Impacts to Anadromous Fish through Groundwater Extraction

Aaron Hebert
University of San Francisco, hebert.aaron@gmail.com
Impacts to Anadromous Fish through Groundwater Extraction

by

Aaron Hébert

is submitted in partial fulfillment of the requirements
for the degree of:

Master of Science
in
Environmental Management

at the
University of San Francisco

Submitted: ....................................... Received: ............................................

........................................... .............................................
Aaron Hébert Date Christopher Ruehl, Ph.D. Date
Research Question:

Under what hydrogeologic conditions does groundwater extraction reduce stream baseflow and limit anadromous fish habitat?

Abstract:

California uses more groundwater than any other state in the United States in order to meet agricultural demand during the growing season when water is naturally least available due to the state’s Mediterranean climate. The state also hosts populations of anadromous fish that are otherwise found exclusively in the wetter Pacific northwest. Groundwater has historically helped maintain baseflow in the summer and fall low-flow periods and acted as a natural buffer against the regular droughts that occur in California. Today, groundwater provides 30-40% of the state’s water supply, but the pumping in many cases has reduced groundwater discharge and baseflow, among other impacts, causing harm to anadromous fish populations.

This paper explores the hydrogeologic conditions where groundwater extraction limits anadromous fish habitat. In the first section, a review of hydrogeology and well pumping explores the conceptual framework around the topic. In the second, third, and fourth sections, individual case studies are reviewed to explore the research question in specific contexts under a range of hydrogeologic conditions. Section two explores the Scott River aquifer in Northern California and impacts to coho salmon (*Oncorhynchus kisutch*) within a shallow, mostly unconfined alluvial aquifer. Section three studies the Cosumnes River aquifer in the Central Valley and impacts to fall-run Chinook salmon (*Oncorhynchus tschawytscha*) within a deep alluvial aquifer with heavily depleted groundwater supplies. Section four highlights the Pajaro Valley sub-basin where impacts to winter-run steelhead (*Oncorhynchus mykiss*) are limited by a confining layer in the upper portion of the alluvial aquifer. The conclusion provides an analytical framework for exploring this topic in other basins, considers the new Sustainable Groundwater Management Act of 2014, and the challenges of recovering groundwater in light of climate change.
Table of Contents

Introduction ..................................................................................................................................... 4
Section I: Background and Conceptual Model................................................................. 13
Section II: Scott River Watershed .................................................................................. 34
Section III: The Cosumnes River .................................................................................. 56
Section IV: Lower Pajaro River .................................................................................... 77
Conclusion .............................................................................................................................. 90
Introduction

In California, anywhere from 30-40% of the state’s water supply comes from groundwater (Department of Water Resources, 2003). Much of that water supports agriculture in the Central Valley but it also supports municipal and residential uses. During one of the state’s regular droughts, groundwater becomes an increasingly important part of water supplies as surface supplies diminish. Prior to 2014, groundwater extraction was not regulated. Rather, groundwater was viewed as a property right controlled by the landowner. The effective limitation on its use was the cost of drilling and operating wells and the chance that groundwater quality was lower than surface water’s. As surface water sources become unavailable during drought, landowners extract more groundwater. This can lead to a number of negative and sometimes permanent environmental impacts of interest to the state, including: lowering of the water table for other groundwater users, land subsidence, and reduced water quality. This ‘tragedy of the commons’ (Hardin, 1968) eventually spurred the State legislature to pass the Sustainable Groundwater Management Act (SGMA) of 2014, composed of three bills AB 1739, SB 1319, and SB 1168 and a technical clarification in SB 13. While the regulation of groundwater is a significant political victory for the State, the fundamental connection between groundwater extraction, surface water, and riparian ecosystems is only touched on by this regulation. One of the defined ‘undesirable impacts’ that would make groundwater management ‘unsustainable’ is the depletion of and impacts to interconnected surface waters. Most groundwater is strongly connected to surface water and plays a significant role in providing water to streams in the summer and fall, when surface water is naturally least available in California. The use of groundwater generally causes depletion of surface waters.

For the first time at the state level, SGMA makes the physical connection between groundwater and surface water a regulatory connection as well, though the regulations are limited. SGMA does not require groundwater impacts to surface waters prior to January 1st, 2015 to be analyzed or addressed. SGMA uses groundwater extraction as of 2015 as a baseline to consider impacts beyond those amounts. Surface waters, by comparison, are highly regulated through the water rights system administered by the State Water Resources Control Board (SWRCB). The technical burden on individual water rights applicants is very high and requires
thorough evaluation and consideration by the SWRCB and the California Department of Fish and Wildlife (CDFW). SGMA defers this level of analysis for groundwater to the local level. Groundwater and surface have different regulatory approaches and systems without a direct connection. By separating groundwater and surface water regulation, the State has diffused the responsibility of managing California’s integrated water resources.

Groundwater and Baseflow

A stream’s “baseflow” is that portion of surface water that is derived from groundwater discharge to the stream and some flows from the stream banks (Glasser et. al, 2007). In California, where the majority of precipitation occurs in the winter, the natural flows in the summer and fall can represent the stream’s baseflow. In the mountainous watersheds areas with snow, spring snowmelt can increase surface flows during the spring and early summer. The remainder of a stream’s flow is derived from surface runoff and shallow subsurface runoff following storm events (“storm flow”). The graph below delineates the relatively stable contribution of groundwater to the stream’s baseflow from the episodic storm events.

![Figure 1: Mean daily discharge hydrograph from the Pajaro River, 1939-1986, showing a qualitative baseflow and stormflow delineation (data from USGS).](image)
Because the baseflow volume represents the groundwater discharge to the stream, it can also be used to roughly estimate the amount of groundwater coming into the aquifer (“recharge“) from the watershed above it. This method fails to account for the sometimes very long period of time it can take for precipitation to percolate into the groundwater system and then move through the subsurface to the stream. In systems with relatively even year-to-year precipitation patterns, this method can provide a useful basis for estimating groundwater recharge. In California, however, the weather patterns during the year and across years are highly irregular due in part because of El Nino and La Nina weather patterns in the Pacific. The baseflow of a stream may represent weather patterns from prior years, depending on the size of the watershed and the residence time of the groundwater (i.e., time spent underground) before it discharges to a stream.

In California, stream baseflow accounts for an estimated 27% to 60% of the total annual stream flow (Howard and Merrifield, 2010). Many streams’ summer and fall flows now reflect the large-scale modification of our watersheds and hydrologic systems. Because many of California’s streams are dammed, the stream flow is often controlled by the dam operator. The baseflow no longer represents just the groundwater contribution, but also the release of water from the reservoir. Water in the state’s rivers are also diverted at many points by individuals, businesses, and municipalities through the surface water rights system as administered by the SWRCB. The water rights system appears to have allocated ten times the amount of surface water that exists in California (Grantham and Viers, 2014). Thus, the remainder of water in the stream at any given point reflects the many upstream diversions of surface water. In addition to the surface water diversions and dams, extraction of groundwater in California has also substantially reduced natural discharge into the stream.

California extracts over 50% more groundwater than any other state and accounts for 16% of the overall groundwater use in the US (Maupin et. al, 2014). This large amount reflects a climate with precipitation primarily outside of the growing season. Figure 2 shows the Mediterranean weather pattern of mean monthly precipitation for four cities distributed across the state and the core growing season for many crops. Groundwater is also used in California because regular droughts reduce the available surface water.
The state’s heavy groundwater use also reflects the abundance of agriculture in California and the Central Valley in particular, which receives relatively little rainfall yet produces most of the state’s agriculture. Almost 70% of groundwater use in California is for agriculture (Mapulin et al., 2010). The abundant use of groundwater also reflects the politics of groundwater in the state. Prior to SGMA, it was the only state in the country without regulation for groundwater (Howard and Merrifield, 2010) and private individuals could generally use as much groundwater as they could access. California’s use of groundwater has lowered water table elevations below many of its streams, causing a reduction of baseflow derived from groundwater. Most of the baseflow in California’s large rivers now represents a combination of damming, surface water diversions, and groundwater extraction.

When the water table is above the elevation of the stream, groundwater will discharge to the stream. Groundwater pumping can lower the water table and thereby reduce the stream’s baseflow. In dammed rivers, the dam operators are forced through regulation to balance the need to release water and approximate the natural hydrology of the river with the need to store water in case winter storms do not replenish the water in storage. In undammed rivers, the combination of surface water diversions and groundwater extraction reduce the amount of flow in the river in
the low flow period. In both dammed and undammed rivers, groundwater extraction can cause the complete loss of surface water from portions of the stream during the low flow period, which impacts riparian ecosystems. This loss of water can be tolerated by certain riparian species, particularly plants and invertebrates that can access water beneath the surface of the stream and the stream banks. But for other species, the stream must have surface water of a certain depth in order to survive. In California, many of the state’s fish populations have been dramatically reduced by modification of our watersheds and natural flow regimes (e.g. Katz et al., 2013). Drying of the stream from the excessive extraction of groundwater and the diversion of surface water has caused fish populations in California harm by stranding fish in isolated pools, preventing migration, and sometimes direct mortality.

Anadromous Fish as Ecosystem Indicators and Species Protections Under SGMA

Anadromous fish (a.k.a. ‘salmonids’), most of which are found in the Pacific Northwest, have adapted to California’s hydrology by carefully timing their migrations from the ocean inland. Their survival in the summer and fall low flow periods is predicated on the availability of water. Groundwater’s role in sustaining baseflow in California is part of what allows these species to survive California’s semi-arid and drought-prone climate. Anadromous fish are an example of “a species whose habitat requirements are sensitive enough to allow for successful identification of environmental problems, yet broad enough to adequately represent a wide array of aquatic species,” (Stillwater Sciences, 2014). In particular, anadromous fish are sensitive to changes in water temperature, dissolved oxygen, sedimentation, and altered flow regimes, including the drying of streams. Groundwater extraction can affect all of those processes.

Many of California’s fish populations and anadromous fish in particular are threatened or endangered under the state and federal Endangered Species Act. The reduction of groundwater discharge to the state’s rivers has caused “harm” and “take” (as defined in the California Endangered Species Act) of these protected species. By excluding the analysis of prior impacts and potentially maintaining groundwater extraction at 2015 levels, SGMA may be failing to properly consider public trust resources, such as fish, under the public trust doctrine. The public trust doctrine requires the State to consider certain common resources (such as fish) held in trust by the State when making decisions. Because the groundwater sustainability plan requirements
do not expressly require analysis of the nexus between groundwater and special status species, impacts to protected species may continue.

Making the Groundwater Extraction and Surface Water Ecology Connection

There are several fundamental challenges in connecting surface water and anadromous fish with groundwater extraction. First, many wells produce a blend of water that comes from groundwater storage and water that would otherwise flow to a stream (“groundwater discharge”). The balance of water extracted from a well varies over time and is dependent, among other variables, on the distance that well is from the stream (Barlow and Leake, 2012). Second, there is predictive uncertainty in any specific hydrogeologic setting until the system is evaluated. Geology is highly complex and often difficult to directly investigate. There are a number of important exceptions and hydrogeologic conditions that may limit stream depletion from groundwater pumping. Stream systems in drier climates can sometimes be permanently ‘disconnected’ from groundwater, i.e., groundwater rarely ever rose to a sufficient elevation to discharge to the stream. Other times, an impermeable layer of silt and clay might surround significant lengths of the stream from the aquifer by conducting such low quantities of water that almost no water is exchanged between the stream and aquifer. Pumping near the coast may also draw from water that would otherwise discharge into the ocean and not a stream. Section IV provides an example of both of these conditions. Finally, wells that draw from a ‘confined’ source of groundwater, i.e. a store of groundwater separated from the surface by impermeable clay/silt layer, ‘aquitard’, and wells that are very distance from a stream may take many years or decades to directly affect a stream. Because hydrogeology is highly varied, answering the question of how a well may impact a stream has to be considered through the specific context of that system.

The inherent complexity of these systems is further increased by a lack of monitoring data in California for groundwater extraction. Because groundwater extraction is seen as a property right in the state, submitting or collecting well meter data has been resisted by many heavy groundwater users, particularly agriculture. As Peter Gleick jokes, “[t]here are certain people who benefit enormously from a lack of information and inefficiency—and those people have lawyers,” (Gies, 2014). The resulting lack of direct data measuring groundwater
extraction has lead to indirect measurements. The two main methods are modeling the rest of the hydrologic system water budget and solving for groundwater extraction, or using a set of assumptions that model evapotranspiration (“ET”) and applied water based on crop type. ET is the loss of water to the gas phase as a result of plant respiration and evaporation due to heat and wind. Both of these methods have some considerable uncertainties and limitations on their accuracy. Without real data, making the connection between groundwater extraction and stream depletion necessarily becomes the domain of hydrogeologic modeling and its inherent limitations. Stanford University’s Water in the West program put the issue of groundwater data this way:

> When it comes to groundwater data collection, California lags far behind other western states, most of which have much stricter disclosure requirements for water users. All this despite the fact that California pumps more groundwater annually than any other state in the US. (Choy et al., 2014).

> Another confounding factor is that most of California’s major rivers, like other states in the West, are dammed (Deitch and Kondolf, 2015). Where there is a clear man-made and highly manageable solution to regulating summer and fall baseflow, there is less of a need to evaluate the hard-to-quantify role of groundwater extraction on those flows. Prior to SGMA, the regulators lacked the tools to reduce groundwater extraction. In dammed rivers, it was more practical to increase baseflow through dam releases and the surface water rights framework than to appropriate responsibility to individual groundwater extractors based on a model whose inputs do not include real extraction data.

The dependence of California’s freshwater ecosystems on groundwater is also relatively unique in the world. Many of California’s streams and rivers require groundwater in order to remain perennial streams (i.e., flow year-round). In most climates, rainfall distributed throughout the year helps maintain river baseflow somewhat evenly. This also alleviates the need for groundwater extraction because summer rains help crops grow at the peak of their water demand (in contrast to Figures 1 and 2). In many places, groundwater plays a contributing role to riparian ecology and agriculture, but does not play a critical role in maintaining either. Other Mediterranean climates, such as in Italy, receive more of their rain in summer. South Africa,
Spain, and parts of Australia have a similar climate to California and share many of its challenges managing water. Climates that are too arid, however, simply do not have enough groundwater to discharge to the stream and therefore do not play an important role in riparian ecology except where springs are present. The definition of “groundwater dependent ecosystems” shifts with the region’s climate. Presumably for this reason, much of the scientific literature on groundwater ecology does not focus on the role groundwater plays in riparian ecology. Rather, the focus tends to be on microbial and invertebrate ecology, wetlands, vernal pools, and springs where groundwater may be the only source of water.

California is unique in the US and arguably the world for being both relatively hot and arid, sharing many of the climatic and groundwater challenges of Colorado, Nevada, and Texas, and yet abundant enough in cold groundwater and snowmelt to provide habitat to anadromous fish that are otherwise exclusively found in the Pacific Northwest. This combination of hosting species that evolved in cold waters of the Pacific Northwest (Deitch and Kondolf, 2015) and a climate regime that oscillates between drought and flooding (Gasith and Resh, 1999) makes managing groundwater and riparian ecology in concert very challenging.

These confounding forces help explain why the conceptual connection between groundwater and riparian ecosystems is relatively strong, but the regulatory and specific connection is an evolving body of research and policy.

Statement of Purpose

In California, groundwater will likely always be an important source of water for people, particularly during drought years. How to best manage this resource and its effects on anadromous fish is an important topic in the years ahead. This paper explores the question, under what hydrogeologic conditions does groundwater extraction reduce streams baseflow and limit anadromous fish habitat?

