rate of almost 1,000 new residents each week, additional sources of water are being sought. In addition to pursuing increased allocation of surface water from the Lower Colorado and the Virgin Rivers, Las Vegas is considering a vast new ground water project. Utilizing 1,200 miles of pipelines to convey ground water pumped from more than 20,000 mi^2 in central Nevada, the $2 to $5 billion project would be one of the biggest and most expensive water projects undertaken in the West (Egan, 1994). The environmental consequences of this pumping, including potential impacts on ground water flow and springs in 4 counties, are being evaluated.

Humboldt River Basin

Within the Humboldt River Basin in north central Nevada is a large gold deposit called the Carlin Trend. Advances in ore extraction technologies have allowed the profitable development of over 15 mines in this area. These mines have or are proposing to dewater local aquifers to enable ore extraction from deep pits. Water table suppression is desired at depths as great as 1,700 ft and pumping rates necessary to accomplish this range from a few hundred to over 70,000 gpm. This magnitude of ground water pumping is unprecedented worldwide (Miller, 1993; Manning, 1994).

The cumulative impacts of all the projected ground water pumping operations on the Humboldt River Basin have never been evaluated thoroughly (U.S. Geological Survey, 1995b). Ecological impacts are expected during the active dewatering phase as well as after dewatering ceases and ground water levels recover.

During the mining operations, many companies are disposing of pumped ground water by discharging it directly to the Humboldt River and its tributaries. This will provide additional flow temporarily for irrigators and riparian habitat along the river. Some of the pumped ground water is reinjected or applied to the land and eventually reaches the Humboldt River as well. As a result, wetlands and springs have been created which are dependent on this temporary water source. If not actively sustained after the mining phase of these operations is completed, these habitats will be lost.

The major impact is expected after pumping has stopped and the affected aquifers re-equilibrate with respect to the natural regional hydrology (Meyers, 1994). When pumping is discontinued, the cones of depression around the pits and the pits themselves will fill by diverting ground water, by reducing surface water discharge, or by reversing hydraulic gradients and drawing water from the Humboldt system. It is estimated that in excess of 3,000,000 acre-ft will be drawn into the cones of depression and pit lakes from both ground and surface water sources. (The relative contribution from each source is unknown (Miller, 1993; Miller, personal communication)). In comparison, the annual flow of the Humboldt River at Winnemucca is only around 150,000 acre-ft. Predictive models suggest that pit refilling could eliminate most surface baseflow from two Humboldt River tributaries, Maggie and Boulder Creeks, and reduce the flow in the Humboldt River by 6 to 66% (Meyers, 1994). Additional mines and proposed expansions of several of the existing mines are not included in this estimate and would exacerbate further these impacts.

Detailed descriptions of the anticipated ecological impacts of the post-mining phase have not been provided in the Environmental Impact Statements for these projects. It is evident that many wetland and riparian habitats in this arid basin would be impacted to some extent. Rough estimates for just two of the pits project the loss of about 2,000 acres of springs, seeps, and wetlands. Several creeks in the area have been identified preliminarily by the U.S. Fish and Wildlife Service as potential recovery sites for the federally listed threatened Lahontan cutthroat trout.

Honey Lake Valley, Washoe County

Developers in the Reno area in west central Nevada have sought to utilize ground water to meet increased water demand. In 1991, Washoe County was granted rights to pump 13,000 acre-ft of ground water from the Honey Lake valley and import it to the Lemmon and Spanish Springs valleys via a 39 mile pipeline.

It was anticipated that this pumping would eliminate or degrade 185 to 485 acres of springs, seeps, and wet meadows as the water table declined to 61 to 78 ft in the area of withdrawal (Bureau of Land Management, 1993b). Even with proposed mitigation measures such as pumping additional ground water to sustain wetlands, the impact in the draft Environmental Impact Statement was considered "significant and adverse". As of 1994, the project was on hold pending resolution of legal matters unrelated to water or wetland issues (Hill, personal communication).

