Sustainable Groundwater Management:

What We Can Learn from California's Central Valley Streams

Reference

This publication is a summary of detailed report:

The Nature Conservancy. 2014. Groundwater and Stream Interaction in California's Central Valley: Insights for Sustainable Groundwater Management.

Available at: http://www.scienceforconservation.org/

Acknowledgements

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Photo on cover: Seasonal vernal pools surface amidst lush grasslands and blue oak woodlands at Dye Creek Preserve, part of the Lassen Foothills project where restorative land management and conservation-compatible ranching techniques are administered by The Nature Conservancy on behalf of the state of California. © Ian Shive

Introduction

Groundwater is intimately connected to surface water, which has profound implications for sustainable water resource management. California has historically overlooked this important interaction and as a consequence, decisions about groundwater extractions have generally failed to address the resulting impacts to surface flows and aquatic ecosystems such as rivers, wetlands and springs. This has contributed to a loss of approximately 95 percent of the historical wetlands and river habitat in California's Central Valley.[1]

With the passage of the Sustainable Groundwater Management Act (SGMA), groundwater sustainability agencies across the state will soon be required to manage groundwater resources to avoid causing undesirable results to groundwater levels and interconnected groundwater and surface water. These groundwater levels and areas of interconnection support groundwater-dependent ecosystems[2] (GDEs). Therefore, an important first step in sustainable groundwater management is to understand how groundwater pumping impacts surface water, including streams, and GDEs.

To build the case for ecosystem protections now found in SGMA, The Nature Conservancy completed a study in 2014 to illustrate how groundwater pumping is affecting streams and rivers in California's Central Valley. The report, entitled *Groundwater and Stream Interaction in California's Central Valley: Insights for Sustainable Groundwater Management*[3], uses an integrated hydrologic model to reconstruct the historical impacts of groundwater use on groundwater levels and stream flow conditions. The results from that detailed study are summarized here.

Our study focused on the state's Central Valley because of its importance in California's overall water supply. We used a model developed by the Department of Water Resources (DWR) to simulate the Central Valley's hydrologic conditions during the years from 1922 to 2009.

1 The Bay Institute (1998) *From the Sierra to the Sea: The Ecological History of the San Francisco–Bay Delta Watershed*.

2 Groundwater dependent ecosystems are "terrestrial, aquatic and coastal ecosystems that require access to, replenishment or benefit from, or otherwise rely on subsurface stores of water to function or persist." Howard and Merrifield (2010) Mapping Groundwater Dependent Ecosystems in California. PLoS ONE 5(6): e11249. doi:10.1371/journal.pone.0011249
Available at: http://www.scienceforconservation.org/

3 The Nature Conservancy. 2014. *Groundwater and Stream Interaction in California's Central Valley: Insights for Sustainable Groundwater Management*. Available at: *www.scienceforconservation.org*

Across the Tulare Basin, San Joaquin Basin and Sacramento Valley these changes have differed in magnitude, but share a similar trend. In areas with hydraulic connection between groundwater and surface water, increases in groundwater extraction continue to cause declines in groundwater levels that reduce stream flow.

Our report found that as groundwater production grew threefold, surface water was seriously depleted in the Central Valley. This region, which accounts for 20 percent of all groundwater pumping in the United States, has now lost nearly all of its wetlands and river habitat. Our modeled results indicate that over 80 percent of the valley's rivers lose more water today than they did in their relatively natural state. By the end of our study period, the valley's rivers were losing almost 1.5 billion gallons of water each day—that is enough water to supply 2.5 times the water needs of Los Angeles. In addition, groundwater aquifers contain 6.5 trillion gallons less water now than they did at the start of the study period.

The results of our study pre-date the extended drought that began in 2011 and it is likely that the drought has exacerbated stream depletions. In addition, our study illustrates that the effects of groundwater pumping can take years—even decades—to recover. This means that the full extent of the impacts of groundwater pumping during the drought will continue to plague us for many years.