This paper first looks at the conceptual framework and general principles describing the groundwater-surface water linkage in closer detail. It then reviews three case studies that illustrate a range of hydrogeologic systems, scientific approaches, and impacts from groundwater extraction to anadromous fish to examine how this issue is evaluated in practice and what limitations these approaches have on how to best manage groundwater extraction. Finally, the
paper concludes by providing an analytical framework for exploring this topic in other basins, considers the new Sustainable Groundwater Management Act of 2014, and the challenges of recovering groundwater in light of climate change.
Section I: Background and Conceptual Model

The Geography of Groundwater in California

In California, groundwater systems are widely distributed. They vary in shape and size from the smallest visible valley to the entire Central Valley. Groundwater can be found near mountain summits or buried in the earth thousands of feet below sea level. It can be as young as days or weeks to as old as thousands of years. It can be an excellent source of drinking water or the target of remediation at superfund sites. Though groundwater is found in many forms in many places, most of the public’s interest is focused on more significant stores of groundwater (“aquifers”). Since 1952, the Department of Water Resources (“DWR”) and its predecessor have mapped and identified groundwater basins and sub-basins in order to provide planners with data to facilitate thoughtful management (DWR, 2003). What were originally 223 valleys with usable groundwater storage in 1952 has evolved into 515 groundwater basins and sub-basins that better reflect the physical and political boundaries around them (Figure 3a).
Figure 3a and 3b. At left, DWR’s “Bulletin 118” mapped groundwater basins (data from DWR). At right, ecosystem groundwater dependent index (originally presented in Howard and Merrifield, 2010).

Bulletin 118, in particular, started a data gathering and estimation effort in 1990 in order to build information and help quantify chronic overdraft in many groundwater basins. Despite the inherent limitations within the data, Bulletin 118 did show that some basins in particular were managing their groundwater in an unsustainable fashion. These medium and high-priority basins and sub-basins eventually became the focus of SGMA’s implementation over the first five years. Under SGMA, the basins mapped by Bulletin 118 will have corresponding political bodies, groundwater sustainability agencies (GSA). By 2022, the 127 high and medium-priority groundwater basins will be managed under a groundwater sustainability plan. Multiple basins may be covered by one GSA and one basin may have multiple GSAs. The remaining low-priority basins are exempt from SGMA’s requirements. These delineations are different from a more ecohydrologic view of the overall hydrologic units and groundwater boundaries,
particularly in sub-basins that are part of larger physical units defined with political boundaries. An ecological view of groundwater or hydrology suggests any area in the watershed that drains to the point of interest is connected in a meaningful way (Vannote et al., 1980). While groundwater often follows surface topography and hydrology, it also can cross watershed divides through deeper aquifers (Winter, 1999). Thus, the eco-geo-hydrologic connection can be over very large areas.

In California, many ecosystems are partly or wholly dependent on groundwater. Howard and Merrifield (2010) considered four different ecosystem types that are groundwater dependent: springs and seeps, wetlands, streams sustained by baseflow, and phreatophytic vegetation, i.e., plants that send their roots into shallow groundwater. By evaluating the presence of these ecosystem types and weighting them by watershed unit, Howard and Merrifield show that almost 90% of California’s sub-watersheds have groundwater dependent ecosystems (Figure 3b).

The differences between Figure 3a and Figure 3b show that the presence of aquifers with significant storage does not strictly correlate with areas where groundwater is present near the surface and utilized by the ecosystem. While the term ‘aquifer’ strictly relates to any storage of groundwater, Figure 3a shows the more common application of the term: areas with significant stores of groundwater. Figure 3b only partially correlates with the quantity of storage expressed in Figure 3a; a deeper and larger aquifer does not necessarily mean more groundwater is naturally interfacing with surface ecosystems. Mountainous regions, in particular, such as northern California and the Sierras often lack significant aquifers and have relatively abundant surface waters, but many of their ecosystems are still dependent on groundwater. The contrast of the two figures highlights the differing views of groundwater as a resource to utilize and its ecological role.
The distribution of anadromous fish in the state is quite broad-ranging, from the coasts of southern California to Humboldt County and as far inland as the Sierra foothills. Figure 4 overlays the distribution of anadromous fish in the state with groundwater use estimates by hydrologic region, based on land use data and crop type used by DWR to estimate groundwater pumping. The distribution of groundwater use by people is a function of the demand for water, the availability of cheap surface water, and the costs of groundwater extraction. Surface water rights or water allocations from state or federal water projects are comparatively cost-effective sources compared to well pumping (Medellín-Azuara et al., 2015); thus the use of groundwater generally indicates the absence of a more desirable alternative (Figure 4).

Figure 4: Map of estimated groundwater extraction by hydrologic unit, distribution of anadromous fish in California, and the three cases studies reviewed in this report.
The impact of this use is a context specific determination that intersects with many other watershed problems. The hydrologic modifications caused by people from hydraulic mining during the gold rush, state and federal dams and water projects, increased agricultural and urban growth, and many local modifications to the stream channel make isolating the exact source of a problem or appropriating responsibility a complex undertaking. Integrating these different variables over space and time is generally the domain of modeling. Despite the inherent complexity of undertaking this task, the fundamental theories and concepts support the notion that groundwater extraction will, in most cases, cause stream depletion. This change is most important when a stream or stream reach goes from receiving groundwater during the summer and fall low flow periods to not receiving it or even losing surface waters to the aquifer. This shift from “gaining” to “losing” means that year round flows can only be supported by dam releases. Figure 5 depicts the effects a hypothetical well can have on a nearby stream. If enough water is pumped from the well, it can reverse the flow of water from the aquifer to the stream and instead draw water from the stream, making it a ‘losing’ stream. Losing streams are more likely to go dry, either stranding or killing the species and ecosystems that depend on year-round water.

Figure 5: Depiction of gaining stream under moderate pumping and losing stream under heavy pumping.
Whether a stream is gaining or losing partly depends on the elevation of the groundwater. Thus, keeping groundwater elevations high enough to discharge into a stream is an important consideration for ecosystem function. Wendell and Hall (2015) illustrates this change from gaining to losing streams in the Central Valley in the early 20th century using the California Central Valley Groundwater-Surface Water Simulation Model (C2VSIM model) developed by the state, which uses real data from 1975 to 2003 to refine the model parameters. Ten rivers became losing in their model, indicated as “switched streams” in red in Figure 6.

Figure 6: Stream gaining/losing model results in the Central Valley (modified from Wendell and Hall, 2015).

Each of these groundwater maps indicate a different aspect of groundwater: Figure 3a shows the lateral extent of groundwater in California; Figure 3b represents the discharge of that groundwater to the surface; Figure 4 shows the distribution of anadromous fish through different
Defining Aquifers in California and Key Variables

The major aquifer systems in California (Figure 3a) consist of large stores of marine or alluvial sediments deposited millions of years ago in low elevation basins, as in the Central Valley, or in folded and faulted depressions, as in the Coastal Ranges (Planert and Williams, 1995). Other stores of groundwater can be found in areas with heavily fractured rock or fault systems. While the materials themselves may not be highly permeable, they can be quite porous—the large voids can conduct modest quantities of water. Figures 7 and 8 show representative depictions of alluvial and fractured rock aquifer systems respectively. For most basin-fill aquifers, such as the Central Valley, the groundwater storage potential is built very gradually over time. Today, where streams are left wild and allowed to flood, they deposit permeable alluvial materials, gradually building up the land surrounding the stream over time. While the materials that store groundwater in high quantities are generally found in the valleys, the upper watershed areas capture the most rainfall and are the source of much groundwater recharge (Hanak et al., 2011). The steeper headwater areas tend to have more localized groundwater...
systems, whereas flatter areas contain more regional groundwater systems (Sophocleous, 2002). Like surface hydrology, varied elevations play a distinct and important role in the overall system.

The United States Geologic Survey (USGS), starting in the 1920s, mapped the aquifer geology in California (Reilly, 2004). Over time, the USGS and other geologists have created more detailed and local descriptions of the aquifer materials. These investigations are often in response to interest in developing groundwater resources or evaluating seismic concerns. Stratigraphy is a discipline of geology that aims to describe the layers and histories of different formations. The more detailed and site-specific the stratigraphy, the greater understanding hydrogeologists have of how a particular aquifer will react in response to pumping at a certain depth. Many general descriptions of groundwater extraction use simple illustrations to convey the fundamental forces of the system, as in Figure 5. Some aquifers, however, need to be depicted in greater detail to convey an important geologic or geographic feature (Figure 7).

![Generalized geologic cross section along A-A’](image)

Figure 7: Generalized cross section of the Santa Clara Valley (modified from Maher et al., 2012). A good example of a basin-fill aquifer.

Wells drilled below the ‘confined area,’ indicated at the top of the cross section seen in Figure 7, which covers most the Santa Clara valley, will have different effects than those drilled into the ‘recharge area.’ The high frequency of the semi-impermeable silt and clay layers that restrict the movement of groundwater (‘confining layers’) are an important consideration in this aquifer. When too much groundwater is extracted from around these layers, they begin to release water from the pressure and compress, sometimes permanently, causing land subsidence.
subsidence has been an important issue in the Santa Clara valley since the 1920s, causing as much as 13’ drop in elevation (Maher et al., 2012). Note that Figure 7 is not precise in its depictions of the confining layers and the varied geology. Other illustrations of aquifers focus on the specific mix of rock types, depths, and faults that illustrate how the aquifer functions. Figure 8 shows the location of multiple wells in Montara, CA, general groundwater flow lines, faults, and other geologic features.

Figure 8: Hydrogeologic cross section in Montara, CA (originally presented in Woyshner et al., 2005). A good example of a fractured rock aquifer system.

A number of newer modeling and computer-intensive techniques have been used to create a much more detailed understanding of aquifer systems. These new statistical techniques help show how complex aquifers are compared to how they are often portrayed and even how most groundwater models simplify the geology. Much of the early thinking in groundwater helped define key aquifer types: confined, unconfined, and leaky. Unconfined are those aquifers where water moves relatively freely within it and the water table marks the upper boundary. Confined aquifers have a layer of near-impermeable materials that severely restrict the movement of water. Leaky aquifers are an average of the two ideas. In reality, actual aquifer behavior reflects a gradient of material types with specific hydrogeologic properties. This fine
scale of accuracy is most useful when trying to model groundwater movement for contamination modeling and groundwater surface interactions. The important variables that control the properties seen in Figs 5, 7, and 8 can be derived through estimation or experimentally and are summarized in the table below:

<table>
<thead>
<tr>
<th>Aquifer Property and Variable</th>
<th>Use and Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic Conductivity</td>
<td>The capacity of rock to transmit water</td>
</tr>
<tr>
<td>Transmissivity</td>
<td>The rate of water moving through an aquifer under pressure</td>
</tr>
<tr>
<td>Porosity</td>
<td>The ratio of voids to rock</td>
</tr>
<tr>
<td>Total Head</td>
<td>The height of water in a well above sea level, made of the elevation and pressure heads for confined aquifer and just elevation for unconfined</td>
</tr>
<tr>
<td>Storage Coefficient</td>
<td>Volume of water released by unit area from a change in head</td>
</tr>
<tr>
<td>Hydraulic Gradient</td>
<td>Change in head per unit distance</td>
</tr>
<tr>
<td>Basin Size</td>
<td>The size of the basin</td>
</tr>
<tr>
<td>Recharge</td>
<td>The amount of water flowing into the aquifer (either from an adjacent basin or as percolation)</td>
</tr>
</tbody>
</table>

Table 1. Aquifer variables (Heath, 1983)

The Hydrogeologic Cycle

The irregular weather patterns of California control how much precipitation hits the land surface. Because almost 70% of precipitation is lost to ET, modifications to vegetation alter the quantities of water percolating downward (Brooks et al., 2012). Soils on the surface are the product of the geologic history, plant communities, and the land use history. The removal of topsoil and subsequent compaction of the soils in many places has reduced the ability of soil to hold moisture. The infiltration capacity of soil can control how much precipitation enters into the vadose zone, i.e., the dry area between the water table and the surface. Some of that water during storm events continues to follow the surface topography beneath the soil as shallow subsurface
flow (‘interflow’) and discharge to the stream after most of the overland runoff has reached the stream. The remainder percolates to lower depths to become groundwater.

It is then filtered through the particular and highly heterogeneous geology of the area. Groundwater movement beneath the surface is influenced by the surface topography and can flow through multiple pathways over different physical and temporal scales (Toth, 1963). Unlike surface waters, groundwater movement is thought of as a pressure gradient, or head. Groundwater moves from areas of higher to lower head as opposed to surface waters that move from higher elevations to lower elevations, though pressure gradients are often influenced by topographic change. Groundwater sometimes does not percolate into deeper aquifer storage. It may run into an impermeable layer of clay or silt (“lens”) and move across the layer and discharge as a spring. For the rest of the groundwater, if the levels are high enough, it may eventually reach the streambed, interfacing across the stream length and from different elevations within stream channel. If the groundwater is limited because of low rainfall or groundwater extraction, it may simply pass beneath the stream and have no connection with surface waters. Before most groundwater reaches the stream, the effects of pumping from wells often alter its path.

Groundwater Extraction, Sources of Well Water, and Stream Depletion

In 1856, Henry Darcy, a government engineer, was asked to evaluate the use of a deep well to provide drinking water to the city of Dijon. Through a series of experiments, he determined the velocity of groundwater movement was related to hydraulic conductivity (the porosity and permeability of a rocky medium) and the hydraulic gradient (Heath, 1983).

\[
Q = KA \frac{dh}{dl}
\]  

(1)

Darcy’s equation defines \( Q \) as the quantity of water per unit of time, \( K \) as the hydraulic conductivity, \( A \) as the cross-sectional area, at a right angle to the flow direction, through which the flow occurs, and \( dh/dl \) is the hydraulic gradient (Heath, 1983). In 1940, C.V. Theis determined that well pumping would produce a drawdown in the water table that was dependent on the aquifer properties, the distance to the areas of recharge, and the distance to the areas of
discharge (Barlow and Leake, 2012). These fundamental equations were then built upon and considered in diverse aquifer types and solved for using different mathematical approaches (Mercer and Faust, 1980). Over time, these models have helped build a conceptual understanding of how these systems work.

Once a well is drilled, predicting its productivity and the effects of the drawdown is a complicated task. When a well pumps groundwater, it first lowers the water in the well itself and then draws in water from around the well. This extraction pressure creates a drawdown of the water table in a ‘V’ shape around the point of extraction. This ‘cone of depression’ grows over time from its initial condition and eventually reaches a state of equilibrium where pumping is equal to the recharge coming to the well, provided enough water is available. This concept is seen in the two ‘V’ shaped depressions around the well in groundwater elevations depicted in Figure 5. The time to reach this equilibrium is dependent on the amount of pumping, the groundwater flowing into the well area, and the storage capacity of the aquifer (Bredehoeft and Durbin, 2009). For a domestic well with limited production, this can be a number of days. For larger wells and aquifer systems, the time to equilibrium can be on the order of decades. The time to equilibrium is an important concept in evaluating the effects of an individual well because before that time, it will gradually lower groundwater elevations around it, potentially affecting other wells, surface water systems, and causing other ‘undesirable results.’ Once a well is in ‘equilibrium’, the effects of the extraction are fully realized. Whether these ultimate effects are desirable or not is a separate question.

The reduction in water table elevations from groundwater extraction can have an impact on connected surface water systems. Evaluating this potential requires considering the magnitude and timing of that impact. The connectivity between a well and stream is partly distance dependent. A well immediately outside of the stream channel is likely to affect the stream immediately. The further away the well is located from the stream, the greater the time lag between pumping and stream effects (Bredehoeft and Kendy, 2008). The distance has no effect on the ultimate magnitude of stream effects. This is an important and often overlooked idea in regulations. Because the connection can take years or decades to form, the ‘proof’ of their connection can only be answered conceptually or through modeling. The effect of this
gradual stream drawdown is in some ways a greater problem for water managers because the source of the impact is remote in time and space.

Another important consideration in well-stream interactions is the medium between them. Hydraulic conductivity is a function of the gradient and soil permeability. Carbonate karst systems, for example, function like pipes and convey water at greater speeds, up to $10^5$ ft/day. Clays and silts conduct water at very slow pace, as little as $10^{-7}$ ft/day (Heath, 1983). Confined (clay containing) and unconfined aquifers respond differently to pumping. Water drawn from a confined aquifer reduces the hydraulic pressure that groundwater is exerting on the materials around it. This change in force results in a compression of the aquifer, reducing pore space, and forcing water out of the aquifer. The expulsion of water from the materials is the main source of water from confined aquifer pumping and is generally very limited compared to unconfined aquifers. The ‘storage coefficient’ variable of aquifers represents the amount of water released by aquifer area per unit change in head. The storage coefficient for confined aquifers ranges from $10^{-5}$ to $10^{-3}$ whereas unconfined aquifers range from .1 to .3. On the other hand, wells in unconfined aquifers get their water from the lowering of the water table (Heath, 1983). The differences in storage coefficient also cause confined aquifers to horizontally propagate hydraulic stresses faster through the aquifer than in unconfined aquifers, causing stream flow depletion, as discussed further below, to occur sooner in time (Barlow and Leake, 2012). The geology, aquifer type, and stream distance alter the effect of well pumping on a stream.