OKLAHOMA

Beaver River, Texas County

The Ogallala Formation underlying most of the Oklahoma Panhandle is part of the High Plains regional aquifer system which extends 174,000 mi^2 from southern South Dakota to northwestern Texas. This aquifer (also known as the Ogallala aquifer) is primarily a water table aquifer deriving recharge from precipitation (Wahl and Wahl, 1988). The average annual precipitation in the Oklahoma Panhandle is about 17 inches, average lake evaporation is 62 inches, and average annual evapotranspiration is about 16 inches. Thus annual recharge to the aquifer in this region is low.

The primary land use in the Panhandle is agriculture, with the land about evenly divided between farming and ranching. The introduction of the center-pivot sprinkler system in the early 1960s resulted in a rapid increase in the use of ground water for irrigation. In 1963 there were about 450 large capacity wells in the Panhandle. The number had risen to 2,500 by 1984 (Wahl and Wahl, 1988).

Because the rate of withdrawal from the High Plains aquifer is much greater than the rate of recharge, widespread water level declines have occurred (U.S. Geological Survey, 1990). In western Oklahoma declines of 25 to 100 ft are common. This has resulted in a substantial reduction in discharge in the Beaver River which drains most of the Panhandle. The 10-year moving average discharge was relatively stable from 1950 to 1965 at about 25 to 30 cfs. By 1986, the 10-year moving average discharge had decreased to about 7 cfs. Prior to 1971, the river was generally perennial, ceasing to flow less than 15% of the year. By the mid-1980s the river was dry about 85% of the year. Changes in river discharge are not correlated with changes in precipitation or surface water diversions (Wahl and Wahl, 1988).

The long annual periods without surface discharge and the associated depletion of bank storage undoubtedly have been detrimental to riparian ecosystems in this semiarid area. Ground water overdraft resulting in reduced stream discharge and adverse impacts to riparian communities also has occurred in other states where ground water from the High Plains aquifer is utilized in excess of recharge (Wahl and Wahl, 1988).

SOUTH CAROLINA

Savannah River Site, Barnwell County

The Savannah River Site is a nuclear production facility operated by the U.S. Department of Energy (DOE). The 300 mi^2 site was purchased by DOE in 1951 and the P Reactor began operating in 1954. Throughout its operation, ground water has been withdrawn from 6 production wells within a 1 mile radius of the P Reactor. Although the primary source of cooling water for the reactor is the nearby Savannah River, some ground water has been used for nuclear production. Since 1985, ground water withdrawal has been reduced drastically and 4 of the 6 wells have been abandoned (Bacchus, 1994).

The Savannah River Site contains numerous seepage wetlands which are typical of the Southeastern Coastal Plain physiographic province. Shallow ground water which flows laterally in response to a small gradient is essential to sustain these wetlands. Highly permeable sandy soils underlain by lower permeability clays sustain this lateral flow.

The aquitard separating the surficial aquifer from the underlying confined systems is locally permeable and discontinuous in extent. Ground water pumping for the site increased downward leakage from the surficial aquifer through the calcareous semiconfining unit to recharge the confined system. As a result, the stage and duration of the hydroperiod of the wetlands was altered significantly (Bacchus, 1994).

Aerial photographs taken between 1943 and 1992 were analyzed to investigate changes in vegetation cover (Bacchus, 1994). Observed changes in vegetation are at least in part a result of these perturbations in the ground water hydrology (Bacchus, 1994). Forested areas in their natural state contain dense canopies of pondcypress (*Taxodium ascendens*) and pond pine (*Pinus serotina*). Vegetation changes included the loss of approximately 2,825 acres of forested wetlands coupled with an increase of approximately 2,183 acres of forested uplands and 141 acres of shrub wetlands including a predominance of fetterbush (*Lyonia lucida*). Only a small portion of the loss in forested wetlands can be attributed to conversion of wetlands along the perimeter to planted loblolly pine by the U.S. Forest Service after the site was purchased by DOE.