These findings have troubling implications not only for the health of our ecosystems, but also for the surface water right holders. If groundwater pumping continues to increase, it will become even more challenging to ensure that surface water is available for the cities, industries, agriculture and plants and animals that rely on surface water systems.

Sustainable groundwater management requires that we acknowledge the critical connection between groundwater and surface water. In addition, in managing this connection, we must acknowledge the protracted time period it can take for groundwater extractions to impact stream flow. The best tools we have to sustain our important groundwater supplies are to proactively manage and monitor groundwater use and to invest heavily in groundwater recharge. Implementation of SGMA provides the impetus to change our approach and to integrate management of groundwater and surface water.

Background

The Interconnection between Groundwater and Stream Flow

Most of California's groundwater occurs in material deposited by streams, called alluvium. Alluvium consists of coarse deposits, such as sand and gravel, and finer-grained deposits such as clay and silt. The coarse and fine materials are usually coalesced in thin lenses and beds that were deposited by streams. In this environment, coarse materials such as sand and gravel deposits usually provide the best source of water and are termed aquifers; the finer-grained clay and silt deposits are relatively poor sources of water and are referred to as aquitards. California's groundwater basins usually include one or a series of alluvial aquifers with intermingled aquitards. DWR has delineated more than 500 alluvial groundwater basins and sub-basins across California, the largest of which are the Sacramento Valley, San Joaquin Basin and Tulare Basin that underlie the Central Valley.

Streams and rivers in the Central Valley typically flow over sediments that are connected to underlying aquifers. Because the sediments that make up the bottoms of these stream channels are porous, water can flow back and forth between the streams and the underlying aquifer.

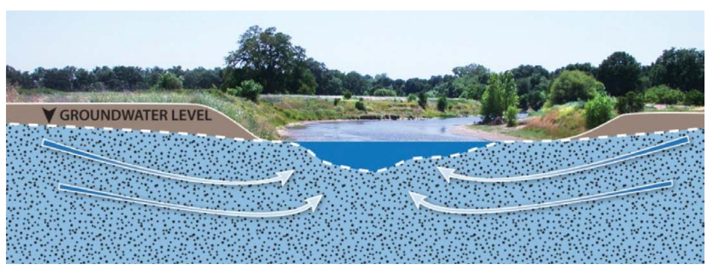
A range of groundwater–surface water interconnections are found in basins in the Central Valley. When groundwater levels in the surrounding sediments are high relative to the streams, groundwater flows from the aquifer into the streams, contributing to the stream flow. This condition is known as a gaining stream—streams gain surface flows from high groundwater levels. In some cases, this groundwater inflow keeps

FIGURE 1: Groundwater and Stream Interaction in Alluvial Aquifers

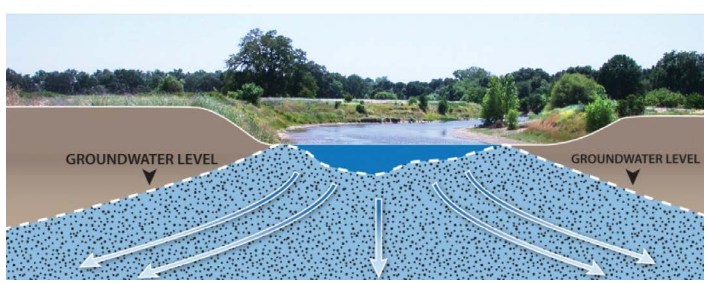
Groundwater basins in California are predominately alluvial or "valley-fill" groundwater aquifers. These aquifers are made up of unconsolidated or loosely-cemented sediments that have been deposited over long periods of time in valleys. These deposits, sometimes thousands of feet deep, are usually underlain by more solid, and less permeable, rocks that make up the geologic floor of the valley and the surrounding hills or mountains. The sediments that make up the valley-fill are deposited in interwoven layers and veins that vary widely in particle size, from cobbles and gravel, to sands, to clay. The water in these aquifers resides in, and moves through, the pore spaces between the sediment particles. Water moves more easily through sediments of larger particles, and moves very slowly, if at all, through sediments of finer particles, like clays.