If the materials between the well and stream are sufficiently conductive as to ‘connect’ them, a number of important changes to the well and stream occur. As described earlier, the time at which well output equals recharge in a steady state is known as equilibrium (or ‘time to full capture’). The recharge to the well, i.e. the source of well water, changes over time. At first, a well is extracting water that comes from the aquifer’s storage. Over time, as the drawdown pressure reaches the stream, the well may begin extracting groundwater that would normally discharge to the stream. Finally, as the well draws down groundwater near the stream, it may lower the water table (as seen in Figure 5) below the area at which stream bank vegetation can use it. This groundwater-reliant vegetation (“phreatophytes”) may desiccate as a result of the lowering. Once they have died, the ET demand and use of the groundwater is reduced, thereby
increasing groundwater availability. Some well water can therefore come from reduced ET (Bredehoeft and Durbin, 2009).

Because groundwater development tends to occur where surface water is unavailable or costly, assessing the impacts wells on surface water systems is an important consideration. Figure 9 shows how this shift of water source over time is also a question of distance for different well systems. Another important point when evaluating potential well impacts is the lag time after a well stops pumping. The greater the distance the well is from the stream, the more likely the maximum amount of stream depletion is to occur after a well has stopped pumping. This also occurs in aquifers that propagate hydraulic stresses from wells more slowly (typically unconfined). Figure 10 illustrates a model where the maximum impact occurs decades after pumping has ceased.

Figure 9: Shifting well water source over time in a hypothetical model over many decades for wells at two distances (originally presented in Barlow and Leake, 2012).
Figure 10: Lag to peak impacts from wells long after pumping stops. The well is 25 miles from the stream and is pumped for 50 years continuously. The maximum stream flow depletion peaks about 44 years after pumping is completed (originally presented in Leake et al. 2005).

Perhaps the fundamental distinction between groundwater extraction as a water supply resource and groundwater as an ecosystem resource is the idea that no matter how sizable an aquifer may be, the ecosystem utilizes the very top of the groundwater system, whereas people can extract water from hundreds of feet deep. The Scott River watershed, Section II in this paper, is a good example of how seasonal fluctuations in groundwater caused by pumping (i.e., not a year-over-year decline in groundwater) have had a significant effect on the ecosystem and only a small effect on the ability of farmers to pump groundwater. This difference in requirements for groundwater dependent ecosystems and what might be considered sustainable management or use of groundwater as a water supply highlights the abstract challenge of managing for both uses. It also suggests groundwater management is more than just a zero-sum problem; there may be disproportionate impacts to groundwater dependent ecosystems from nominal amounts of extraction.

Overview of Methods to Analyze Well Impacts
A number of different experimental and scientific methods can be used to estimate and evaluate the effects of groundwater extraction on stream depletion. The most basic understanding of impacts from wells comes from an overall water budget. If data exists for stream flow, precipitation, ET, and other water uses, it is possible to estimate the amount of groundwater recharge and discharge in a system. This approach cannot be used to estimate groundwater storage capacity. Water budget accounting has several challenges. Because groundwater is often used for irrigation of crops, much of it is lost to ET and some of percolates back the water table (“return flow”). Because groundwater pumping is not monitored, ET rates are usually estimated by crop type, and return flows are not directly measured, the accounting of groundwater can be quite complex. For example, much of the work behind the groundwater models in the Scott River case study (Section II) was in this phase of analysis. While not answering the question of how much stream depletion occurs from groundwater pumping, the water budget does suggest how much water is being pumped and the overall scale of water usage. The overall budget is useful (and is a required element of SGMA’s groundwater sustainability plans) but is more of an accounting tool than an analytical method.

For individual well owners, an aquifer test is the most basic evaluation they might make for their well. This method uses a continuous and heavy pumping from the well in order to understand the hydrogeologic system around it. By pumping much more than may be required by the user, the hydraulic stresses are likely to be more pronounced. The aquifer test measures the drawdown and recovery of water table elevations and recharge time in the well to determine what amounts of water can be pumped continuously over time. The test can also be used to monitor and measure reductions in groundwater elevations in other wells, springs, or stream systems during the heavy pumping. The duration of the test depends on the desired well output.

This method is useful where detailed geologic information about the aquifer is lacking, the exact source of groundwater recharge and discharge is undetermined, and it can be the most affordable option to evaluate an individual well’s effects (e.g. the granitic and fractured aquifer beneath Montara in Figure 8). It provides strong physical evidence about effects in the immediate area over the short term and can be used in a variety of aquifer types and contexts. This method is impractical at larger scales because it requires the consent of neighboring well owners and sometimes the construction of monitoring wells. It also requires that other
groundwater extraction or changes to the systems (such as a storm) be limited during the test or separated mathematically (Barlow and Leake, 2012). The construction and initial pump testing of a well also provides some of the basic localized data for other techniques to use, such as the depth of the water table, the layering and types of aquifer materials, the specific capacity of the well, hydraulic conductivity, and, sometimes, the depth of the aquifer. What the pump test lacks is a broader view of how wells might have an effect over time and over larger distances. If the well’s effects on the stream occur beyond a reasonable monitoring period (e.g., a month), it may be impractical to monitor these effects using this method. In order to answer that question, a mathematical model is necessary to understand how the well might function over time.

In the 1940s and 1950s, Theis and then Glover and Balmer independently developed the first analytical solutions to stream depletion from wells (Barlow and Leake, 2012). Jenkins in 1968 elaborated on the basic equation and set up a number of useful tables and graphs for practitioners. This approach is known as the Glover Solution or Jenkins’ Approach.

\[ Q_s = Q_w \times \text{erfc}\left(\frac{d^2S}{4Tt}\right) \]  

(2)

The equation relates the volume of stream depletion \(Q_s\) as a function of time. It incorporates the pumping rate of the well \(Q_w\), distance from the well to the stream \(d\), the specific yield or storage coefficient \(S\), transmissivity \(T\), time \(t\), and the complementary error function \(\text{erfc}\) that gives the data an asymptotic curve. Jenkins defined the distance squared times the specific yield over the transmissivity as the ‘Stream Depletion Factor’ (SDF), expressed in units of time, to compare the time depletion factors from different wells using a shared metric (i.e., wells with equal SDF values and pumping rates will have a similar effect on the stream).

\[ SDF = \frac{d^2S}{T} \]  

(3)

The SDF also happens to equate to that moment in time where 28% of well’s water comes from stream depletion (Barlow and Leake, 2012). This is useful in that it provides a basic
sense of impact at a glance, but can be confusing because the source of a well’s water shifts from groundwater storage to stream depletion in asymptotic fashion.

![Figure 11: Glover Solution applied to two wells 250’ and 500’ distant from the stream with SDFs of 6.25 days and 25 days. (Barlow and Leake, 2012).](image)

The Glover Solution and Figure 11 help visualize an important point about groundwater extraction from different wells: the larger the SDF, the longer it is until the effects of stream depletion are fully realized. Or said another way, very distant wells or wells separated from the stream by materials with poor transmissivity take a much longer time to extract the same proportion of surface water as nearer wells. Bredehoeft (2011) showed that wider aquifers have a similar effect on individual wells; the wider the aquifer, the longer it is until the effects of stream depletion are fully realized.

While the analytical solution does a good job of approximating the effects of well drawdown, there are limitations to its accuracy. The equation solves for stream depletion in a hypothetical aquifer that could not exist in reality in order to simplify the mathematics. At its most basic level, the equations require the transmissivity variable to represent an average of the aquifer materials between the well and the stream. If localized knowledge about transmissivity is poor, the quality of the results will be reduced. The required assumptions and methodology are further reviewed in Section II in the Scott River.

The most common method used to evaluate the effects of wells at a large scale is through a 3D model. This model is, at its core, built upon Darcy’s law but with the use of partial differential equations that are input into computer programs. This allows for a 3D representation
of all aspects of groundwater hydrology, including well drawdown. These models require considerable expertise to create. Once created, they often go through an extensive period of calibration where the model results are compared observed data sets. The variables and parameters of the model are then estimated and adjusted to produce model results that conform to the observed information. As the observed data record grows, particularly the hydrologic and weather record, the quality of the calibration increases.

The USGS developed a freely available model called MODFLOW (Harbaugh, 2005). Many public and private software extensions are available to build upon MODFLOW to answer specific questions about groundwater-surface water interactions, farmland water use, groundwater contamination, and more. In California, because of the size and importance of the Central Valley groundwater basin, special models have been developed by the State and USGS, namely C2VSIM and the Central Valley Hydrologic Model respectively. Many other established groundwater agencies around the state have developed groundwater models for their basins, including the local agencies in the Pajaro and Cosumnes basin case studies discussed in Sections III and IV. Each model must be custom built and periodically upgraded. Because these models are built upon many assumptions, estimations, and simplifications, they often conflict with other models built to answer the same question. One of the most challenging aspects of the models includes the incorporation of ‘boundary conditions’, i.e. those inputs and outputs from areas outside of the model where the data collection is likely not as robust. Models are inherently limited by the data provided, the complexity of the geology, and the simplifying assumptions necessary to make them work. George Box’s quote ‘all models are wrong, but some are useful’ was a common refrain at a February 2016 conference on groundwater modeling for SGMA.

The built-in uncertainty in the models and the scale at which these models are useful and cost-effective can limit their application to an individual well. Localized hydrogeology may conflict with the model assumptions in the larger areas. The presence or absence of impermeable layers or highly conductive materials may significantly affect the accuracy of the model at the local scale. Compared to the alternative approaches, however, these models are often the best available science. The more detailed the data input, the better the output. Examples of these models are reviewed later in Section II, the Scott River, and Section III, the Cosumnes River.
Overall, groundwater extraction has different effects on streams under different hydrogeologic conditions. The distance of the well to the stream, the width of the aquifer, and the aquifer materials have a significant effect the timing of depletion, spanning from days to decades. The magnitude of that depletion is reduced in the short term by those variables, but only because the time to maximum stream depletion is often very long. The source of well water shifts from reducing aquifer storage to stream depletion over time before reaching a steady state where no further effects will occur. Investigating the effects of wells occurs at different scales, using simple mathematical, physical, analytical, and computer-based methods. Each approach has limitations. These limitations are inherent to the problem of stream depletion because of the complex behavior of the system and the complexity of incorporating that into an analytical framework.

Potential Impacts Not Reviewed by this Paper

This paper reviews the potential impact of stream depletion caused by groundwater extraction on anadromous fish through the question of whether enough water is available. There is, however, compelling evidence that the reduction in groundwater discharge to California’s streams has more complex and negative effects on anadromous fish. Table 2 below is intended to briefly list those potential impacts not reviewed in this paper. The case studies and the supporting analysis in this paper mention these issues, but do not directly address them. The impact of reduced groundwater discharge to these streams can be presumed to a have a greater effect than is discussed in this paper.
<table>
<thead>
<tr>
<th>Ecosystem Functions</th>
<th>Mechanism</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flora and fauna</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phreatophytic vegetation</td>
<td>Lowered groundwater elevation</td>
<td>Increased temperature, sedimentation, organic matter reduction, and loss of pooling habitat.</td>
</tr>
<tr>
<td>Macrobenthic invertebrates</td>
<td>Lowered groundwater elevation</td>
<td>Lowered primary production and food for fish</td>
</tr>
<tr>
<td>Stream water quality</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>Lack of groundwater upwelling in still reaches</td>
<td>Reduced viability of redds</td>
</tr>
<tr>
<td>Temperature</td>
<td>Lack of groundwater upwelling</td>
<td>Excess summer heat, potential fish kills</td>
</tr>
<tr>
<td>Pollutants</td>
<td>Lack of dilution or exchange in benthic zone</td>
<td>Harms most aquatic life</td>
</tr>
<tr>
<td>Hydrology and geomorphology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perennial flow</td>
<td>Seasonal groundwater drawdowns</td>
<td>Disconnected pools separated by dry river, favors non-native fish</td>
</tr>
<tr>
<td>Sorting of spawning materials</td>
<td>Surface flows go subsurface</td>
<td>Diminished surface flows alter sorting processes</td>
</tr>
</tbody>
</table>

Table 2: A list of ecosystems functions supported by groundwater and the impacts of reduced groundwater flow. Sources: Groeneveld and Griepentrog (1985), Brunke and Gonser (1997), Woody and Higman (2011), and Moyle et al. (2003).
Section II: Scott River Watershed

Figure 12: Map of the Scott River watershed, aquifer, and Coho habitat.
Background Information and Hydrologic Setting

Land Use and Political Boundaries

The Scott River Watershed (Figure. 12) is located in Northern California near the Oregon border and is a major tributary of the Klamath River. It is located 20 miles southwest of Yreka and much of land is within unincorporated Siskiyou County. The Scott River Valley’s primary land use is agriculture (Foglia et al., 2013a). Four small towns are located within the Scott River Valley with a total population of 8,000 (Harter and Hines, 2008).

Hydrogeology

The Scott River watershed is roughly 650 square miles and ranges from 2,500 to 5,000 feet elevation (Echols, 1991). The mountains around the Scott River Valley receive significant snowfall in the winter months. Snowmelt in the spring and summer months helps to maintain summer stream flows. The Scott is generally considered to be a gaining stream with varying localized amounts of groundwater discharge and small losing stretches where surface water infiltrates into the groundwater. The water content of snow in the Scott River watershed from 1951-1998 shows a downward trend, likely caused by climate change (Van Kirk and Naman, 2008 and Drake et al., 2000). Precipitation is concentrated in the winter months, as seen in Figure 15. Storms generally come from the west or southern part of the Scott Watershed (Harter and Hines, 2008); snow is more abundant on the western peaks and the tributaries that run off those mountains are generally cooler. Perennial and intermittent tributaries are more common on the western side, whereas the eastern tributaries are generally ephemeral (NOAA Fisheries, 2014). Thirty small, high-elevation natural lakes in the watershed store and slowly release water (Harter and Hines, 2008). While the outlets of these lakes have been modified to more slowly release water, the Scott Valley remains just one of four undammed tributaries in the Klamath (Foglia et al., 2013b). An estimated 700 miles of stream are found in the watershed (Harter and Hines, 2008).

A USGS stream gage, located west of the town of Fort Jones (see Figure 12), has been tracking streamflow in the Scott since 1940, providing a robust hydrologic record.
Figure 13: Decadal box plot graph from the USGS stream gage near Fort Jones. The middle notch is the median, the box top and bottom indicate the 75th and 25th percentile respectively, and the whiskers define the interquartiles ranges.

The low flow period of August, September, and October shows a downward trend across decades, whereas no discernible trend occurs from December through April, as seen in Figure 13. Changes in the May and June runoff may be explained by the lower water content in snow, leading to less spring and early summer flows. The five years of the 2010 decade have also seen a multi-year drought. The contribution of groundwater to the Scott River baseflow is at its highest (and surface water contribution is at its lowest) during the fall period, which shows declines since the 1970s. This indicates the majority of the decline in August, September, and October is attributable to groundwater pumping, surface water diversions, and only partially due to climate change (Van Kirk and Naman, 2008).

The Scott River Valley is roughly 100 square miles or 15% of the whole watershed. The valley aquifer is mostly younger alluvial deposits and is bound by bedrock materials that also comprise the surrounding mountain ranges. Numerous faults are present in the mountains and the
valley (Mack, 1958). The bedrock materials are partly fractured and release water from springs in the mountain regions and the valley margins, though these quantities of water are small compared to the alluvial system. The alluvial deposits are partly from the Pleistocene, but are mostly made of recent alluvial deposits in the Scott River floodplain area and alluvial fan deposits. Alluvial fans are large fan-shaped debris deposits usually found where mountain streams enter valleys and deposit materials. These deposits are also found in the past locations of the Scott and its tributaries (“paleochannels”). This aquifer begins at the land surface and extends as much 400’ deep in some places, though no alluvial material between 210’-250’ is suspected to be sufficiently coarse enough to support groundwater pumping (Foglia et. al, 2013a, SSPA, 2012). The materials in the aquifer vary in sorting, permeability, and water-bearing properties. Materials closer to the streams tend to be sand and gravel, while other parts of the valley also contain clays and silts.