Ground reconnaissance revealed that the portion of the wetland complex closest to the ground water withdrawals exhibited standing dead and dying trees, canopy dieback of pondcypress, and tree pathogens. Under natural conditions, cypress are relatively free of disease and pests. However, cypress associated with excessive subsurface drainage are susceptible to internal fungal pathogens and bark and leaf beetles. In addition, encroachment of wetland tree species more tolerant of abnormal hydroperiods such as tulip poplar, sweet gum, wax myrtle, and American holly was observed suggesting that ground water levels had been lowered. Lastly, subsidence of surface soil of approximately 30 cm had occurred exposing cypress roots (Bacchus, 1994). Because cypress roots are adapted to anaerobic conditions, exposure is potentially lethal (Bacchus, 1995).

TEXAS

Harris (Houston) and Galveston Counties

Rapid population and industrial growth since World War II in the Houston - Galveston area have combined with agricultural demand to increase the need for additional water supplies. Prior to 1954 when Houston began augmenting its water supply with surface water, it was the largest city in the nation utilizing only ground water for public supply. Over 80% of the ground water demand in some of the outlying areas of this region is for rice irrigation (Neighbors, 1981).

As a result of large amounts of water having been pumped from the ground, water levels in the artesian aquifers have declined by as much as 200 ft in the Chicot aquifer and 325 ft in the Evangeline aquifer. Associated with these water level declines is extensive subsidence of the land surface. Subsidence was first noticed in this area in 1938. Between 1940 and 1952 subsidence averaged 0.4 ft/yr. After the utilization of ground water was curtailed beginning in the mid-1950s, subsidence rates declined to about 0.1 ft/yr. Cumulative subsidence of over 9 ft has occurred near the Houston Ship Channel and subsidence of at least 1 ft has affected over 4,500 mi^2 (Neighbors, 1981).

Land surface subsidence has become critical to parts of the Houston - Galveston area causing permanent inundation or increased exposure to flooding. Since 1943, several thousand acres of bayfront land have been permanently submerged and if uncontrolled, subsidence would have increased that total to 20,000 acres. In Harris County, 945 mi^2 have been heavily impacted by permanent submergence and increased flooding (Neighbors, 1981). Presumably much of this nearshore environment has or had some wetland values which have been irrevocably lost due to subsidence.

Although subsidence is not reversible, the rate of subsidence can be slowed or stopped with reduction or cessation of ground water extraction. Several decades of supplementing ground water with surface water to meet the Houston - Galveston region's growing demand have resulted in reduced rates of compaction and subsidence. However, current projections indicate that all readily available water supplies will be exhausted during the remainder of this century (Neighbors, 1981). Conservation or increased ground water pumping and renewed loss of nearshore acreage will be among the few alternatives remaining.

Balcones Fault Zone Edwards Aquifer

The Balcones Fault Zone Edwards Aquifer is located in south central Texas and parallels the Balcones Escarpment. It consists of massive limestone deposits averaging 400 to 500 ft thick (Longley, 1992). It is the sole source of water for San Antonio's population of about 1,000,000 (U.S. Geological Survey, 1990).

Water levels in the aquifer and the numerous prolific springs which are supported by the aquifer are at risk of serious decline. The average recharge to the San Antonio portion of this aquifer is 637,000 acre-ft per year.

Annual recharge is highly variable and directly related to annual precipation. Pumping is also directly related to annual rainfall. Pumpage in 1989 was 542,000 acre-ft. During the summer of this year, aquifer levels decreased by more than 1 ft per day, an occurrence which has become commonplace in the spring and summer of recent years (Longley, 1992). In 1991, the "largest well in the world" was drilled in this area (Swanson, 1991). Capable of flowing under artesian pressure at a rate of 27,000 to 35,000 gpm, it potentially could produce an amount equal to 111% of the annual recharge to the aquifer in 1956, the low year of record (Longley, 1992).