Gaining Stream—Where rivers or streams run across valley floors underlain by valley-fill aquifers, there will inevitably be exchange of water between the streams and the underlying and surrounding aquifers. If surrounding groundwater levels are higher than the water levels in the river, the river will "gain" water from the surrounding groundwater. This is called a **"gaining" reach of stream**. This groundwater inflow is often a large portion of the flow in streams after precipitation events have passed. This is often the natural condition of streams, since streams are commonly the major discharge location for groundwater flow.

Losing Stream—Pumping of groundwater draws down the groundwater levels near the pumping well, and multiple wells can lower groundwater levels over large regions of the aquifers. If groundwater levels are drawn down, by pumping or by natural processes, to levels lower than the stream, water will flow from the stream into the aquifer sediments below. In this condition, the stream segment is said to be a **"losing" reach of stream**.



Gaining Stream—Groundwater flows into the stream, increasing surface flows



Losing Stream—Stream flows depleted by outflows to groundwater streams flowing in the dry seasons, even when there is no rain or snow to maintain them. This is referred to as base flow. When groundwater levels drop, the amount of groundwater flow into the stream is correspondingly reduced.

When groundwater elevations in the surrounding basin sediments are lower than the water level in the stream, the flow direction is reversed and water from the stream leaks or seeps through the streambed sediments, flowing into the surrounding aquifer, recharging the groundwater basin. This seepage or leakage of stream flow into the groundwater basin reduces the flow in the stream. This condition is called a losing stream—streams lose surface flows to groundwater recharge.

In short, what is a gain for the groundwater is a loss for the stream. The loss of flow in streams due to groundwater pumping is formally known as "stream depletion," meaning groundwater pumping ultimately comes at the expense of surface waters—from depleting surface flows. This stream-aquifer relationship can change seasonally or annually between gaining and losing conditions based on the flows in the river and the status of the groundwater system.

Because of the interaction between stream flow and groundwater in alluvial systems, pumping water from wells essentially diverts surface water, with the aquifer functioning as a large storage facility for water that comes from surface flows. Deep wells in confined portions of the aquifers, and wells distant from streams are similarly connected to streams; they simply take longer to impact rivers and streams. Groundwater pumping is therefore only sustainable to the extent that it can be replenished by surface water systems and also to the degree that we are willing to compromise ecosystems and established surface water rights.

Study Approach

Recognition of the groundwater–surface water connection in the Central Valley is especially critical in managing California's water supply because of the importance of Sacramento and San Joaquin river flows and underlying groundwater in meeting local and statewide water supply needs.

Our study describes how groundwater pumping over the past century has changed conditions in the Central Valley using DWR's integrated groundwater and surface water model, the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim). The model covers the hydrologic, land use and water use conditions in the Central Valley for the period of 1922 to 2009. While the model is not a perfect representation of the natural system, it represents the clearest comprehensive picture available for the Central Valley hydrologic and water use conditions and the interaction between streams and groundwater system.

Salamander at small freshwater stream on The Nature Conservancy's Mueller Ranch located in the Arroyo Seco River and Uplands Conservation Areas of Monterey County, California Central Coast Ecoregion, California. © Mark Godfrey/TNC

One of the biggest challenges in understanding the status of groundwater conditions is the lack of reliable data on pumping rates, since measuring or reporting of groundwater pumping volumes has not historically been required in California. Consequently, pumping volumes must be estimated. This is done within C2VSim by dynamically calculating crop water demands, allocating contributions of water from precipitation, soil moisture, and surface water diversions (which are reported), and then estimating the amount of groundwater pumping required to meet remaining demand. Experts generally agree that the C2VSim model provides some of the best estimates of agricultural water demand, and therefore groundwater pumping to meet agricultural demands for the Central Valley because estimates are based on water budgets developed for various management areas, considering various crop mixes, soil conditions, irrigation practices, rainfall, surface water supplies and variation in both space and time throughout the valley.