Foglia et al. (2013a) built a geostatistical model of the Scott River valley using well logs to depict the vertical dimension and soil maps of the valley to depict the horizontal dimension. These data were put into a 3D grid and translated into texture values of clay, gravel, and sand. Transition probability curves were generated describing the length, proportion, and vertical transition probability between each texture. These probabilities were then used as inputs in a Markov-chain random field generator to create equally probable realizations of the aquifer. Figure 14 shows one such realization.
Foglia et al. (2013a) note that although random, their realizations shared some basic conclusions: greater hydraulic connectivity in the north-south axis than east-west, that highly permeable gravel and sands make up more than half of the aquifer sediments, and that therefore these materials are “well-connected” to the Scott River. This north-south trending of groundwater appears to reflect a groundwater elevation map developed in 1991 by the DWR, which shows a general trend of groundwater flowing down gradient towards the Scott River and in the northern direction (SSPA, 2012). The realization also suggests the clay layers may not be large enough to act as confining layers, but rather there may be semi-confined areas, which appears to correspond with geologic cross sections drawn based on boring logs (Foglia et. al, 2013a).

This analysis of the clay confining layers partially differs from an earlier depiction. Mack (1958) described how the valley aquifer properties and sediment distributions come from the geologic and sedimentation processes that gradually build “diverging and poorly connected aquifers” (Harter and Hines, 2008) in the alluvial fan streams, which are generally found on the west part of the valley (Foglia et. al, 2013a). Large storm events that cause flooding in the alluvial fan streams create confined aquifer systems by layering materials of different size and
permeability. Typical flows mobilize “well-sorted sand and gravel” within the channel. Floods, however, can spread coarse materials over the whole alluvial fan area but concentrate those materials in the channel in the lower part of the fan head. As the floods subside, fine sediments are deposited everywhere. Floods also cut new channels as they overtop the original stream’s banks. The low gradient at the foot of the fan causes silt to accumulate in the channel, eventually causing the channel to fork. Over time, this processes leads to an irregular pattern of impermeable and permeable materials, of confined and unconfined aquifers. The current and buried channels are sources of recharge during normal flows in the fan head aquifers and the flows discharge towards the fan head base. This layered hydrogeology and recharge/discharge pathway explains the presence of several artesian wells in the Valley (Harter and Hines, 2008 and Mack, 1958). Artesian wells occur where the well draws water from a confined aquifer under pressure, typically from a downhill hydraulic gradient (pumping is often not required for artesian wells). The presence of the artesian system suggest some confining layers exist in the aquifer, but their distribution is likely limited given the number of wells that have explored the aquifer and how few are known to be artesian (Mark, 1958 and SSPA, 2012). The presence of “numerous springs and wetlands” on the west- side of the valley margin also suggests water table elevations are regularly near the surface partly due to the presence of clay lenses in the lower fan head areas (SSPA, 2012). The boring logs indicate some clay layers are common and are likely semi-confining features (Foglia et al. 2013a).

Overall, the geologic literature on the Scott Valley shows a large and relatively shallow alluvial aquifer with highly mixed materials. Impermeable layers and clay lenses are found throughout the valley, though none appear to represent a true broad, confining feature. Portions of the aquifer contain semi-confining layers and a few confining aquifers are present in the central and western side of the valley near the artesian wells. Highly permeable gravel and sands are likely the majority of the aquifer materials and appear to connect most of the aquifer to the stream. These materials are likely to trend in the N-S direction. The Scott River is generally considered a gaining river, suggesting the N-S groundwater flows have E-W connection to the Scott in the middle of the watershed where the Scott River flows N, as seen in Figure 12. There are several areas with a greater abundance of highly conductive materials near the middle of the valley and near the current stream channels. The Scott aquifer is also notable for its relatively
high elevation in California. Unlike the Central Valley and many coastal aquifers, the down
gradient side of the Scott aquifer terminates into the kind of mountainous and narrow stream
valleys that mark its upper watershed.

Mack (1958) divided the aquifer into six storage units based on the “thickness of
deposits, specific yield, and areal extent of the deposits” from wells records and pumping tests.
Foglia et. al (2013a) used a similar method. The units are estimated to have a storage capacity of
400,000 acre-feet of water (Harter and Hines, 2008).

Water Use

No water is imported into the Scott River valley. The primary demand for water is from
agricultural crops, primarily hay, grain, and alfalfa, and pasture for cattle (Foglia et al., 2013b).
Water has been a limiting resource for agriculture for almost 70 years. Court decrees in 1950 and
1958 allocated water in Shakelford Creek and French Creek, both tributaries to the Scott (Harter
and Hines, 2008). Beginning in the late 1960s, wells began using groundwater in greater
quantities, likely in response to less surface water availability and the desire for pressurized
sprinkler irrigation. In 1980, an adjudication allocated the surface water of the Scott River to
different agricultural users in the valley (Decree 30662). Most of this water is still diverted
through several large irrigation ditches. The adjudication also mapped certain interconnected
groundwater that was near to the Scott River (as seen in Figure 12) and any groundwater with
500’ of the river as subject to the adjudication.

The inclusion of these officially interconnected groundwater areas in the adjudication
was based on a California Water Resources report from 1975. Based on materials from well
drilling logs, the author of that report identified wells and well distances that were likely to cause
stream effects from groundwater pumping within a given season (Hathaway, 2012). Why this
particular temporal boundary was used in the adjudication is unclear. Prior technical reports such
as Mack (1958) had identified the potential for the entire aquifer to be connected to the stream.
The adjudication and the California Water Resources report supporting it were developed around
the same time that analytical solutions to stream depletion (such as the Glover Solution in 1954
and Jenkins in 1968) and computer-aided modeling allowed technical experts tools to analyze
well and stream connections in a quantitative way. While it was understood that most of the
valley floor had productive wells, a number of technical challenges in the late 1970s would have made analyzing the connection from more distant wells to the Scott River difficult. Groundwater was also not considered part of the State’s jurisdiction until 2014; there may have been as many political and legal reasons for the limited delineation of interconnected groundwater as there were technical.

Since the 1980 adjudication, the number of wells outside of the designated “interconnected groundwater” has grown steadily over time (Harter and Hines, 2008); the 1980s level of groundwater pumping has been estimated at 60% of the 2000s of groundwater pumping. Van Kirk and Naman (2008) estimate a 115% increase in overall applied irrigation since 1953. The increased demand for groundwater likely stems from the lack of availability of surface water due to the over allocation in the adjudication (as discussed later), climate change altering the water content of snow and thus decreasing summer flows, and increased agricultural demand.

<table>
<thead>
<tr>
<th>Estimate Source</th>
<th>Groundwater Pumping</th>
<th>Surface Water Use</th>
<th>Total Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>DWR (2000)</td>
<td>40,568</td>
<td>51,632</td>
<td>92,000</td>
</tr>
<tr>
<td>Van Kirk and Naman (2008)</td>
<td>+41,750</td>
<td>-41,750</td>
<td>83,500</td>
</tr>
<tr>
<td>Foglia et al., 2013b</td>
<td>44,000</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3. Groundwater and surface water use estimates in the Scott River Valley.

The total range of estimated groundwater pumping (Table 3) is roughly 10% of aquifer storage. If this pumping only occurs during the growing season (Apr 1-Oct 15), that equals to 102-112 cubic feet per second of groundwater extraction. The total range of surface water uses from Apr 1-Oct 15 is equivalent to 106-132 cfs. The various groundwater use estimates rely on land use data of different crop types, irrigation methods, and the best available knowledge about which farms utilize surface water. Water use and the type of water (surface or ground) vary significantly by crop type in the Scott Valley. During dry years, surface water supplies and uses diminish, while groundwater use increases (Foglia et al., 2013), as is typical of other agricultural areas in California.

The 1980 adjudication allocates 894 cfs over 680 diversions (Harter and Hines, 2008). This includes 235 cfs for the priority 1 allotment and the junior rights holders receive the rest.
when the SWRCB determines that flow is available (SSPA, 2012). As seen in Figure 15, the junior rights are not generally available from mid-July through mid-November. Because the Fort Jones gage is downstream of the diversions and is used to determine the availability of water for junior rights holders, it can be assumed gage flows reflect the upstream diversion of the priority 1 allotment during the growing season (April through mid-October). The priority 1 allotment during the growing season equates to ~105,000 acre feet, much more than is needed for irrigation but also much more than is likely available during that season; portions of the main stem go dry during many years and especially during drought years (NOAA Fisheries, 2014a). Exactly how much water is taken from surface water diversions is unclear because withdrawals are not monitored. Several users have opted out of the Shakleford Creek watermaster service. NOAA Fisheries noted this data void in their 2014 Coho recovery plan, writing, “There is no accounting of the actual timing or volumes of water diverted for the vast majority of the watershed,” (NOAA Fisheries, 2014a). While yearly maximum groundwater elevations have remained relatively constant over time, the yearly minimums has shown a declining trend during the period in which groundwater pumping has increased, even accounting changes in precipitation (Harter and Hines, 2008). This suggests that even if groundwater elevations are not being chronically lowered over time, seasonal lowering can have the same effect on the ecosystem.

Instream Uses, Anadromous Fish, and Stream Depletion

Instream Uses

The 1980 adjudication also included junior water rights for the US Forest Service, which owns land in the upland areas, to provide flows in the summer and fall months for anadromous fish. These rights are inferior to most of the rights in the watershed and have historically not received the allocated amount in most years (Echols, 1991). From 1980 to 1995, the flows only met the USFS decreed amount three times (Harter and Hines, 2008). The mean monthly average from 1980-2015 for flows in the Scott River during July through November is less than the USFS decreed amount for fish (as seen in Figure 15). The SWRCB allows junior users to take water in the winter months after the 10-day average exceeds the priority 1 allocation of 235 cfs. The USFS decreed amount is unlikely to be met during the boundary months of July and late October because any flows above the priority 1 allocation may be consumed by other junior
users. In August, September, and most of October, there is presumably not enough water for the priority 1 allotment because the diversion could theoretically satisfy the Valley’s entire water needs in the growing season.

The gage understates the extent of the flow problems in the Scott River. There are typically a number of dry portions of the Scott River upstream of the gage that impair anadromous fish from reaching spawning and rearing habitat further up the watershed. These are visually documented by CDFW staff and by some very partial stream gage data collected at different points in the Scott River by CDFW (NOAA Fisheries, 2014a and SSPA, 2012). The exact amount of flows required for the fish species vary seasonally and may not fit exactly with the USFS decreed amount, but the decreed amount would likely help maintain a minimum amount needed to prevent take of the species. A more technical answer to the question of how much water is needed by fish would be based on a reach specific analysis that would consider water for habitat features such as riffles, pools, off-channel refugia (i.e. fluvial geomorphology), the localized groundwater-surface exchange, and the life stages of the species.

In the Scott watershed, the eastern tributaries are mostly historically ephemeral and therefore not an important part of anadromous fish habitat. Some portions of the western tributaries are believed to have historically gone dry in the summer months (NOAA Fisheries, 2014a), suggesting the availability of spawning and rearing habitat for anadromous fish has been traditionally limited by the natural variability of surface flows. This would help explain why the seasonal decreases groundwater elevation in the Scott River Valley, as documented in Harter and Hines (2008), could cause certain tributaries to grow dry, resulting in large changes in the availability of habitat. Streams that naturally oscillate between permanent in normal years and intermittent in dry years, such as the western tributaries, are likely highly sensitive to surface diversions and groundwater extraction. The groundwater basin is not considered exploited or in overdraft because the groundwater elevations have stayed relatively constant over the last 30 years. Another interpretation of the relatively small change in groundwater elevations is that significant portions of the pumping draw from the stream and not groundwater storage.

Species of Interest
The Scott River and the Klamath watershed host a number of fish species, including speckled dace (*Rhinichthys osculatifs*), Klamath smallscale sucker (*Catostomus rimiculus*), Coastrange sculpin (*Cottus aleuticus*), and several anadromous fish: pacific lamprey (*Entosphenus tridentatus*), steelhead (*Oncorhynchus mykiss irideus*), Coho salmon (*Oncorhynchus kisutch*), and fall run Chinook salmon (*Oncorhynchus tschawytscha*) (Echols, 1991). Most steelhead and Chinook populations are federally threatened in California, though these particular populations are not. The Coho run in the Scott River, part of an “evolutionary significant unit”, is considered state and federally threatened (NOAA Fisheries, 2014a). While almost all of these species use the Scott River for most if not all of their lifecycles, anadromous fish are unique in that their life cycle has evolved to require specific range of seasonal flow patterns.

Coho and Chinook are considered to have more inflexible lifecycle patterns compared to steelhead, which is reflected in their limited population sizes. Steelhead are potentially more adaptable because they can access habitats at a higher gradient (i.e. they can swim up steeper streams), can jump over larger physical barriers, and are less sensitive to stream temperatures increases (Echols, 1991). There are two steelhead ecotypes in the Scott River that return from the ocean during the winter and summer (and for which the ecotypes are named). Further, some steelhead do not migrate to the ocean at all and are then known as rainbow trout. Each of these variations utilizes the natural flow regime in a different way. While the population is relatively abundant in the Scott watershed, the species requires year round water in order to survive and is therefore affected by the summer and fall low flow periods and intermittent flow of the Scott River.

Coho have been the main focal point of regulatory and conservation efforts in the Scott River because of their protected status. Coho migrate upstream starting in November, though certain individuals begin in October (Harter and Hines, 2008 and NOAA Fisheries, 2014a). The incubation period lasts throughout the summer until they become juveniles, which then spend a year or two of residency before migrating to the ocean at ages 2-3. In the Scott River watershed, potential Coho habitat is considered to be within most of the Scott Valley and the low gradient areas (as seen in Figure 12). Coho utilize these streams for spawning, egg incubation, and rearing. The low-gradient stream reaches are present in the valley because of the same geologic
histories that created the alluvial aquifer system. Currently, Coho appear to utilize the middle portions of the main stem of the Scott River, though their intrinsic habitat (see NOAA Fisheries, 2014a) includes habitat upstream and in the western tributaries. Altered hydrologic conditions are considered the highest ranking stress in the Coho recovery plan because it affects every life stage from egg, fry, juvenile, smolt to adult (NOAA Fisheries, 2014a). The low-flow periods are mostly likely to affect juvenile rearing; their most utilized habitat in the Scott is also that area where stream reaches dry in the summer.

Chinook appear to be better adapted to the challenge posed by the low-flow limitations. They largely migrate in October, spawn, complete their incubation in the winter, and out-migrate before July (Harter and Hines, 2008). Chinook utilize much of the same habitat in the Scott as Coho but at a different time. Figure 15 shows how the different anadromous fish species life cycle interacts with the streamflow, precipitation, and diversion amounts in the Scott.
Figure 15: Mean monthly discharge at Fort Jones gage 1980-2015, mean monthly precipitation 1936-2015, and USFS decreed fish flows (data from USGS, WCCR, and SWRCB 2016). Anadromous fish life cycle chart adapted from Harter and Hines 2008.

In 2014, the multi-year drought combined with on-going water use to stand a major adult Coho run of 2,700 fish in disconnected pools along the Scott River (Bull et. al, 2015). The SWRCB issued a notice of curtailment for all of the junior water rights holders in the winter, but not for the priority 1 or pre-1914 water rights holders. Despite the drought, the winter of 2013 was the biggest Coho run, since the data collection effort began in 2006. To provide temporary relief, the Scott River Water Trust purchased water from priority 1 users for an undisclosed value. The 7660 -acre feet of water leased (i.e. left instream by non-use) benefited 18.6 miles of
tributaries and stream habitat (Bull et. al, 2015). In the Trust’s 2012 annual report, $55/acre foot was the reported price of water in the summer, equating to an estimated $42,000 of cost for the 2014 water leases. This additional water helped, but did not prevent disconnection of the stream between early July and late September for the monitored portion of the rescue effort. During the peak of the problem in mid August, an estimated 50% of the monitored area was without surface flows (Bull et. al, 2015). CDFW conducted a mass relocation of juvenile fish to wetter portions of the Scott River and even outside of the sub-watershed to a Klamath River hatchery. CDFW and NOAA estimate over 132,000 juvenile salmonids were relocated.