The Balcones Fault Zone Edwards Aquifer supports a diverse assemblage of over 40 species of aquatic organisms. Some species are subterranean and others inhabit the many springs. Several species are extremely limited in distribution. For example, the Texas blind salamander (*Typhlolmolge rathbuni*) is found only in a limited area around the San Marcos springs. This highly adapted amphibian was the first species to be placed on the federal Endangered Species list. Eleven other species of invertebrates, salamanders, and fish are being considered for federal listing (Longley, 1992).

This unique community is at risk of being impacted severely by declining water levels in the aquifer (Longley, 1992). In addition to reduced spring flow, aquifer overdraft promotes the encroachment of highly saline water which threatens the fresh water biota of this system. A test well located less than 100 yards from major San Marcos springs was found to be highly saline. Without immediate improved water management, this ecosystem is likely to be impacted severely (Longley, 1992).

WISCONSIN

Yahara River, Dane and Columbia Counties

The City of Madison is situated on a series of lakes in south central Wisconsin which are part of the Yahara River system. The river, lakes, and ground water form interdependent parts of the regional hydrologic system.

The ground water bearing units in the 323 mi^2 drainage basin of the upper Yahara consist of two aquifers. The lower sandstone unit is confined by an overlying heterogeneous sandstone layer (Fetter, 1977). There is a considerable amount of leakage between these two units.

The majority of the municipal and industrial water supply comes from deep wells drawing from the confined aquifer. These wells are the primary source of ground water discharge from the basin. As a result of pumping, the water level has been lowered as much as 70 ft in the confined aquifer and as much as 20 ft in the upper unit. Downward leakage from the upper aquifer has been enhanced. An estimated 5.6 billion ft^3 of the upper aquifer have been dewatered. The water table decline in the upper aquifer has created a gradient toward the well field areas causing ground water which formerly flowed into the lakes and streams to be intercepted (Fetter, 1977).

Prior to 1958 treated sewage effluent was discharged into the Yahara River. This effluent was a significant component of the annual discharge of the Yahara River, particularly in the summer months of low flow. Beginning in 1958 the effluent was exported from the river basin as part of a water quality improvement program for the lower Madison lakes.

The loss of ground water discharge and the effluent in the Yahara River resulted in a 50% reduction of streamflow during periods of low flow. The river now is predicted to be dry for periods in some years (Fetter, 1977). Undoubtedly the combination of increased water table depth, loss of bank storage and reduction of stream flow to the point of an occasional dry river bed will have a detrimental impact on the riparian ecosystem.

Section 7

Evaluation of the Adequacy of Existing Information on Ecological Impacts of Ground Water Overdraft

Introduction

Based on the literature and data reviewed for this study, the investigation and documentation of ecological impacts of ground water overdraft is clearly not a major focus of attention for most researchers and regulators at this time. Compilations of more than 6,300 citations published primarily in the last decade on ground water hydrogeology, hydrology, and wetland ecology were reviewed for this study (examples include van der Leeden, 1991; Atkinson et al., 1986; Emery, in preparation; Hood, 1988; Jalink, personal communication; Fisk, 1989; Stanford and Simons, 1992; Stanford and Valett, 1994). Fewer than 30 papers dealt directly with the ecological impact of ground water overdraft. Applicable citations were also infrequenty found in government publications and refereed journals.

As was described in Section 6, ground water overdraft can be extensive in many diverse areas. In some regions, research is occurring to accurately evaluate the nature and extent of ecological impacts of ground water overdraft. Notable examples include several basins in Arizona, California and Florida. Other researchers present sufficient data to document the need for further study to understand this important aspect of wetland hydrology. However, this topic definitely is addressed inadequatey in the technical literature at this time.

Clearly, investigation of the ecological impacts of ground water overdraft is an emerging issue. Historically, studies on ground water decline have focused primarily on the economic impact of water shortage and the costs of developing new water supplies. Impacts of ground water decline which affect people's use of the land and water such as saline intrusion and land subsidence have been well documented. Investigation of these impacts has centered on the resulting geologic hazards, structural damage, and economic impacts of abatement with little or no attention being focused on the actual or potential ecological impacts of these processes (for example Katzer and Brothers, 1988; Atkinson et al., 1986; Schumann et al., 1985).