In addition to illuminating historical conditions and current trends in groundwater–surface water conditions, we used the C2VSim model to illustrate possible future conditions that could result from water management scenarios. These scenarios include a groundwater substitution transfer and development of new irrigated lands using groundwater.

Observations and Results

The following are some general observations drawn from the C2VSim simulations. More details on each of these can be found in the full technical report.

Declining Groundwater Levels

Water development and use within the Central Valley increased dramatically in the 1900s as new irrigated agricultural land was progressively brought into production. Combined surface water and groundwater use rose from about 9 million acre-feet per year in the 1920s to about 22 million acre-feet per year in 2009, with groundwater production rising from about 3.3 to 10 million acre-feet per year over this same period.

The proportion of groundwater use to total water use in the Central Valley averaged about 45 percent between 1922 and 2009, with the actual amount varying year to year depending on rainfall. In 1977, a severe drought year, groundwater provided nearly 70 percent of the supply for this area, with pumping totaling nearly 16 million acre-feet. In 1983, an extremely wet year, groundwater provided only 30 percent of the supply, totaling only 7 million acre-feet. The Tulare Basin accounts for as much groundwater production as the other regions combined.

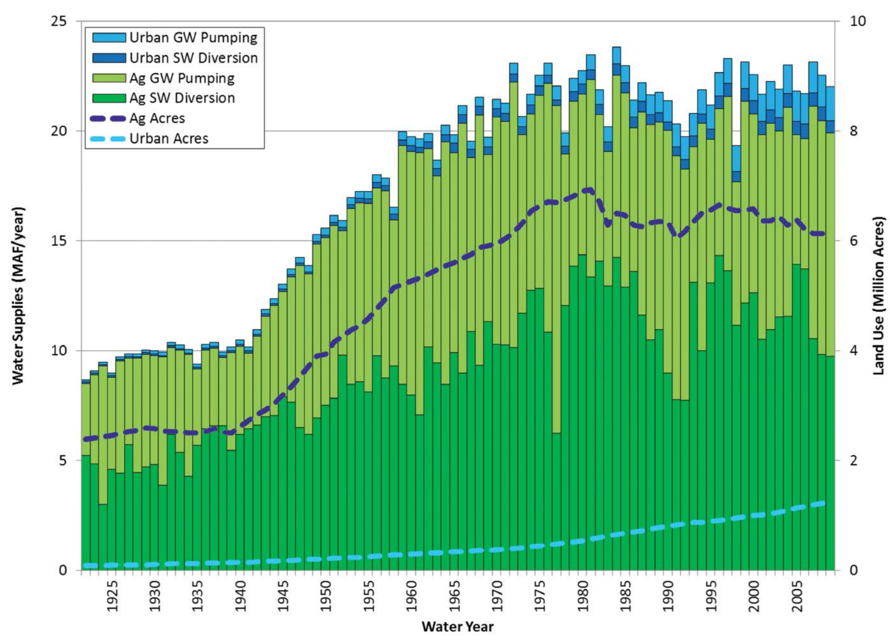
Increases in groundwater pumping resulted in lower groundwater levels throughout most of the Central Valley in 2009 relative to the 1920s. These lower water levels correspond to a decrease in stored groundwater, meaning more water was pumped from the aquifer than was recharged. Estimated stored groundwater in the Tulare Basin region underwent a dramatic decline, with total pumping exceeding recharge by more than 120 million acre-feet. Over the same period in the San Joaquin Basin, the estimated reduction in storage was more than 20 million acre-feet. Meanwhile in the Sacramento Valley, a similar though less dramatic trend can be seen, with less than 5 million acre-feet estimated reduction in storage.