While the effort was a success in some ways, it also highlights the challenge advocates and regulators faced in managing fish populations in the Scott River; they cannot control the occurrence of drought, the priority 1 allocation of water rights holders, or the quantity of pumping that effects stream flows. One private landowner with a “significant property ownership” declined to give CDFW and the relocation operation access to the property and stream in key Coho habitat areas. While the $40,000+ of compensation for the farmers and the many hours of government staff time spent on the project were necessary, the question of what necessitated these actions and who is responsible for them is not addressed in the “Cooperative Report” written by the participants.

These species are threatened by numerous other factors besides the low flow period. NOAA’s recovery plan (2014) lists them in order of priority: agricultural practices, dams/diversions, channelization/diking, climate change, roads, high severity fire, hatcheries, mining/gravel extraction, development, timber harvest, stream barriers, and fishing. Formally evaluating the relative contribution of each of these threats can be a difficult scientific undertaking. These species have complex life cycles and specific requirements affected by many factors, yet none are more important than water, their most basic requirement, without which all the other threats are irrelevant.

Limited data exists for two critical pieces of information connecting fish and groundwater: the number anadromous fish in the Scott River at their different life stages at different times and the number of days that portions of the Scott River go dry and strand those fish. Nonetheless, it is apparent that in drought conditions such as 2014 large portions if not the majority of the fish populations will die without costly rescue efforts. Alternatively, reductions in
Stream diversions and groundwater pumping could prevent the rescue efforts from needing to occur by maintain a more natural flow regime.

Stream Depletion from Wells

Two studies have analyzed the question of how wells in the Scott Valley have caused stream depletion. In 2012, S.S. Papadopulos & Associates, Inc. (“SSPA”) created a 3D numerical model using MODFLOW for the Karuk Tribe. The Karuk Tribe are a large, federally recognized tribe in the Klamath watershed that consider salmon a sacred natural and cultural resource. The second research effort was from UC Davis that analyzed the soil-water budget coupled with Jenkins’ analytical stream depletion function. Each approach arrives at a slightly different soil-water budget based on the data sets and methodologies used, though their conclusions about water use are similar. The principal differences are level of hydrogeology and data that the model can incorporate beyond the inputs for the Jenkins’ equation.

SSPA included two layers in MODFLOW: a top layer that contains the water table and a bottom layer that contains the deeper sediments that represent storage. SSPA modeled and incorporated important parts of the overall hydrogeologic system: precipitation, surface elevations, recharge and discharge areas, and riparian ET. The depth of the stream relative to the aquifer and water table elevations is an important consideration in reality and in the SSPA simulations.

UC Davis built a fairly sophisticated soil-water budget that considered different crop types (Foglia et al., 2013b). This water use data by crop type and land use was then coupled with Jenkins’ analytical solution to stream depletion from wells. Jenkins’ solutions makes several important and physically improbable assumptions: the aquifer width is infinite, the aquifer is isotropic (i.e. homogeneous materials throughout) and that the stream channel and well penetrates the full depth of the aquifer. The first assumption is a physical impossibility. The second assumption is also impossible, but does not especially matter where a ‘mean’ value of the aquifer materials is sufficiently representative of the whole. As long as the materials in the Scott aquifer are heterogeneous everywhere, this assumption may not cause large errors. In the case of the Scott Valley aquifer, some wells do reach near the full depth of the aquifer because it is relatively shallow. Streams are unlikely to penetrate the full depth of the aquifer, although a
shallow aquifer with a very incised stream may approach that. Jenkins’ solution can produce important and relatively accurate predictions about stream depletion from wells, especially when coupled with the robust water budget built by the Davis researchers.

Foglia et al. (2013b) combine the presumed seasonal pumping patterns of the wells, the estimated groundwater volume, distribute that across the wells by crop type, and then apply the Jenkins equation to obtain the SDF. In this particular aquifer, the storage coefficient varies little, while the transmissivity varies with each well (Mack, 1958). A lack of data on local transmissivity reduces the accuracy of the solution. In this setting, the distance of the well from the Scott River has the greatest influence over SDF, which ranges from 1 day to 3600 days. Because pumping is generally seasonal, those wells with SDF values above 1000 appear to “have limited effect on stream depletion during the 4 month pumping season,” (Foglia et al, 2013b). Or said another way, the majority the pumping from high SDF wells reduces groundwater storage volume for multiple years before causing significant stream depletion. The stream depletion for those wells is also spread out across the year, when water is more available, and not just in the growing season. This can be seen in Figure 16 in the purple line along the X-axis showing a well with an SDF of 1504. While these high-SDF well effects are not individually significant in the season and their effects occur slowly, they do contribute over time.

![Figure 16: Stream depletion effects from eight example wells with different SDF values in days calculated with the Jenkins solution (originally presented in Foglia et al. 2013b).](image)
The long-term effects of the stream depletion are estimated to be fully realized (i.e. reach a steady state equilibrium) after 20 years (Foglia et. al, 2013b). This appears to support the idea that more wells have been constructed since the 1980 adjudication, yet the problem has only worsened in recent years and that climate can only partially explain the decline of water evident at the USGS gage. The Karuk Tribe state in their press release for the groundwater model that “there were 99 irrigation wells in 1979; 130 irrigation wells by 1999; and 172 irrigation wells as of 2010.” It is difficult to estimate whether surface water use has changed much since the adjudication without monitoring data. If it is assumed that priority 1 users always take as much of the allocated amount as feasible, the amount of water at the USGS gage reflects this increased use of groundwater and the time delay from those distant wells to the stream depletion evident at the gage.

Foglia et al. (2013b) test a number of climatic and pumping scenarios and estimate a range of 21-55 cfs stream depletion in July and August. They test the scenario with the least stream depletion against SSPA’s numerical model to evaluate the accuracy. The SSPA model estimated 16 cfs of stream depletion under the same conditions. The ~25% difference in the results affirms other studies that show the analytical solution can potentially overestimate stream depletion and is a conservation tool analyzing potential impacts (Foglia et al., 2013b).

The SSPA model also analyzed impacts from pumping on tributary streams in addition to the Scott River. The model also directly analyzes the impacts of wells outside of the adjudication (the results of the Foglia et. al 2013b could be used to the same effect). Their results are consistent with the analytical solution. The model “shows that, on average, increases in groundwater pumping are entirely conveyed to equivalent reductions in streamflow within approximately five years, with the bulk of the impact occurring in the first year or two,” (SSPA, 2012). This finding is supported by Foglia et. al’s (2013b) research that shows only 6% of estimated groundwater pumping has an SDF > 1000 and therefore does not produce significant stream depletion during the growing season. The remaining 94% of pumping volume causes stream depletion in the near term.

Management Options and Research Question Review

Management Options
The Scott valley’s water problems typify many of California’s structural challenges in managing water: an over-allocated and adjudicated surface water system, an excess of groundwater pumping, the majority of flow volume outside of the growing season, and special status anadromous fish that require water just at the time it is most in demand by people. The technical, regulatory, and policy connection between groundwater and ecosystems that depend on it has been non-existent until SGMA. Farmers are pitted against environmentalists and Native Americans. Unlike many watersheds, the Scott does not have a dam to control surface water flows in the summer. The merits of constructing a dam have been discussed since water became an issue in the Scott. In 1991, DWR conducted a preliminary analysis to augment flows for fish. One of their principal proposals was to construct a dam to store water. A dam would provide a mechanism for managing low flow periods, but it would also cause other negative effects to anadromous fish that may defeat the purpose of the dam. The dam was never constructed.

The DWR report also suggested pumping distant groundwater directly to the stream to augment flows, though further hydrogeologic study was needed at the time to determine the feasibility of the idea (Echols 1991). Foglia et al. (2013b) recommend something similar in effect by evaluating the transfer of groundwater from distance wells to groundwater users closer to the stream during July and August. After many years, the total volume of stream depletion would likely be the same, but the timing of that depletion may be partially shifted from July and August. They also recommend using winter and spring surface flows to store groundwater near the stream, though they do not describe the physical mechanism such as recharge ponds or recharge wells that would achieve that result. The groundwater model report by SSPA and a related technical memo do not directly contain management recommendations. Rather, they build the scientific case that groundwater pumped outside of the adjudicated areas is causing stream depletion in relatively short time spans. In the accompanying press release by the Karuk Tribe, the Karuk chairman Buster Attebery asks, “Can we solve this problem by recharging groundwater stores with off channel reservoirs or beaver ponds? Do we need a shorter irrigation season?” None of the other studies, such as the Groundwater Study Plan (Harter and Hines, 2008) or the Scott Valley Integrated Hydrologic Model (Foglia et. al, 2013a) make management recommendations, though each acknowledge the data and analysis generated will be used for that purpose.
While the technical part of solving the Scott valley’s water problems is complex, the political challenge is perhaps greater. The Scott Valley has a long history of water shortages, regulation, adjudication, and lawsuits. Some of the milestones are presented in Table 4.

<table>
<thead>
<tr>
<th>Event</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shackleford Creek and French Creek (Scott River Tributaries) Adjudications</td>
<td>1950, 1958</td>
</tr>
<tr>
<td>Scott River Adjudication</td>
<td>1980</td>
</tr>
<tr>
<td>DWR Studies Chinook and Increasing Instream Flows</td>
<td>1991</td>
</tr>
<tr>
<td>Increased Groundwater Pumping Outside of the Adjudication</td>
<td>1980-2014</td>
</tr>
<tr>
<td>SWRCB TMDL for Temperature &amp; Sediment</td>
<td>2005</td>
</tr>
<tr>
<td>TMDL Requires Community-based Groundwater Study</td>
<td>2008</td>
</tr>
<tr>
<td>ELF &amp; Fishermen’s Groups sue Siskiyou &amp; SWRCB</td>
<td>2011</td>
</tr>
<tr>
<td>Karuk Tribe release groundwater model study conclusions</td>
<td>2012</td>
</tr>
<tr>
<td>UC Davis Researchers Model Stream Depletion</td>
<td>2013</td>
</tr>
<tr>
<td>ELF successful in suit</td>
<td>2014</td>
</tr>
<tr>
<td>SGMA starts regulation of medium and high priority basins</td>
<td>2014</td>
</tr>
</tbody>
</table>

Table 4. Timeline of key water events in the Scott River watershed

The two notable developments that may change this existing pattern of groundwater management (or lack thereof) are SGMA and the Environmental Law Foundation suit. Because the Scott Valley aquifer was identified by DWR as a ‘medium priority basin,’ SGMA requires the groundwater sustainability agencies (‘GSA’) to form and create a groundwater sustainability plan within the next 5-7 years. The plan must define a “minimum threshold” at a monitoring location to define when surface water depletion becomes “significant and unreasonable.” As of May 13th, 2016, no entity has elected to become the GSA for the Scott Valley aquifer. DWR will
shortly be issuing some state-level maps indicating areas of interconnected groundwater and the locations of groundwater dependent ecosystems. The method the SWRCB and DWR will be using to review these locally defined minimum thresholds is unclear. The plan has the right to just maintain the status quo.

The lawsuit from the Environmental Law Foundation and the fishermen’s group centers around the idea that Siskiyou County (as well permit issuer) and the SWRCB (as the agency regulating surface waters) had failed to consider the Public Trust Doctrine. This doctrine was used successfully by the Audubon Society against the Los Angeles Department of Water and Power over the diversion of tributary streams to Mono Lake that caused harm to ‘public trust resources’ (California gulls) in a ‘navigable’ waterway. ELF argued the use of groundwater outside of the adjudicated areas was tantamount to the same kind of diversion. The public trust doctrine requires the State to consider harm to public trust resources, not necessarily to prevent them. ELF was successful in its suit and now the County cannot issue any additional well permits. While the SWRCB initially argued it did not have jurisdiction over groundwater, they switched positions, eventually affirming their obligation to consider public trust resources.

The management of the aquifer and the Scott River has no easy solutions. A very large amount of technical data and analysis has been assembled to date. Key data gaps are a comprehensive inventory of wells, well metering that directly measures groundwater extraction, direct measurements of instream diversions, more reach-specific monitoring and data about low-flow conditions that harm fish, and more detailed hydrogeologic and geomorphic data to assess the effects of individual wells on specific reaches, and better fish counts. None of these data, however, appear likely to change the issues that face the watershed as a whole, but may be useful to assess the role of individual wells and help in the appropriation of responsibility.

Research Question Review

While the amount of stream depletion by well vary between the analytical and 3D model, the data share the same basic conclusion: the vast majority of wells in the Scott aquifer cause stream depletion in a relatively short time frame in amounts approaching their pumping rates. The materials between the well and stream affect the timing and short-term magnitude of the
depletion but appear to suggest nearly of all of the aquifer materials are interconnected to the Scott River. The materials are highly complex and have a range of hydraulic conductivities.

The research does not address the limited number of wells in the mountain areas outside of the aquifer. Because storage is limited in those settings, these wells are likely to reduce groundwater discharge to streams. These wells, however, are more likely for domestic use, which requires much smaller quantities of water. How significant this effect is uncertain. Some wells in the western parts of the valley may be using water that naturally does not reach the stream and instead discharges to the wetlands and springs. This type of well is not analyzed in either model, though the SSPA model includes ET from the wetlands and could be used for that purpose. The SSPA model also indicates the presence of several artesian wells in the Scott aquifer. How the reduction in pressure from these small confined areas affects surrounding semi-confined and unconfined layers and discharge is not clear, though it can be presumed to have some effect.

Overall, nearly all of the groundwater in the Scott Valley aquifer is ‘interconnected’ with the surface water systems. The relatively shallow depth of the materials and their hydraulic conductivities facilitate stream depletion. The effects of more distant wells occur over many years and for long periods of time within the year after pumping has ceased. While these effects on anadromous fish are lessened because they mostly cause stream depletion outside of the low flow period, some portion of their depletion does occur during the low flow period. The scale of stream depletion from groundwater extraction, estimated between 16 cfs and 55 cfs during July and August, is significantly less than 235 cfs allocated to the priority 1 users. Yet the use of both system influences the other: if surface water is unavailable, more groundwater is likely to be pumped, causing less surface water to be available. While the scale of total stream depletion from pumping is much less than the priority 1 allocation, the near equivalent overall estimated groundwater and surface water use (~40,000 – 50,000 acre feet/year for each) suggests the priority 1 allocation is often not met, surface waters are too limited to divert, and therefore compensated for with groundwater pumping. While groundwater extraction may have lesser and slower impacts to the stream during the low flow periods than direct surface water diversions, they are not mutually exclusive actions in the Scott River watershed because not enough surface water is available during the times it is needed.
The estimated volume of groundwater use is also only 10% of the total estimated storage in the aquifer. Further, the SSPA model estimates that ~25% of groundwater irrigation percolates to recharge the system; net groundwater use may be closer to 7% of groundwater storage. This highlights the idea that even small reductions in the overall storage and water table elevations can have significant effects on the groundwater discharge to the stream. The SSPA model, while not directly addressing the question of the low flow period, does suggest that reductions of 70% of the 2000 levels in groundwater pumping would increase flows by 13.5 cfs or nearly 10,000 acre feet. The timing and stream-specific effects of this action were not evaluated by the model, but the benefits can be presumed to be concentrated in the summer months, just as the impacts appear to be, due to the proximity of and transmissivity of materials around the wells. The current net use of groundwater (pumping – recharge) equals roughly 47 cfs. If concentrated in the summer months as predicted, this would represent up to 30%-50% of the summer/fall flows available in the less-developed period of the 1940s and 1950s.