Another example of the shortcoming of the available literature in addressing the ecological impacts of ground water overdraft is that major changes in surface hydrology are frequently documented without noting the unavoidable impacts on associated riparian and aquatic ecosystems. For example, abundant literature is available on springs, lakes, and rivers which are almost or completely dewatered without noting the associated ecological consequences (for example Wahl and Wahl, 1988; Fetter, 1977). Therefore it is undoubtedly the case that the extent of ecological impacts resulting from ground water overdraft exceeds those instances currently documented in the available literature.

Technical Perspective

A major reason for the paucity of information on this subject is the technical complexity of performing meaningful studies. Site-specific studies are needed. Adequate data must be available on surface and ground water hydrology as well as sufficient ecological data to measure valid trends and physiological effects of sublethal stress. Studies must be of sufficient duration to identify long-term and cumulative impacts.

Most wetlands and riparian areas are subjected to a variety of anthropogenic and natural perturbations. In some cases it may be difficult to distinguish ecological impacts due to ground water pumping from other causes of impacts. For example, water level decline in riparian aquifers can result from pumping as well as upstream surface water impoundment, stream channel incision, and natural drought cycles (Swift, 1984; Scurlock, 1987). Likewise, livestock grazing, watershed degradation, recreation, and the introduction of exotic species may result in vegetation changes similar to those associated with ground water overdraft (Stromberg, 1993c; Stromberg, 1994; Hendrickson and Minckley, 1984). Accurate identification of causal relationships requires extensive knowledge of the history of land uses and carefully designed investigations.

Another reason for the dearth of studies on this subject is that the current scientific foundation for understanding wetland hydrology is weak. Until recently, there have been relatively few studies done on the relationship between ground water and wetlands (Carter and Novistzki, 1988). According to Winter (1988), "Most hydrologic information relative to wetlands has been based largely on theoretical studies of generalized settings, on scattered field studies, and on hydrologic intuition". Calculation of a water budget may be fraught with inaccuracies (Siegel, 1988). Particularly problematic is the quantification of evaporation and transpiration from wetlands as well as the seasonal and annual changes in ground water flux in wetlands (Winter, 1988). Without an accurate understanding of the spatial and temporal changes in water movement in wetlands and riparian areas, determination of the magnitude of impact of ground water pumping is difficult.

Adequate surface and ground water monitoring data are essential but often are unavailable and difficult to obtain. For example, the fact that springs, wetlands, and seepage faces may be supported by shallow, localized unconfined aquifers can complicate efforts to obtain sufficient data in some locations (Winter, 1988). Such systems may be characterized by considerable seasonal and annual fluctuation in water level independent of pumping. For example, Gerla (1992) noted that in some intermittent wetlands, the water table rose over ten times the amount predicted by infiltration due to physical processes in the capillary fringe. Furthermore, while of essential ecological significance, hydrologic systems such as these may be unimportant as major water supplies for human needs and of low economic value. Consequently, adequate long-term water level data may not be readily available.

Ecological monitoring for impacts from ground water overdraft also may be problematic. To be of use in preventing irreversible damage to wetlands and riparian areas, investigations must focus on sublethal stress responses rather than mortality. According to Bacchus (1995), "Field methods for monitoring wetlands were designed primarily to estimate dominance and (community composition) rather than to detect and measure responses of natural systems to imposed stresses. Although standard approaches may provide some insight into stress responses, such interpretations are difficult because the majority of monitoring is short-term and there is a dearth of data on stress responses in wetland species." Factors such as changes in species composition and density, reproductive success, susceptiblilty to pathogens, and introduction of new species should be considered (Stromberg, 1994; Bacchus, 1995).