Assuming the existing land use and water use conditions continue in the future, model simulations suggest that groundwater storage could potentially decline by an additional 75 million acre-feet through the year 2083.

Resulting Stream Depletion

As described above, when groundwater levels decline in alluvial aquifers, the flow in the overlying streams that have some level of hydraulic connection with groundwater is affected. The historical effects of increased groundwater pumping on stream flow between 1922 and 2009 are clearly evident from the results of the C2VSim simulations. As groundwater

Figure 2: Historical Land Use and Water Supplies in the Central Valley.



extractions tripled, groundwater discharge to streams gradually decreased. In fact by the end of our study period, major Central Valley rivers were being depleted at a rate of 1.5 billion gallons per day. This is 2.5 times the amount of water needed to support Los Angeles each day.

Streams in the San Joaquin and Sacramento Valley hydrologic regions were gaining water overall in the 1920s, while streams in the Tulare were already losing flows to groundwater. Streams in the San Joaquin largely converted in the 1960s, at which time they began to lose more water than they gained. While these findings do not indicate that all streams reversed from gaining to losing rivers—or that any particular river became disconnected—the results clearly show that the general relationship between groundwater and stream flow has been significantly altered.

Up north in the Sacramento Valley, the model simulation indicates that streams reached their tipping point by 2009, losing more flow to groundwater than they gained. The Sacramento River and its tributaries were net-gaining streams in the early 1900s, but now they

Figure 3: Cumulative Change in Groundwater Storage, by Region.

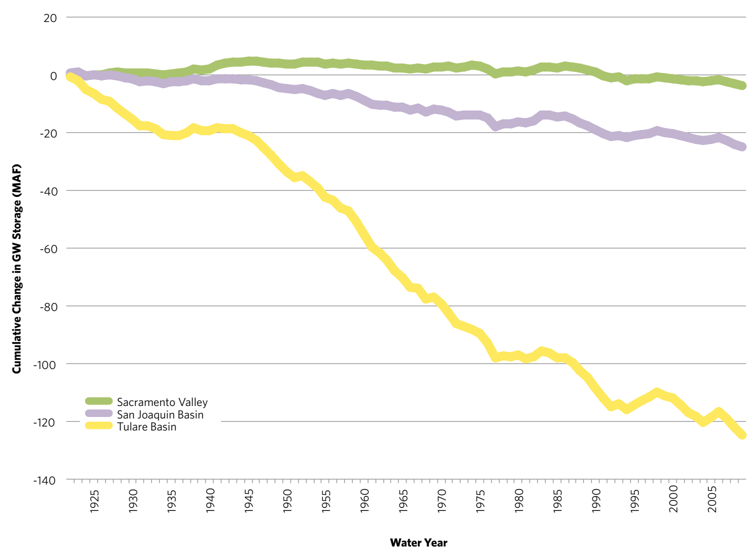
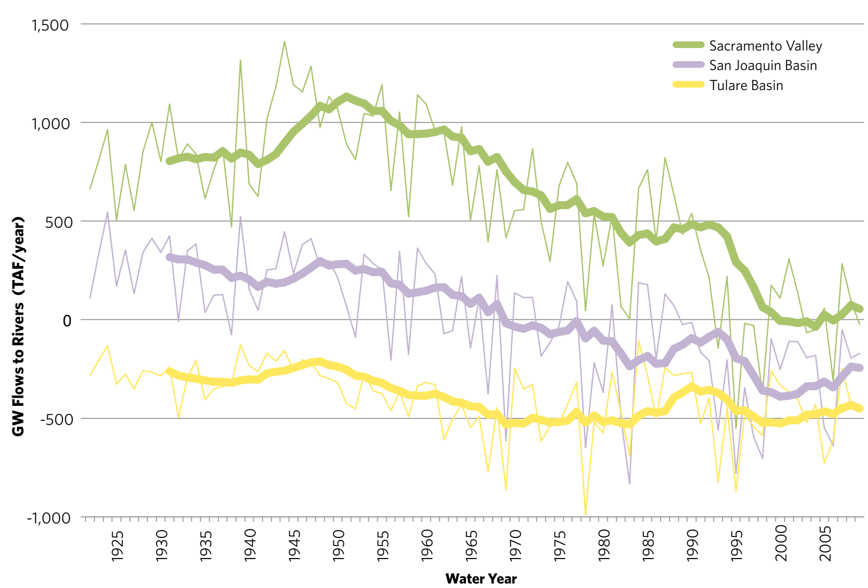