The Scott River’s fish populations appear susceptible to the impacts of groundwater use for several reasons. The over-allocation of surface water creates a baseline of water shortages that makes the Scott River susceptible to disconnection during drought. The overall lack of storage in the watershed also appears to cause a seasonal shift from surface waters to groundwater in the summer. The nature of the aquifer materials means that shift to groundwater pumping further reduces surface water, even within the season. The preferred habitat of the Coho is also those low gradient areas where the alluvial deposits built up over time to create the aquifer. Some of the western tributaries that have historically gone dry during droughts are intrinsically vulnerable habitats to minor reductions in streamflow. The presence of the aquifer is what naturally maintained baseflow and helped the anadromous to evolve and thrive in this watershed, but it also what kept farms growing in the valley even as surface water was unavailable.
Section III: The Cosumnes River

Figure 17: Map of the lower Cosumnes watershed and aquifer and adjacent groundwater basins
Background and Hydrogeology

Land Use and Political Boundaries

The ~1300 square mile Cosumnes River watershed runs from the Sierra Nevada Mountains in Amador County at an elevation of 7500 feet down to just below sea level near the Sacramento-San Joaquin Delta. On its 80-mile path way to the Delta, the Cosumnes passes through El Dorado and Sacramento Counties before its confluence with the Mokelumne River. While the Sierra portion is steep, the gentle slopes of the lower watershed makes the Cosumnes a low-gradient river (Kleinschmidt, 2008).

The focus area of this case study is the lower half of the Cosumnes River in Sacramento County, below the confluence of the North, Middle, and South fork of the Cosumnes. Near the Delta, this area contains many farm fields protected by low-lying levees that can be seasonally flooded (Moyle et al., 2003). Much of the land use in the middle portion of the study area is vineyards and row crops along with some single-family homes. Hydraulic mining and placer dredging for gold substantially altered the top of the study area. A mix of grazing, vineyards, and urbanization occurs in the area today (Moyle et al., 2003).

The upper half of the watershed (outside of the study area) is mostly Sierra and foothill forest: blue oaks, pines, and conifers. In the lower half, much of land is naturally grasslands, vernal pools, and riparian woodlands. This area is also where agricultural and urban development has occurred and is more likely to grow in the future (Kleinschmidt, 2008). These developments in the lower areas cut off the Cosumnes from some of its historic multi-braided channels and confine the river to a single area (Booth et al., 2006).

Hydrogeology

The Cosumnes River is considered “the last major undammed river in California,” (Fleckenstein et. al, 2006). There are, however, several small impoundments for diversion and a small dam on Camp Creek, a tributary of the North Fork of the Cosumnes, though it is considered to have a minor effect on the overall hydrology (Kleinschmidt, 2008). The Cosumnes River has some of the least altered hydrology of any watershed in California, though diversions, flood control, mining, timber harvest, and urbanization all occur in the watershed.
Moyle et al. (2003) divided the watershed into eight hydrogeomorphic segments to describe the different watershed characteristics as seen in Figure 18. The principal division is between the Sierra Nevada and Central Valley physiographic provinces. Steep-gradient and bedrock-controlled watersheds define the former area, whereas the alluvial depositional processes of the Central Valley characterize the latter. The case study area begins approximately at the divide between the two in the Lower Foothill Area (IV in Figure 18), which is coincidently around the Sacramento County line and a USGS stream gage.

Figure 18: Depiction of hydrogeomorphic segments of the Cosumnes watershed (originally presented in Moyle et al., 2003).

The lower three hydrogeomorphic segments on the watershed differ from the upper portions in that they have historically had a strong physical connection with the surrounding upland ecosystems through flooding and channel migration. Today, the channel is confined in the ‘Tidal Floodbasin’ and the ‘Incised, Meandering’ portion of the watershed due to agricultural levees.
More than 80% of the watershed is below 5000 feet elevation and so much of the hydrology is driven by rainfall and not snowmelt, resulting “higher winter flood pulses and, relative to other Sierran drainages, smaller spring flood flows,” (Moyle et al., 2003).

Flow volumes in the upstream Michigan Bar gage (located east in Figure 17) show relatively little variation between decades as seen in at the top of Figure 19. In the lower basin, however, volumes have steadily decreased overtime at the McConnell gage (located west in Figure 17) as seen at bottom of Figure 19 (Mount et al., 2001), although the data is limited to 1940-1982.
Figure 19 At top, two-decade box plot hydrograph 1907-2016 for Michigan Bar (MHB) stream gage. At bottom, decadal box plot hydrograph for 1941-1979 for the McConnell gage (MCC) (data from USGS).
Because precipitation has not been decreasing, increased groundwater extraction is the most likely explanation, which is supported by the decreasing groundwater elevations that have been observed over time, as seen Figure 20 below. The majority of the decline appears to have occurred from 1940-1982. In the last 30+ years, groundwater levels have been relatively steady. Groundwater elevation data across the region indicates the Cosumnes River is located between two major cones of depression that are the result of the cumulative effect of groundwater pumping (Figure 21).

Figure 20: Groundwater elevations in three monitoring wells and projection back to 1935 for one well (originally presented in Mount et al., 2001).
Figure 21 Modeled groundwater elevations Sacramento County as of Spring 2000 (originally presented in Robertson-Bryan and RIME, 2011).

Figure 20 simulates the pre-1952 levels of groundwater pumping for well 06N06E18G01M and indicates groundwater elevations were once near surface water streams; the Cosumnes River was likely hydraulically connected and received greater quantities of baseflow before heavy groundwater pumping began. Today, the majority of the Cosumnes River in the study area is disconnected from the aquifer and is considered a losing river. As can be seen in the McConnell hydrograph in Figure 19, there is very little measurable flow in August and September. This regular drying of the river indicates groundwater is not contributing appreciable
quantities of baseflow. In 2001, the groundwater elevation was down to 55’ below the Cosumnes (Mount et al., 2001).

Flooding plays an important role in maintaining the hydrology of the lower portion of the Cosumnes (Kleinschmidt, 2008 and Booth et al., 2006). The floods provide sediments and nutrients to the riparian forests and disperse seed from different plants during different times of the year. Booth et al. (2006) characterize two main flood types in the Cosumnes: a winter flooding period from November to February that has larger peak flows with shorter durations and a spring flood period from March to May with smaller peak flows that occur more frequently. The latter event contributes greater volumes of water because of the increased frequency. The spring floods may be caused by some combination of snowmelt and precipitation. Rising springtime temperatures in the late twentieth century may point to a climate change related trend that may increase floods (Booth et al. 2006). These flood processes also provide an important source of recharge for shallow and deep groundwater (Fleckenstein et al., 2006 and Mount et al., 2001).

The flood processes in the lower Cosumnes River have gradually built up the alluvial sediments that make up the local aquifers. Alluvial fan processes, particularly in the middle portion of the watershed (segment III in Figure 18), created many of the aquifer materials during the Pleistocene (Kleinschmidt, 2008). The water bearing aquifer units are described as the Quaternary Riverbank, the Tertiary Laguna, and Mehrten formation, as depicted in Figure 22.

Figure 22: Generalized depiction of geologic formations south of the Cosumnes (Robertson-Bryan and RIME, 2011). X-axis right is the highly eastern beginning of Central Valley. X-axis left is the central valley.
The Laguna and Riverbank are difficult to differentiate, came about in similar processes, and can be grouped together as the Laguna-Riverbank complex. The Laguna-Riverbank complex ranges from 100 meters thick (as in the study area) to possibly 300m in the lowest parts of the Central Valley. This complex is made of tannish, granitic clay and silt deposits interspersed with sand and gravel channels. Alluvial sediments are typically highly heterogeneous with a very wide range of hydraulic conductivities (Fleckenstein et al., 2006) and the Laguna Formation appears to conform to that idea (DWR, 1980). Nearly all of the well logs in the study area are from this complex (Fleckenstein et al., 2006). Different parts of the formation, reflecting different textures, produce varying quantities of water.

The Mehrten Formation was originally created by volcanic mudflow and volcanic fluvial depositional processes. Its permeability is highly variable due the mixture of brown, dark-brown fine texture clays and sediments, ‘tuff breccia’ (compressed volcanic ash), sands, and gravels (DWR, 1980). The formation ranges from tens of meters in thickness near the mountains to the several hundred meters in the valley (Fleckenstein et al., 2006). The Mehrten is generally deeper than most wells in the study area, but provides large quantities of aquifer storage and water to wells outside of the study area (DWR, 1980), except where the tuff breccia creates an impermeable layer. Due to the heterogeneous nature of the both the Laguna-Riverbank Complex and the Mehrten Formation, the aquifer has a range of partially or mostly confined areas, except for the alluvial deposits near the surface that are largely unconfined. This mix of materials and layers is evident in the well logs and some of the shallow, perched aquifers near Highway 99 that support riparian vegetation communities (Kleinschmidt, 2008).

The same depositional and layering processes that built up the aquifer units likely formed the perched aquifers in certain stream reaches. These perched aquifers units play an important role in the Cosumnes River because they are largely free of wells and are separated from the rest of the system by aquitards (Niswonger, 2006). In the study area, these perched aquifers are most present in the lower reaches near the Delta around Highway 99 (Kleinschmidt, 2008). Evaluating different water management alternatives to restore disconnected stream reaches requires understanding the extent of these perched aquifer systems. In the Cosumnes, the extent of riparian vegetation in the last thirty years generally indicates the presence of these perched
aquifers (Niswonger, 2006). It also conversely indicates the limited areas where the Cosumnes is not a losing river.

Fleckenstein et al. (2006) analyzed how alluvial soil textures affected stream losses and low flows by combining a geostatistical simulation of the geologic materials (“hydrofacies”) with a 3D groundwater and surface model. The authors grouped materials in the study area by type (Table 5).

<table>
<thead>
<tr>
<th>Hydrofacies</th>
<th>Geologic Interpretation</th>
<th>Texture</th>
<th>Hydraulic Conductivity (m/s)</th>
<th>Specific Yield</th>
<th>Specific Storage</th>
<th>Volumetric Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel and coarse sand</td>
<td>Channel</td>
<td>Gravel and coarse sand</td>
<td>4.0 x 10^{-3}</td>
<td>.25</td>
<td>2.0 x 10^{-3}</td>
<td>11%</td>
</tr>
<tr>
<td>Sand</td>
<td>Near channel/levee</td>
<td>Sands (fine to coarse)</td>
<td>1.5 x 10^{-3}</td>
<td>.20</td>
<td>8.0 x 10^{-3}</td>
<td>9%</td>
</tr>
<tr>
<td>Muddy Sands</td>
<td>Proximal floodplain</td>
<td>Silty and clayey sands, sandy clays, and silts</td>
<td>2.5 x 10^{-4}</td>
<td>.15</td>
<td>2.0 x 10^{-4}</td>
<td>19%</td>
</tr>
<tr>
<td>Muds</td>
<td>Floodplain</td>
<td>Clays, silty clays, and shale</td>
<td>6.5 x 10^{-6}</td>
<td>.10</td>
<td>5.0 x 10^{-4}</td>
<td>61%</td>
</tr>
</tbody>
</table>

Table 5: Geologic material attributes and hydraulic parameters, adapted from Fleckenstein et al., 2006.

This depiction connects the distribution of materials with the processes (“geologic interpretation”) that created them. The challenge in analyzing the materials is that the streams and rivers have migrated in the study area over the course of time. Though the distribution of materials follows a conceptual pattern, the actual distribution is very heterogeneous.

Water Use

Estimates of water use in the groundwater basin around the Cosumnes River are difficult to evaluate. The main problem is that the Cosumnes River is roughly the political boundary

65
between two groundwater management areas (the South and Central sub-basins). Therefore, the available figures reflect use in other sub-basins and watersheds.

Surface water diversions account for a smaller portion of water use in the basin. The largest diversion is the Camp Creek dam, which sends roughly 23,000 acre feet across the watershed divide to a reservoir that feeds the American River. Moyle et al. (2003) describe the surface water diversions for the entire watershed as ~12,500 acre-feet per year via two large diversions and 135 small diversions. This aligns with the ~10,000-11,000 acre feet of surface diversions water reported for the area by the groundwater management plan for the Central sub-basin (Norton et al., 2006). Besides the Camp Creek dam, the two main diversions are for the gated community of Rancho Murieta and the Omochumne-Hartnell Water District (OHWD), which mostly provides water to agricultural users. Over 575 potential diversions are in the SWRCB’s water rights database, though “many are apparently not active at the present time because water allocated for diversion exceeds the natural summer flow,” (Moyle et al., 2003). The Electronic Water Rights Information Management System (eWRIMS accessed in March, 2016) indicates that many of the waters rights are riparian and have no allocated diversion amount. The seasonal lack of water in the Cosumnes River in Sacramento County and the study area prevents the use of diversions and causes an increased reliance on groundwater. Norton et al. (2006) report that minimum flows in the Michigan Bar gage must at 76 cfs before water can be diverted, suggesting that much of the use is outside of the July-October period. How much water is diverted, especially by riparian users in the winter, is not clear. Because the Cosumnes is now a losing river, the increased diversion of surface water results in decreased groundwater recharge. The OHVM maintains some abandoned flashboard dams from former riparian diverters in order to increase recharge.

The Central Valley Water Project (CVP) also provides some water to the OHVM. Norton et al. (2006) use the Integrated Surface Groundwater Model (IGSM) for Sacramento that has data from 1975-1990 suggesting widely varying amounts of CVP water are being delivered via the Folsom South Canal (FSC), which conveys American River water south across the Delta. This water is released from the FSC at its crossing with the Cosumnes for riparian diverters. About half of the years received less than 100 acre feet, while the remainder vary from 400-3000 acre
feet. Some of this water is likely recharged to the aquifer via stream seepage after release, though this quantity is likely very limited.

The 1994 levels of groundwater pumping in the study area are estimated at 570,000 acre-feet per year using data from the IGSM (Mount et al. 2001). In 2003, the estimate of groundwater pumping was 350,000 acre-feet. The Sacramento Water Forum defines the sustained yield of the groundwater basins around the Cosumnes (and which includes other watersheds totaling roughly 50% of additional area) to be 273,000 acre-feet north of the Cosumnes and 115,000 acre feet south of the Cosumnes. Water use data is generally unavailable for the study area. Additional modeling of water usage by land use, particularly crop type, or increased well metering would provide additional data.

Overall, the data indicate the lower Cosumnes area relies on more groundwater than surface water by several orders of magnitude. This makes sense given the regularly dry conditions of the Cosumnes and the small quantities of imported water. The number of diversions along the Cosumnes River also suggests water is available in the winter for diversion and likely also indicates water was once available during the summer period when water is most needed on farms. Groundwater elevations in the Cosumnes appear to have dropped quick rapidly from 1950-1980 and stabilized since then. The large-scale cones of depression north and south of the Cosumnes likely formed towards the end of this period and have remained since. Well monitoring data indicate that wells closer to the Cosumnes have higher elevations while those further away have lower levels. This is likely due to the recharge the Cosumnes now provides to the aquifer (Robertson-Bryan and RIME, 2011).

**Instream Flows**

**Species of Interest**

The Cosumnes river supports a number of native fish species, including Sacramento suckers (*Catostomus occidentalis*), Sacramento pikeminnow (*Ptychocheilus grandis*), Prickly sculpin (*Cottus asper*), California roach (*Lavinia symmetricus*), Hitch (*Lavinia exilicauda*), rainbow trout (*Oncorhynchus mykiss*), and several anadromous species including Pacific lamprey (*Lampetra tridentata*) and fall-run Chinook (*Oncorhynchus tschawytscha*). The river is also considered to have suitable habitat for a number of other native fish including, hardhead (
Mylopharodon conocephalus), speckled dace (Rhinichthys osculus), riffle sculpin (Cottus gulosus), and the anadromous form of rainbow trout, steelhead. These species are presumed absent because of the low summer flows and the disconnected summer pools that favor non-native fish (Moyle et al., 2003).

Not far above the study area, as seen in Figure 17, the 45’ Lathrope Falls creates a natural barrier to anadromy. The 35 miles of anadromous fish habitat on the Cosumnes below the Falls is mostly within the study area and the groundwater basin. The relatively low gradient of the lower Cosumnes (400’ - 0’ over 35 miles) may help explain why the Central Valley steelhead population does not appear to regularly use the Cosumnes. The 2014 Recovery Plan for Central Valley Chinook and steelhead considers the Cosumnes potentially suitable rearing habitat for steelhead that spawn in other rivers during wet years (NOAA Fisheries, 2014b).