Inadequate information on several key aspects of wetland ecology further hinders researchers' ability to develop predictive models of the impacts of ground water drawdown. In many instances it is not known whether certain plant species are obligate or facultative phreatophytes in riparian settings. Consequently the impact of water level decline beneath the depth of root penetration may be difficult to evaluate (Busch et al., 1992). Furthermore, studies of wetland ecosystems are rarely designed to identify the earliest indicators of stress resulting from water level decline. Lastly, ecophysiological studies have focused more heavily on the effects of flooding on root tissue, leaving greater uncertainty regarding the physiological tolerance of short-term and long-term desiccation (Busch et al., 1992).

Regulatory Policy Perspective

It is not within the scope of this report to thoroughly explore the adequacy of current regulatory policy in identifying and addressing instances in which ground water pumping results in ecological impacts in wetlands. However, several key factors are readily apparent in reviewing the literature available on this subject. Foremost is the fact that federal agencies and most states have very limited regulatory controls on ecological impacts from ground water overdraft (Smith, 1989). While the ecological values associated with maintaining surface water flows are well recognized, the concept is not reflected in ground water management in most instances (Fort et al., 1993).

At present, most approaches to management of ground water quantity are for the purpose of fulfilling senior water rights and not for the protection of associated ecosystems. In some states, utilization of ground water is unlimited as long as the water is put to beneficial use (Smith, 1989; Parfit, 1993). Limitations to this broad right may be technically difficult to invoke. For example, in Texas, ground water drawdown may be limited if the ground water meets the definition of an "underground stream" (Longley, 1992). Furthermore, the ongoing evolution of the regulatory definition of wetlands complicates the issue (Lehr, 1991). For example, a decision by the U.S. Supreme Court was required to include wetland areas saturated by ground water (as opposed to surface water) under protection by the Clean Water Act (Want, 1988).

Other regulatory provisions which provide some measure of protection to wetland ecosystems may not be applicable to impacts from ground water drawdown. Permits issued under Section 404 of the Federal Clean Water Act are required for surface water diversions which involve fill or excavation of waters of the United States including ditching, channelization and discharge of dredged materials. However, permits generally are not required for dewatering wetlands and riparian areas through ground water pumping. This is particularly ironic as the areal extent of ecological impact may be far greater from dewatering than from placing fill for a project such as a road crossing (Bacchus, 1994; Hill, personal communication). Furthermore, because the permits are issued for individual wetland sites, the permitting process is not conducive to the evaluation of cumulative impacts in an entire hydrological system (National Research Council, 1991). Likewise, Environmental Impact Statements may be inadequate in evaluating the cumulative impact of pumping operations on an aquifer and also greatly may underestimate the actual drawdown which occurs (Bureau of Land Management, 1994). Finally, mining reclamation plans may include revegetation but not the replenishment of ground water pumped during pit excavation (Ross, 1992).

Improved regulation of ground water quantity to manage impacts of water level decline including rising pumping costs has not been readily accepted. In many states, increased federal involvement is extremely unwelcome. In parts of the High Plains dependent on the Ogallala aquifer, water level decline is extensive and rising pumping costs threaten the profitability of agricultural water users. However, in a broad survey of water users conducted in this area, regulatory controls to manage this shared water resource were found to be unpopular and voluntary use of conservation measures in response to economic necessity was favored (Kromm and White, 1986). However, while market mechanisms have been successful in some instances, they may be ineffective in prevention of impacts to natural resources of limited monetary value such as some wetlands (Smith, 1989).

Another impediment to improved management of depleted ground water resources is the multijurisdictional nature of many ground water systems. Where aquifers cross state or local boundaries, individual pumpers have little incentive to unilaterally restrict withdrawals of ground water. Without cooperative agreements, a "use it or lose it" mentality may prevail. The need for cooperation between states is large. In a survey to determine the extent of interstate competition for ground water resources in the western continental United States, interstate competition was found somewhere on the borders of all states except Oregon (Smith, 1989).

Water use planning may be further complicated by the absence of a detailed understanding of local hydrogeology. Unlike surface water users, individual ground water pumpers may not recognize their co-dependence on a shared water resource. Consequently, the effects of overexploitation may not be recognized until they are considerable (Llamas et al., 1992).