Figure 4: Net Historical Groundwater Discharge to Rivers, with 10-Year Moving Average.



Lush, riparian forest surrounds Dye Creek in the Dye Creek Preserve, part of the Lassen Foothills project where restorative land management and conservation-compatible ranching techniques are administered by The Nature Conservancy on behalf of the state of California. © Ian Shive

are estimated to be gaining much less or even net losers of water overall due to increases in groundwater pumping. These stream flow depletions in the Sacramento Valley occurred as groundwater level declined as little as 25 feet over most of the valley.

Compromised Groundwater Dependent Ecosystems

The reduction in stream flows has degraded the plants, animals and ecosystems that rely on rivers and streams, as well as the ability to maintain water quality, stream temperature and other beneficial uses. As a result, there has been a drastic decrease in the extent of wetlands and river habitats, drying of seeps and springs, and an interruption of the dry season stream flow needed for passage of salmon and for the health of other aquatic species. Some of these declines in ecosystem health have resulted in listing of species under the Endangered Species Act and/or California Endangered Species Act, in some cases forcing regimented water system operations that could be avoided if the rivers or wetlands were restored to functional levels.

In addition to declines in groundwater storage and degradation of GDEs, increased groundwater pumping in the San Joaquin and Tulare Basins has resulted in some of the world's most extreme examples of subsidence—a condition where the land surface slowly loses elevation due to the compaction of sediments—in some cases by more than 30 feet

Our study reflects impacts up to 2009. Since then, California entered a drought that increased groundwater pumping and exacerbated stream depletions, habitat losses and subsidence.

Scenario 1: Groundwater Substitution Transfer

During times of drought, transferring water from areas with relatively abundant water supplies to areas of shortage is often a means to reduce supply constraints in the state. One form of this is called a "groundwater substitution transfer." This occurs when water users forgo their surface water entitlement for transfer and substitute groundwater pumping to meet their irrigation needs.

Our study modeled a scenario to isolate the impact of a single year of a groundwater substitution transfer. It assumed a transfer from the Sacramento Valley to an area south of the Delta, with pumping of 186,000 acre-feet.

This scenario resulted in groundwater levels declining at locations of increased pumping, with varied affects on the surface water system. The groundwater level declines are less in pumping areas close to the major river systems, and more at greater distances from the rivers, indicating that rivers are major sources of recharge to the groundwater system.

These groundwater level declines persist for years to decades, resulting in long-term depletion of stream flow. Our modeling analyses indicate that over this period, the total stream depletions approach the 186,000 AF volume of water pumped for the substitution.