Fall-run Chinook are the anadromous species most affected by the low -flow period in the Cosumnes. The Central Valley population of Chinook are considered to be an evolutionary distinct population with four distinct runs, spring, fall, late fall, and winter. NOAA considers the winter and spring runs as evolutionary distinct units and lists the Central Valley spring run and the Sacramento winter run as threatened under the endangered species act. No federal listing is given for Central Valley fall or late fall run Chinook, which NOAA considers as part of the same evolutionary significant unit (ESU). CDFW considers the fall and late- fall to be two distinct ESUs and both are listed as being a species of special concern. The Central Valley population of fall-run Chinook is relatively abundant due to their success as a hatchery species in other watersheds. Their State listing reflects the variability in the population size and the influence of hatcheries on the genetics.

From 1997-2005, 100-1,200 Central Valley fall-run Chinook spawning adults returned to the Cosumnes compared to over 4000 from 1953-1973 (Kleinschmidt, 2008). The Cosumnes River Preserve, a 46,000 acre area in the lowest portions of the watershed owned primarily by the Nature Conservation, sets a goal of maintaining a spawning population of 2,000 over a 10-year period. It appears the Chinook wait at the river mouth near the tidally influenced zone for the first large flush of water in the fall and winter. Fleckenstein et al. (2004) estimate a minimum of seven inches of depth is necessary to initiate migration, corresponding to 20.13 cfs
(.57 m³/s) at the McConnell gage. As can be seen below in Figure 23, the number of days during October and November that provide this flow has been decreasing over time.

![Graph showing downward trend of minimum migratory flows](image)

Figure 23: Downward trend of minimum migratory flows for Chinook in October and November 1942-1982 at the McConnell gage (originally presented in Fleckenstein et al., 2004).

The decline in days with minimum migratory flows corresponds to the period in which Chinook have declined. If the spawning of the Chinook is delayed, the time smolts have to grow in the river is diminished, reducing their size and vigor. Fall-run Chinook naturally return to the ocean smaller than other Central Valley fish runs (Moyle et al., 2015), which may make them more vulnerable to fewer days in the winter rearing period. Without sustained minimum flows, Chinook may also become stranded in pools that may dry out before the next flow event. Fall flows were considered to be the ‘critical limiting factor’ by the USFWS for Chinook in the Cosumnes (Hall, 2010). In the 1990s, there were several years where no migration occurred at all because of inadequate flows. Flow magnitude is also positively correlated with the migration rate for Central Valley fall-run Chinook (Moyle et al., 2015). The fall-run Chinook out-migrate in the spring before stream temperatures rise (Moyle et al., 2015). The absence of spring-run and winter-run Chinook is likely be explained their requirement for year-round cold water. Their historical presence in the river is unknown.
Several other factors could be affecting the viability and success of the fall-run Chinook population in the Cosumnes. The substantial reduction in riparian forest habitat and associated floodplains appears to be a contributing factor to the species’ decline. Because Central Valley fall-run Chinook have a relatively short residency time in freshwater, they require as much nutrients to grow as rapidly as possible. Floodplains are rich in organic matter and provide faster growth for the fish than those that are raised in rivers (Moyle et al., 2015). Floods also provide significant quantities of groundwater recharge. The construction of agricultural levees that reduce flooding has reduced the ability of the Chinook to grow rapidly and reduced the groundwater recharge. Sedimentation, stream temperature, and several small instream barriers have also contributed to the decline of the Chinook.

Overall the data indicate the Cosumnes population of Central Valley fall-run Chinook has declined in the same period as groundwater pumping likely disconnected the Cosumnes and it became a losing stream. Their ability to migrate for spawning appears to be delayed by limited fall flows.

Stream Depletion from Wells

Fleckenstein et al. (2004) tested multiple scenarios of groundwater and surface water management in order to provide the necessary volumes of water to reconnect groundwater to the Cosumnes River. Their results show that only the ‘no pumping’ scenario (S2 in the Figure 24) reconnects the river through a change in groundwater management. Because the area relies almost exclusively on groundwater, this is not feasible. As discussed in the management portion of this section, they also analyzed the effects of augmenting surface water with some groundwater pumping reductions as an alternative to providing the necessary flows for Chinook. Their analysis relies on the 3D model developed by the local groundwater management agencies (Integrated Groundwater Surface Water Model Version 3.1).
Figure 24: Visualizations of multiple groundwater and surface water management scenarios showing the groundwater elevation relative to the streambed elevation (originally presented in Fleckenstein et. al, 2004).

Fleckenstein et al.’s (2004) analysis indicates that the elevational difference between the stream and water table is so great (over 55’ in some places) that only very substantial reductions ranging from 400,000 to 570,000 acre feet in groundwater pumping would reconnect the aquifer and the Cosumnes within most of the study area. In the aquifer’s current condition, the source of well water is mostly from storage. Some of the water in storage is the result of ~70,000-140,000 acre-feet per year of seepage from the Cosumnes (Mount et al., 2001). Groundwater extraction has reduced baseflow in the Cosumnes by reducing discharge from the aquifer to the stream and by capturing seepage from surface flows.

Because the Cosumnes is now a losing stream in the study area, it may require several storm events for the flows not to be lost through seepage to groundwater. This ‘pre-wetting’ of the channel is now necessary for surface flows to be sustained and initiate Chinook migration. Because surface water beneath the channel takes some time to percolate into the aquifer, large quantities of surface flows can ‘back up’ and sustain the first surface water flows in the fall. If less of the water was lost to seepage, more would be available to meet the minimum flow
requirements, presumably at an earlier date. This helps explain the reduced number of days in the fall that meet the flow criteria for Chinook, as seen in Figure 23.

At a smaller scale, the aquifer materials play an important role in site-specific hydrology and are an important consideration for management. Niswonger (2006) collected detailed soil and geologic data around the perched aquifers near the McConnell gage. The rate of vertical seepage from the river to the groundwater was dramatically reduced in these areas. Further, the riparian vegetation that has generally been lost because of aquifer disconnection is present in these areas because of the shallow water table. In this particular reach, the perched aquifers did not appear to provide significant baseflow quantities because of the fine sediments around the streambed. In other reaches with coarser sediments, perched aquifers could play an important role in maintaining baseflow.

Fleckenstein et al. (2006) elaborated on Fleckenstein et al.’s (2004) analysis, shown in Figure 24 above, by accounting for the heterogeneity of the aquifer materials in their model. They built a geostatistical simulation using data from well driller’s logs to depict the vertical dimension and a blend of soils surveys, geologic maps, and expert knowledge of the depositional environment to create the horizontal data. Transition probability curves were generated describing the length, proportion, and transition probability between the “hydrofacies”. These probabilities were then used as inputs in a Markov-chain random field generator to create six equally probable realizations of the aquifer. The authors only used six realizations (and not the Monte Carlo method) in order to keep the experiment “computationally tractable” because this data then had to be plugged into the groundwater-surface water model. After incorporating these realizations into the groundwater-surface water model, they were able to better fit the simulated stream elevation with observed levels, as seen in Figure 25 below.
Figure 25 Simulated water table elevations derived from six equally probable geostatistical realizations of aquifer materials (originally presented in Fleckenstein et al. 2006).

These simulations described the observed conditions in the Cosumnes that did not conform to the prior model: that parts of the river near the Michigan Bar USGS gage (MHB) and the McConnell Gage (MCC) are temporarily reconnected with the aquifer during storm events. Their work also shows that modeling based on the assumption of a homogenous aquifer can lead to inaccurate depictions. Localized stream-aquifer interactions are an important management consideration because groundwater extraction is inherently a spatial issue. Well pumping that is separated from the river by the confining layers of the perched aquifers is likely to have a smaller impact on baseflow.

Management Options and Research Question Review

Management Options

Reconnecting the Cosumnes to the aquifer and returning the Cosumnes to its historical condition as a gaining river will require many decades of systematic change and a favorable climate. Several management steps can be taken to effect this change.
Flooding in the Cosumnes will help both the viability of the Chinook population through the creation of nutrient-rich rearing habitat and will provide much needed quantities of groundwater recharge to the regional aquifer and to the localized perched aquifers. Most of the available area for flooding is within the lower portion of the watershed, but some farm levees further upstream could also be breached. How much the absence of flooding has affected the aquifer is unclear, but restoring this process appears to have multiple benefits.

Direct recharge is the process of either pumping water into the ground with injection wells, using constructed recharge basins, or using a permeable streambed to recharge the aquifer. The source of direct recharge water varies, but in the study area there are only two available sources of surface water—the Cosumnes in the winter and imported water from the American River via the Folsom South Canal. The South Basin Groundwater Management Plan tested a direct recharge scenario using recharge basins over a 31-year period. The scenario assumed 19,000 acre feet of imported water would be available during wet years. The recharge ponds were assumed to be near the Cosumnes and thus helped groundwater elevations rise from 5-30 feet by the end of the simulation.

Conjunctive use (i.e. the use of surface water instead of groundwater, AKA in lieu recharge) is one of the Sacramento Water Forum’s principal strategies to managing groundwater (Norton et al., 2006). Importing and diverting surface water reduces the use of groundwater and stabilizes or increases groundwater elevations. Both the central and southern groundwater management agencies around the Cosumnes River have conjunctive use programs. The South Basin Groundwater Management Plan tested a conjunctive use scenario over a 31-year period. The analysis include the addition of 12,300 acre feet of imported surface water during normal and wet years and 2,400 acre feet of recycled water. Their data show a rise in groundwater elevations of 5-15 feet around the Cosumnes after 31 years. The limits to this approach are that the lack of surface water in the first place is often the reason groundwater is used.

The south basin’s model results for direct recharge and conjunctive use appear reasonable given Fleckenstein et al.’s (2004) analysis, which used the same groundwater model, showing a groundwater pumping reduction of 13-17x the amounts described above of over 15 years would be necessary to partially reconnect the river in the study area. Because these alternative management scenarios rely on the same imported water, they are mutually exclusive and suggest
reconnecting the Cosumnes to aquifer is infeasible over a 30-year period with the potentially available water and current demand. These results also indicate that very little can feasibly be done to the groundwater system in order to restore fall flows for Chinook in near term.

Fleckenstein et al., (2004) tested a sort of direct recharge scenario where water from the Folsom South Canal is released at its crossing with the Cosumnes, as seen in Figure 24. Their model indicated a release of 50 cfs into the Cosumnes from September through December (~12,000 acre feet) over a 15-year period would raise groundwater levels around the Cosumnes more than any potential reduction in groundwater pumping. While not reconnecting the aquifer to the Cosumnes, it did increase the number of days flows were sustained during the migration period.

Their model results were modified and put to practice in 2005 by the consulting firm Robertson-Bryan, Inc. on behalf of the Sacramento County Water Agency, Sacramento County Agricultural Water Authority, and the Nature Conservancy, working in conjunction with the SWRCB, U.S. Bureau of Reclamation, and the US Fish and Wildlife Service. Their goal was to ‘pre-wet’ the Cosumnes so that the first storm events were not ‘lost’ to seepage and instead initiated the flows necessary for migration. They used 750 acre feet to maintain a minimum of wetter channel area. The releases were not to be used to initiate migration with an ‘attraction flow’ because of concerns from the USFWS that chemical signals from American River water would confuse and possibly harm the Chinook adapted to the Cosumnes, as is the case elsewhere in the Central Valley. The project continued until the first large storm event on December 1st, 2005. Though the project successfully pre-wet the channel, it does not appear the program has continued since. While it is technically feasible to import water for the purposes of pre-wetting or even initiating migratory flows in lieu of the natural baseflow groundwater provides, the risks outweigh the benefits in the eyes of the wildlife regulatory agencies.

Research Question Review

Before wells were used in the Cosumnes river sub-basin, the river was likely a gaining river. Some stretches during the late fall may have been losing, but baseflow appear to have been sustained by groundwater. While the migration of the Central Valley population of the fall-run Chinook was likely tied to weather patterns, the losing condition of the Cosumnes River due to
groundwater extraction appears to have delayed the timing of their migration. Because the species is adapted to a short residency time in freshwater systems, limiting their migration and rearing period appears to have diminished the population.

The alluvial aquifer materials are highly variable in the Cosumnes. While most of the aquifer was once strongly connected with the Cosumnes river, only the areas that are sustained by perched aquifers have the same connectivity as they used to. These areas and the other impermeable layers play an important role in evaluating site-specific water management strategies. In a setting with limited groundwater and surface water available to augment fall flows, targeting the right areas is an important consideration. While the heterogeneous aquifer materials likely control the localized effects of stream depletion from wells, the potentially permanent disconnection of the Cosumnes from the aquifer is an overriding consideration. The volume of storage in the aquifer has provided significant quantities of water during the growing season, far and above volumes the Cosumnes ever could have. This helped create a substantial decline in water table elevations such that it now almost infeasible that the Cosumnes could naturally flow in the fall.
Section IV: Lower Pajaro River

Figure 26: Integrated Hydrologic Model of Pajaro Valley map (originally presented in Hanson et al., 2014).
Background and Hydrogeology

Land Use and Political Boundaries

The Pajaro river is located in a 1,300 square mile watershed on the Central Coast of California. It flows out to Monterey Bay near to the town of Watsonville and originates inland near the town of Hollister. The watershed spans the four counties of San Benito and Santa Clara Counties inland and Monterey and Santa Cruz near the ocean. Agricultural land uses cover most of the watershed with several small towns and cities. The focus of this case study is on the Pajaro Valley, the ‘lower Pajaro’ sub-watershed, centered around the town of Watsonville, which has a population of ~52,000. This area covers 237 square mile portion of the watershed (Hanson et al., 2014).

Hydrogeology

Elevations range from 0 feet at sea level to 2,400 feet near the Mt. Madonna. The groundwater basin study area begins roughly at 400 feet elevation and ends at sea level. Precipitation in the Pajaro Valley is concentrated in the winter and averages around 20” in lower elevations, as seen in Figure 27 below. Higher elevations may receive up to 40” of rain. Snowfall is an extremely rare event. Flow on the Pajaro River and coming into the groundwater basin is partly regulated upstream at the Uvas Dam and Pacheco dam. Many of the stream reaches in the groundwater basin are lined with levees. One USGS stream gage provides data on the Pajaro in the upper portion of the study area and another gage is on Corralitos Creek, a main tributary near the center of the study area.
Figure 27: Mean daily stream flow 1939-2016 at Chittenden Pass entering the Pajaro sub basin with mean monthly precipitation 1909-2008 at Chittenden pass (data from USGS and Western Regional Climate Center).

The Pajaro Valley geology has three main layers of geology. Alluvial deposits from the Holocene and late Pleistocene are the superficial layer. Aromas Sand from the Pleistocene underlies those materials. The Purisima Formation from the Pliocene is found below the Aromas Sand. These layers of geologic materials were used in the “Integrated Hydrologic Model of Pajaro River, Santa Cruz and Monterey Counties, California” developed by the USGS in 2014 (Hanson et al., 2014). The alluvial materials are a mix of marine terrace, landslides, and other materials of alluvial origin and are 15-380 feet thick. These materials also contain a “basal fine-grained confining layer” that ranges in thickness from 15-55 feet, which originated from flooding processes or sediment deposits during the Pleistocene periods of sea level high stand. This layer is defined as those materials comprised of 33% or more of fine-grained materials and acts as a confining layer where present. This layer plays an important role in the groundwater-surface water interaction, as described later in this section.

The Aromas Sand ranges in thickness from 100 feet - 900 feet by the ocean and can be subdivided into different layers. It consists of well-sorted sands with clayey layers and poorly
sorted gravel. These materials are considered the water-bearing aquifer in the Pajaro sub-basin. The upper layer of the Aromas Sands is separated from a lower layer by a confining layer that is 15-115 feet thick in some places and is comprised of 16% of fine-grained materials.