Legal Perspective

There is no single legal approach to ground water overdraft in water law in the various states. State laws often do not explicitly address overdraft so policies may have to be inferred from other management mechanisms such as special management districts or provisions for well interference. Among the western states, many states have a de facto policy of permitting unlimited ground water mining (Fort et al., 1993). Furthermore, there is frequently poor integration between the legal framework for regulating the utilization of surface water and ground water. While these two resources are often very different in terms of their development and distribution, they are hydrologically highly interconnected and in some instances must be managed as a unified system (Llamas et al., 1992). A noteworthy example of a statutory initiative in this regard is the Arizona Riparian Protection Act of 1992. The act directs the Arizona Department of Water Resources to "evaluate the effects of ground water pumping and surface water appropriations on riparian areas in the state" (Stromberg, 1992).

One of the primary challenges with regard to improved management of ground water overdraft stems from the fact that legal controls on ground water quantity frequently are in the private domain. The present use of ground water has resulted largely from the accumulation of individual private operations rather than larger scale, often publicly funded, impoundment and distribution systems more commonly associated with utilization of surface water (Llamas et al., 1992). Water rights often are attached to property rights provided pumped water is used for a beneficial purpose. This has led to the practice of water farming in some areas. For example, tens of thousands of acres of irrigated farmland in rural Arizona have recently been purchased by municipal water purveyors. Their intention is to retire the land from agriculture and export the ground water pumped on the property to rapidly growing nearby cities (Checchio and Nunn, 1988). If not carefully managed, such export may result in environmental impacts in the area of origin. It is ironic that state statutory provisions intended to curtail declining ground water levels in urban areas have provided the incentive for this extensive water farming (Checchio and Nunn, 1988).

Section 8

Recommendations

The primary recommendations from this study fall into two categories which will be discussed below. First, under certain circumstances, the potential for ecological impacts from ground water overdraft is significant. However, this phenomenon commonly is not investigated in most ground water or wetland studies. Therefore, it is recommended that the issue receive more research and regulatory attention in a broad array of contexts. Second, one primary focus of this attention should be on an enhanced predictive capability for early detection of "high risk" hydrologic settings and "high risk" wetland and riparian communities and species. With care to avoid erroneous oversimplification, this information should be used to improve planning and policy regarding water use and wetland protection.

As was described in Sections 6 and 7, the existing literature is sufficient to conclude that adverse ecological impacts from ground water overdraft have occurred in many diverse ecosystems. The potential exists for similar impacts to be occurring in many ecosystems which have not yet been investigated. Studies to identify and quantify consequences from pumping should be conducted more frequently and more comprehensively. The potential for wetland and riparian impacts should be considered in regional water use planning programs where water level decline is a concern. Similarly, this issue should be adequately addressed in regional hydrological studies and wetland surveys. Investigations regarding other impacts associated with ground water overdraft such as saline intrusion and subsidence should be coupled with or should include an assessment of the potential for ecological impacts when wetlands are involved. Permitting processes pursuant to federal, state, and local environmental protection and natural resource management statutes should include an assessment of the potential for impact from subsurface drainage for any development projects which may affect wetlands and riparian areas. In particular, a more rigorous and comprehensive approach should be employed in Environmental Impact Statements. To the maximum extent feasible, emphasis should be on cumulative impacts of regional ground water resource development rather than on individual wells or well fields or individual development projects.

Because hydrologic settings and wetland ecosystems are individually unique and complex, site-specific studies will be essential. Therefore, achieving the preceding recommendation will be time-consuming and costly. To maximize the efficiency with which impacts can be identified, or ideally prevented, additional research effort should be focused on developing predictive capabilities for identifying "high risk" hydrologic settings and "high risk" ecosystems and species. This approach can then be used as a starting point to improve planning and policy. A goal of these efforts should be prevention instead of restoration. Restoration of wetlands is technically limited at this time and often politically difficult and costly. Therefore, use of a more proactive predictive approach is likely to achieve better results at a lower cost.