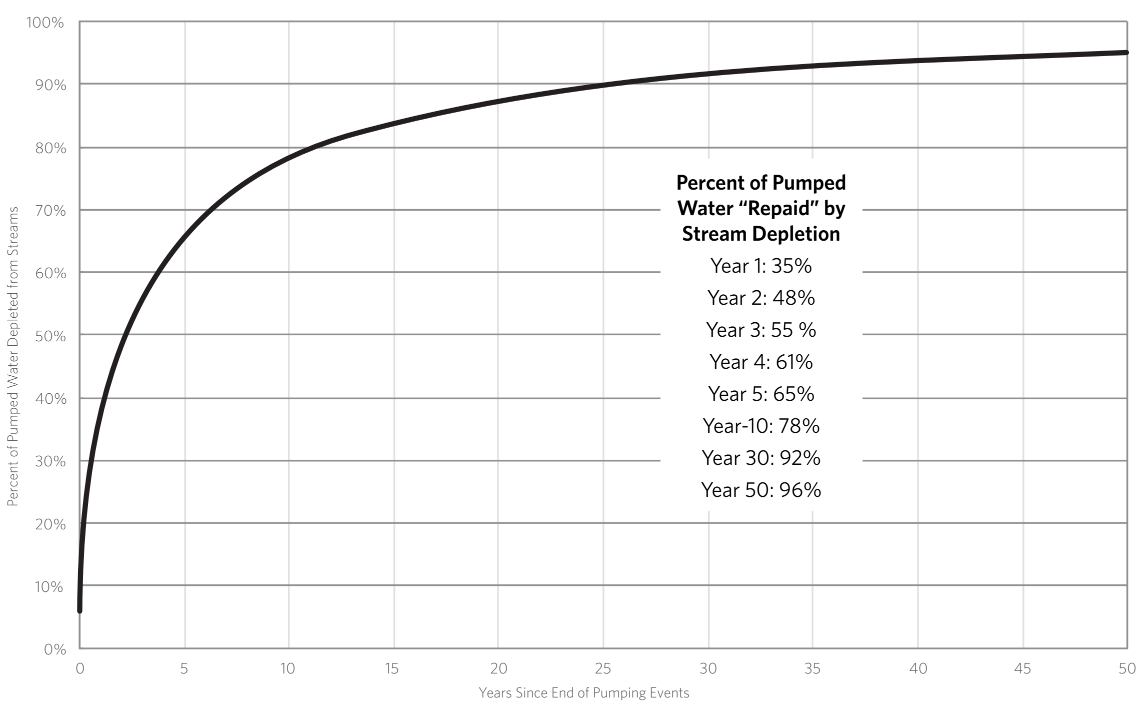
Scenario 2: Stream Flow Impacts from Development of New Irrigated Lands

Recent years have seen significant levels of new agricultural development in the Central Valley, where previously non-irrigated lands are being irrigated using groundwater. To estimate the impacts of new pumping on stream flow in the Central Valley, we simulated a hypothetical case of 10,000 acres of new irrigated lands being brought into production on the northwest side of the Sacramento Valley using groundwater as the water supply.

Our modeled scenario assumed a groundwater pumping need of 30,000 acre-feet per year. Since a portion of the irrigation (~5,000 acre-feet per year) returns to the groundwater through deep percolation from irrigation applied water, we assumed a net new-groundwater use of approximately 25,000 acre-feet per year.

The additional groundwater use resulted in a reduction in groundwater levels that inevitably led to new stream depletions. Once the new pumping is initiated in the area, it takes approximately 25 to 30 years for a “new equilibrium” to be reached in the groundwater levels and for all the stream depletions to fully develop. Eventually, however, all of the net new groundwater use, 25,000 acre-feet per year, is reflected as reduced stream flows.

Figure 5: Sacramento Valley Stream Depletion and Groundwater “Repayment” Curve.



Conclusions

Our report illustrates how increased groundwater pumping in the Central Valley has resulted in stream depletions, essentially reversing the historical interconnection where streams gained flows from groundwater. The result of these stream depletions includes loss of surface water supplies as well as declines in the health of plants and animals that depend on surface water and sufficient groundwater levels. These impacts are significant because the volumes of lost groundwater are frequently replaced by corresponding depletions in stream flow, and because these stream losses can persist for many years—even decades.