The lowest layer in the Pajaro is the Purisima formation, which is comprised of poorly consolidated materials mostly of marine origin (Allen, 1946). It is unevenly distributed horizontally and vertically in the area with some outcrops at the very top of the watershed. The Purisima formation is considered the bottom layer of the aquifer and represents a large portion of storage, which is below most wells (Hanson et al., 2014). The Purisima formation meets the bedrock formation (or ‘basement’ in Figure 28 below) with insignificant water bearing properties at variable depths. The model contains six layers, not including the basement/impermeable bedrock.

Figure 28: Geologic cross section of the Pajaro sub-basin (originally presented in Hanson et al., 2014).
Two large faults trend from the SE to the NW, roughly perpendicular to the flow of surface water. The San Andreas Fault marks the eastern boundary of the groundwater model and is near the watershed divide. The Zayante Fault runs through the upper third of the sub-basin. Both can be seen in Figure 28. The San Andreas is considered a ‘no-flow’ boundary in the groundwater model, whereas the Zayante is considered a partial horizontal boundary in the Purisima formation.

Water Use

About 85% of water use in the valley is for agriculture and almost 98% of water used is groundwater (Hanson et al., 2014). Domestic and municipal groundwater pumping in the study area has ranged from 6,000-acre feet/year in the 1960s to a peak of 12,000 in the late 1980s before leveling down the 11,000-acre feet/year in the 2000s. Irrigation pumping has not been monitored over time, except for 2002-09 period by the Pajaro Valley Water Management Agency. From 2002-09, the reported and model simulations agree that about 43,000 to 48,000 acre-feet are pumped each year for irrigation. Roughly 2,700 wells are in the study area, ~1000 of which are irrigation wells (Hanson et al, 2014). The Integrated Hydrologic Model for the Pajaro estimates an overdraft condition of ~12,510 acre-feet per year or slightly less than 25% of the annual estimated groundwater pumping.

This overdraft has resulted in lowering groundwater elevations and two cones of depression centered around the Pajaro River, as seen in Figure 29 below. Most of the lowered groundwater elevations appear to have occurred during a drought in the late 1980s and early 1990s. Seawater intrusion into the aquifer is occurring as a result of reduced groundwater outflows and has become a significant groundwater problem near the coast (Hanson et al., 2014).
Figure 29: Groundwater elevations and contours modeled as of 2006 (originally presented in Hanson et al., 2014).

Surface water diversions are relatively few within the groundwater basin. The City of Watsonville operates two diversions along Corralitos Creek and its tributary. The amount of
diversion varies annually. The city’s filter plant has the capacity for 2,400 acre feet per year but averages around 900 acre feet per year, generally diverted from spring to fall because water in winter is too turbid for filtration. Watsonville mainly relies on ~8x that amount of groundwater pumping annually. The city also constructed a water recycling facility in 2009 for agricultural res-use that can produce up to 4000 acre feet per year, though it only produced ~1,600 acre feet in 2010 (City of Watsonville, 2010). The Pajaro Valley Water Management Agency (PVWMA) has also recently diverted surface flows in the Harkins Slough area (located between Watsonville and the coast) in order to provide groundwater recharge through a percolation pond (Schmidt et al., 2011). The PVWMA may divert up to 2000 acre feet/year from November-May, though the actual amount has averaged ~760 acre feet.

Instream Flows
Species of Interest

The Pajaro River hosts steelhead (*Oncorhynchus mykiss*) that are part of the southern-central California Distinct Population Segment and are federally threatened species. It is also a protected State species and part of an Evolutionary Significant Unit. The Pajaro River in the study area primarily services a migratory path to upper watershed areas and not as spawning or rearing habitat, though parts of the upper Corralitos creek appear to provide suitable spawning habitat. The Pajaro River is considered poor rearing habitat because of its minimal summer flows and high water temperatures. It is considered poor spawning habitat because the substrate is too fine and lacks the gravels used by steelhead for spawning (Smith, 2002). Steelhead appear to spend 1-2 years rearing in the upper watershed before out-migrating as smolts (Pajaro River IWRMP, 2014). Like many of the coastal stream south of San Francisco, Coho salmon were present in the Pajaro until the late 1960s (Pajaro River IWRMP, 2014).

A seasonal lagoon forms at the mouth of the Pajaro behind a sandbar in early summer and naturally breaks after storm events erode it in the winter (Smith, 2002). Steelhead migration occurs once the lagoon is open and flows are sustained. The County regularly breaches the levee if the lagoon water rises without breaching the sandbar in order to prevent flooding of farms and residences (California Coastal Commission, 2006).
The NOAA Fisheries South-Central California Steelhead Recovery Plan of 2013 and the Pajaro River Integrated Regional Water Management Plan of 2014 both mention groundwater pumping reductions or increasing stream baseflow in the Pajaro as important ecosystem restoration action. It is not clear from the reports whether they are referring to the areas within this groundwater basin or in the upper watershed areas. Except for the upper Corralitos watershed, very little of the watershed is utilized by steelhead during the low flow season when groundwater’s contribution is generally most important, though the former presence of Coho suggests a historically different water condition.

Stream Depletion from Wells

The horizontal distribution of the confining layer near the surface plays an important role in the overall groundwater surface water interaction. This superficial confining layer acts like an impermeable lining around many of the stream reaches in the study area. The very low hydraulic conductivities between the unconfined alluvium or Aromas Sand layers (layers 1 and 3 in Figure 28) and the confining layer results in a negligible interaction between groundwater and surface water in most of the basin. The range of vertical and lateral hydraulic conductivities of each geologic model layer are depicted in Figure 30 below. The lateral hydraulic conductivity of the alluvial confining layer (in black in Figure 30) may be the limiting factor for stream-aquifer interaction.
Figure 30: Log graph of ranges of vertical and lateral hydraulic conductivities.

Even if groundwater elevations were above the streambed, groundwater discharge into
the stream would likely be limited. Conversely, relatively little surface water is lost through the
streambed. Where the stream and aquifer are connected, the stream reaches are generally losing.
Figure 31 below shows the limited distribution of aquifer-connected stream reaches.
Figure 31: Median simulated infiltration by stream reach in acre-feet per year (originally presented in Hanson et al., 2014).
Additional short-term stream gaging was in place from 2002-2006 as part of UC Santa Cruz research project and provided data for flows between stream reaches in several locations. By subtracting downstream flow volumes from upstream volumes, the modelers were able to estimate stream gains and losses. The same gains and losses were estimated using the estimated hydraulic conductivities of the stream reaches. The modeled stream loses were generally in agreement with the observed volumes. They also indicate that several reaches along Corralitos Creek can sometime be gaining. The area around “Murphy’s Crossing” has the highest conductivity (as seen in Figure 31) of any stream reach in the groundwater basin and also shows a consistently losing pattern. Net stream infiltration (stream losses and gains) from the Pajaro is estimated at 14,470 acre feet of additional groundwater recharge per year (Hanson et al., 2014).

The model’s predicted groundwater elevations in wells that are screened within the perched alluvial aquifer in the Corralitos area are generally less accurate and predict lower levels than observed. It is possible the model also underestimates that amount of stream gains that may result from the perched aquifer, though how the wells in that area affect or reduce the kind of stream gains observed in Figure 32 is unclear. Additional aquifer layers and more site-specific detail would need to be incorporated into the model in order to analyze the effects of this perched
aquifer (Hanson et al., 2014). The baseflow around Corralitos may also be the result of irrigation return flow combining with discharge from the perched aquifer.

Some portion of wells also draw water that would otherwise discharge into the ocean and not a stream. This explains the sea-water intrusion problem now found in the basin. Wells that are closer to the coast or downgradient from a stream are likely to have much less of a potential connection to a stream.

Overall, groundwater elevations have been lowered in the Pajaro sub-basin as a result of excess groundwater pumping. Due to the low hydraulic conductivities present in the superficial confining layer, the majority of streams reaches are not connected to the aquifer. Where they are connected, the net effect is the stream recharging the aquifer. Further, some portion of the aquifer and the wells therein naturally discharge into the ocean and the streams.

Management Options and Research Question Review
Management Options

While more localized investigations around the perched aquifer and the upper part of the Watsonville slough system would likely yield a more accurate depiction of the groundwater-surface water interaction, the additional data and analysis is unlikely to alter the general conclusions of the model (Lockwood, personal communication, 2016 and Hecht, personal communication, 2016). The extent of the perched aquifer is limited relative to the overall system and is unlikely to contribute significant quantities of baseflow that are unaccounted for in the model.

While it is theoretically possible that the Pajaro River was once a gaining river around Murphy’s Crossing, it is very unlikely. Most of the stream loses in the entire basin (~14,470) appear attributable to the reach around Murphy’s crossing. Natural groundwater inflow to the entire basin is estimated around 32,000-42,000 acre-feet per year (Hanson et al., 2014). If reversing these losses takes an equivalent amount of groundwater, it would also require a disproportionate volume of groundwater inflow and recharge to occur in a small fraction of the entire groundwater basin.
Research Question Review

The Pajaro groundwater basin illustrates that where a superficial confining layer is present, it may limit groundwater-surface interaction in a way that greatly minimizes the role groundwater generally plays in providing baseflow. While the relative contribution of those connected stream reaches has not been formally analyzed, it is unlikely historic groundwater elevations would have provided sufficient quantities of discharge in order to sustain year-round flow. It appears the Pajaro in the study is likely a historically losing river. The presence of steelhead in the upper Corralitos and upper watershed area outside of the groundwater basin suggests the groundwater basins plays a supporting role in the steelhead’s lifecycle and likely did so for Coho at one time. How those wells that are screened in the Corralitos perched aquifer area affect the limited steelhead use is unclear. The Pajaro groundwater basin also illustrates the not all alluvial-type aquifers are necessarily broadly connected to streams.
Conclusion

The heterogeneous nature of the materials created by geologic processes, particularly in alluvial aquifers, requires a basin-specific analysis in order to hypothesize what may be occurring in these hydrogeologic systems. Special circumstances are found in each of the case studies examined in this report. Historically intermittent tributaries and a shallow, widely connected aquifer define the Scott River aquifer. Highly heterogeneous materials and perched aquifers define where the Cosumnes River is a losing river. An extensive and superficial confining layer plays an important role in limiting the groundwater and surface water connectivity in the Pajaro basin. Yet each of the studies can be approached with a common analytical framework. A series of basic analytical questions can help articulate where this issue matters most.

- What stream reaches were historically gaining?
- Has groundwater extraction seasonally or annually lowered groundwater elevations below the stream channel?
- Are there confining layers near the surface and where are perched aquifers present?
- Does the current or historic life cycle of anadromous fish spatially interact with the affected stream reaches?
- Based on the aquifer materials and distances wells are from the stream, is there a likely temporal delay to stream depletion yet to be observed?

The historic and current presence of anadromous fish in a watershed generally suggest adequate quantities of cold water available all year. If California’s anadromous fish habitats represent an ecotone from the arid southwest and the rainy northwest, it follows the quality of these habitats naturally cycle with drought and El Nino. Groundwater’s contribution to baseflow in the summer and fall periods buffers the annual stress of the Mediterranean climate and the periodic stress of drought. Where groundwater extraction has seasonally or annually lowered groundwater elevations below the stream channel, the climate-buffering effects of groundwater on ecosystems are reduced. In the 2011-15 drought, Scott River coho regularly became stranded in isolated pools (Bull et. al, 2015). In some cases, as in the Cosumnes, the lowering of groundwater reduces the availability of surface water by creating a losing stream, extending the
period without water. The number of days in October and November that provide adequate flows for the fall-run Chinook migration has been reduced by almost 50% since the 1940s (Fleckenstein et al., 2004). Many of California’s streams naturally oscillate between gaining and losing and thereby providing habitat. Relatively small amounts of groundwater extraction around these streams, as in the Scott River case study, can tip this balance.

Confining layers play a critical role in determining the localized effects of groundwater and surface water interaction. These layers can create an effective barrier between the aquifer and the surface water, as in the Pajaro case study, where the horizontal conductivity of the surface confining layer can be as low as .01 feet/day (Hanson et al., 2014). Confining layers can also create localized perched aquifers that sustain groundwater elevations. The Jenkins Solution shows that low hydraulic conductivities or long distances create an important temporal-lag between groundwater extraction and stream depletion. This lag can shift depletion away from the growing season when water is generally pumped, which can be important where seasonal groundwater levels limit habitat. Because some percent of groundwater extraction generally comes from aquifer storage, the effects of groundwater extraction are generally less than the equivalent volume of surface water diversions. Over many years, however, stream depletion from groundwater extraction approaches 100% of the volume pumped.

Climate change appears to already be affecting the hydrologic cycle of California’s watersheds. In the Scott River, the lowering water-content of snow is reducing summer flows and thus requiring more groundwater in order to sustain flows. If snowpack in general is declining in California, as appears to be the case, the buffering effect of groundwater will becoming more important, even as the volume of recharge is potentially reduced. Almost all of the hydrologic analysis and models reviewed in the course of this research use a reference or simulation period, usually a decade or more of hydrologic data from recent years, to project ‘sustainable’ levels of groundwater extraction in future years. The Sustainable Groundwater Management Act (SGMA) uses a similar approach. This method is flawed for the obvious reason that the past is only a partial predictor of the future and there is strong evidence that climate is and will continue to change in California in challenging ways (Dettinger et al., 2015).

SGMA absolves groundwater extractors from previous impacts to protected species by setting a baseline/reference condition of January 2015. If climate reduces recharge and thus the
‘sustainability’ of these plans, these reference years will provide a floor. It is clear from the case studies that there are many circumstances in which the collective lowering of groundwater has caused the take of protected species. The successful litigation from the Environmental Law Foundation against Siskiyou County affirms that the Public Trust Doctrine applies to all interconnected groundwater. SGMA ignores this requirement by failing to consider existing impacts to public trust resources (anadromous fish) that occurred prior to 2015 and will continue to occur as a result this ‘sustainable’ baseline. While SGMA may be have politically palatable, it relies on the language of sustainability to mask important environmental impacts that will occur as a result of the legislation. How SGMA, DWR, and the SWRCB analyze and define ‘interconnected groundwater’ is to be determined, but there is a strong case to be made that the groundwater is generally connected to surface water and is more the rule than the exception.

SGMA takes the approach that no single solution can solve the challenges groundwater management faces in California. Part of this stems from the political reality of the State controlling a resource that was once considered a property right, but it also emerges from the technical reality that each groundwater basin is somewhat unique. These case studies bear that out. In some instances, like the Scott River, there are logistical and financial solutions to addressing their groundwater management issues. In others, like the Cosumnes, there must be a multi-decade commitment to reducing water use, augmenting recharge where feasible, and hoping climate change does not make the situation much worse. In the Pajaro, the groundwater management may have some small effect on the steelhead, but if the effect exists, it is likely a minor one compared to other factors. The Pajaro illustrates the exception to the type of alluvial aquifers that are found in the Central Valley, though the Pajaro also highlight how groundwater pumping can cause significant seawater intrusion.

Two main concepts have supported the spatial understanding of how hydrologic systems function: the River Continuum Concept described by Vannote et al. (1980) and the Flood Pulse Concept described by Junk et al. (1989). The River Continuum concept articulates the longitudinal ecological connectivity between the upper, middle, and lower watershed areas. It provides a predictive framework for the species, functions, and physical features within each area. The Flood Pulse Concept describes the lateral ecological connectivity between the areas outside of the stream banks. The dynamic movement of rivers and floods interact with more than
just the areas within the present top of the stream banks. The concept of groundwater dependent ecosystems suggests a third-dimension plays a critical role in the function of aquatic ecosystems. The semi-arid nature of California in particular requires the climatic-buffering of groundwater to bridge the seasonal gap in precipitation and the inter-annual variation caused by droughts and El Nino. While groundwater plays an important role everywhere through its contribution to baseflow, many of California’s aquatic ecosystems may be more accurately viewed as ecosystems that exist because of the hydrogeologic landscapes that support them (Hecht and Woyshner, 1984).
Bibliography


Hathaway, Deborah L. *Stream Depletion Impacts Associated with Pumping from within or beyond the “Interconnected Groundwater” Area as Defined in the 1980 Scott Valley Adjudication*. N.p., 2012.


Hecht, Barry, Senior Principal with Balance Hydrologics, in discussion with the author, February 2016.