As a starting point, examples of high risk hydrologic settings might include locations with shallow ground water, rapidly drained soil, discontinuous confining layers, or a large seasonal difference in precipitation which results in ground water dependence during the dry season. For plant species which may be particularly sensitive to hydroperiod perturbations, optimal rates of ground water drawdown should be investigated to allow maximal use of the resource with minimal ecological impact. Soil type and meteorological factors would have to considered (Mahoney and Rood, 1992).

Another predictive tool which should be developed is the species specific indicators of earliest water stress. Impacts must be identified before structural degradation occur in plants. In some cases this will involve a better understanding of the physiological effects of water deprivation on plant tissues. In other cases, research will be required to identify the source of water utilized by plant species, which may vary seasonally, by location or by age of the plant. Understanding seasonal dependence on ground water, precipitation and surface water is essential to establish safe limits on drawdown. Tracer studies using the stable isotopes deuterium and oxygen-18 to distinguish facultative versus obligate phreatophytes appear to have promise (Dawson and Ehleringer, 1991; Busch et al., 1992; Dysart, 1988) as opposed to earlier studies in which plants were extracted from the soil (for example Gary, 1963).

In addition to an improved understanding of the response of individuals and species to water level decline, it is important to consider that wetlands and riparian areas are among the most spatially and temporally complex natural systems on earth (Richter and Richter, 1992). Riparian systems respond to water stress by undergoing changes that occur in a hierarchical fashion. Whereas low levels of stress cause changes at the level of the individual, high levels of stress result in ecosystem and community level changes (Stromberg, 1992). Few studies have quantified relationships between water stress and riparian ecosystem response, particularly in arid regions.

Although highly complex, enhanced predictive capabilities are needed at these levels as well. Linking ground water and ecological models is one potential approach (Richter and Richter, 1992).

Predictive information of this type should be used more widely in ground water management programs. A major objective should be to create a management approach in which there is feedback between the occurrence of hydroperiod perturbations, water stress tolerance limits, and allowed pumping rates. For wells sited in highly sensitive areas, permit conditions could require pumping to be slowed or stopped when plant limiting soil moisture or water level depths were reached (Groeneveld, 1989; Stromberg et al., 1993b). The long-term monitoring of ground water levels and ecological impacts required by the Soutwest Florida Water Management District is a useful example which could be utilized more widely.

Section 9

Conclusions

A review of the existing literature on the environmental impacts resulting from ground water overdraft revealed that localized wetlands and riparian areas throughout the United States have undergone changes consistent with a loss or reduction of the ground water discharge which previously had been available. While many instances are localized, in some cases these impacts have occurred on a regional basis throughout entire drainage basins or aquifer systems.

The locations in which discernable impacts have been documented in this study are not hydrologically or ecologically unique. It is likely that similar impacts are occurring in other locations which have not been investigated, particularly in the arid west where ground water is frequently the only perennial water source available. It is probable that the existing body of literature significantly underestimates the extent of ecological impacts which are a result of ground water overdraft.

As the demand for ground water continues to grow and the remaining wetland and riparian areas are subjected to an increasing array of developmental pressures, the importance of this issue is clear. Left unaddressed, it is probable that ecological impacts of ground water overdraft increasingly will undermine other environmental efforts such as wetlands restoration and endangered species protection.

Efforts to assess and rectify impacts from ground water overdraft must be approached with a full understanding of the complexity of hydrologic systems and wetland ecosystems. Many human activities and natural processes can result in ecosystem changes. Causal relationships are often difficult to identify. Detailed, site-specific, and often long-term studies are needed to determine pumping rates which can be sustained without undesirable impacts. A better predictive capability for optimal rates of drawdown and early indicators of ecological stress will be needed to assist water resource planners in being more responsive to this issue.

A deliberate effort should be made to incorporate this issue into existing environmental assessment and water resource planning processes. To the maximum extent possible, emphasis should be on cumulative ecological impacts and regional water allocation.

Section 10

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