As California implements the Sustainable Groundwater Management Act, our study provides clear lessons learned that should inform sustainable management:

- **Groundwater withdrawals result in surface water depletions.** In many areas of California's Central Valley, groundwater and surface water resources are intimately interconnected. As groundwater production tripled in the 20th century, many portions of the Central Valley's rivers and streams converted from systems that gained flows from groundwater to systems that lost surface flows to groundwater.
- **Conditions are worsening in the Sacramento Valley.** While groundwater overdraft has long been recognized in the southern parts of the Central Valley, conditions in the Sacramento Valley region have, until recently, been reasonably stable. Our study indicates that groundwater conditions in the Sacramento Valley are worsening and, as a result, adverse impacts to surface flows are increasing.
- **Stream flow impacts from pumping may be delayed by decades.** Although the effects of groundwater pumping on stream flow may be fairly immediate when the pumping location is close to the stream, the effects of groundwater pumping miles away from a stream or deeper in the aquifer will lead to stream depletion that is not fully expressed for years or even decades.
- **Small changes in groundwater levels can make a big difference.** Because it can take decades to recover groundwater levels, even small groundwater level declines can lead to potentially significant stream depletion when aggregated over time.
- **Without action, Central Valley groundwater conditions will continue to decline.** Our modeling results show that groundwater storage in the Central Valley has declined by about 150 million acre-feet since the early 1920s. Assuming the existing land use and water use conditions continue in the future, model simulations suggest that groundwater in storage could potentially decline by an additional 75 million acre-feet through the year 2083.
- **Groundwater substitution transfers affect stream flow.** Modeling results clearly indicate that supplies for groundwater substitution transfers initially comes from groundwater. Although pumped groundwater for transfers initially comes from groundwater in storage, eventually it is balanced by an equivalent amount of stream depletion that occurs over many years or even decades. While groundwater transfers may be a useful drought mitigation measure, such measures need to be designed and implemented with full recognition of long-term impacts to streams and surface water rights.
- **Expanding irrigated agriculture means lower groundwater levels and less flow in streams.** Increased agricultural development in the Central Valley supplied by groundwater will result in further declines in groundwater levels. These declines will ultimately result in stream depletion similar in amount to the consumptive use of the new crops. Stream depletion impacts from this new groundwater pumping may take years to decades to fully develop.

While our study focuses on the Central Valley, the same hydrologic and physical principles apply where streams and rivers flowing over alluvial aquifers are pumped for water supply across California. Sustainable groundwater management requires recognizing and understanding how declining groundwater levels lead to stream depletions. Stated simply, groundwater pumping in alluvial aquifers as just another way of diverting surface water. When viewed in this way, it is clear that groundwater pumping is only sustainable to the degree that we accept associated impacts to surface water rights and plants and animals.

Over the next few decades, we will learn much more about groundwater dependent ecosystems and the connection between groundwater and stream flows. But today, one lesson is clear: healthy rivers are strong indicators of effective and sustainable groundwater management.

Photo on back cover, clockwise from top: Cattle graze along the Shasta River on the Conservancy's recently acquired Shasta Big Springs Ranch near Shasta, California. Heavy grazing on the ranch has seriously degraded the river, damaging this crucial salmon habitat. The Conservancy purchased the ranch as part of a major project to restore the river habitat and protect the salmon fishery. The upper reaches of the Shasta River hold the best hope for restoring salmon populations in the Klamath Basin of northern California and southern Oregon. The 4,136 acres Shasta Big Springs Ranch (formerly, Busk Ranch) contains large cold water springs that support over 80% of the coho salmon found rearing in the Shasta. Protecting this ranch and restoring its river habitat is a major link in restoring the salmon habitat in California. © Bridget Besaw; Wetland at Lost Slough Wetland in the California Cosumnes River Preserve. © Harold E. Malde; Riparian forest line the banks of a slough along the Sacramento River in California. ©Harold E. Malde; Pond with mountains in the background and trees and grasses on the side in the Sequoia Foothills, near Three Rivers. The Sequoia Foothills region supports the greatest biodiversity of native vegetation and the 2nd highest concentration of rare and endemic plants in the Sierra Nevada. TNC's Sequoia Foothills Project began due to the principal threat to the natural habitats and native species of the area driven by population growth. The project area covers just under 1 million acres within Tulare County. © Gary Crabbe/Enlightened Images Photography