DRAFT FOR REVIEW

California's Cascade Aquifers: Resilient and Unrecognized Source Waters

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Executive Summary

California’s snow-capped Cascade mountains – Mount Shasta, Medicine Lake Volcano, and Mount Lassen recharge geographically extensive volcanic aquifers. These California Cascade Aquifers store and release large quantities of groundwater to spring-fed rivers that supply water for multiple human uses, sustain refuge habitat for cold-water aquatic species and provide ecological and economic resilience to drought and projected climate change.

Despite their importance to the state’s economy and ecosystems, these aquifers have never been systematically studied, leaving many as-yet unanswered questions about how much water they take in and store annually before emerging as springs and rivers. This paper highlights the role of California Cascade Aquifers, the need for further study and monitoring, and most importantly, the need for effective policy to ensure sustainable management of this groundwater.

Rain and snow that falls on Mount Shasta is stored underground and released to the Shasta, Upper Sacramento, and McCloud Rivers. Groundwater stored in Medicine Lake Volcano emerges at the largest spring system in the Western US – the Fall River Springs, which supply Fall River a major tributary of the Pit River that flows into Shasta Reservoir. These spring-fed rivers are major sources of inflow into Shasta Reservoir, which can supply 14- 30% of the total storage during drought years and are a major asset to the Central Valley Project. Total spring discharge to the Sacramento River averages about 3000 cubic feet per second, or nearly 700 billion gallons per year. Volcanic aquifers near Mount Lassen emerge to form spring-fed Hat Creek to the north and Lake Almanor in the south. Lake Almanor receives nearly half of its water from springs and supplies flow to the North Fork of the Feather River, which flows into Lake Oroville and the State Water Project.

Spring-fed water from California Cascade Aquifers generates up to 40% of the state’s hydroelectric power and is integral to reaching California’s renewable energy goals. The Pit River hydroelectric scheme supplies approximately 820 megawatts (MW) of generating capacity, and nearly half of the river’s flow comes from volcanic aquifer springs. Another 120 MW of capacity is generated on the North Fork of the Feather River by flow supplied by spring-fed Lake Almanor. The spring-fed river flows captured by Shasta Reservoir contribute to the Shasta Dam Power Plant and contribute up to 30% of a nearly 700 MW generating capacity.

Groundwater from volcanic aquifers keeps rivers flowing even when there is little rain or snow to generate runoff. Climate change is predicted to cause more frequent and intense droughts and shift precipitation to less snow and more rain, and increase temperatures in California, making these aquifers even more important for water supply resilience. Spring-fed rivers also enhance ecological resilience - as temperatures increase they maintain base flow and cold water temperatures, providing stable spawning grounds and refugia for cold-water fish species and other aquatic life. Although storage levels in Shasta Reservoir fell well below their historical averages during the drought, inflows from spring-fed rivers helped to stave off potentially disastrous losses of downstream endangered fish and agricultural productivity (California Department of Water Resources, 2015).

Currently there is a lack of policy to protect and sustainably manage California Cascade Aquifers. Although the Sustainable Groundwater Management Act (SGMA) was passed in 2014 as the first major policy to regulate and manage groundwater in California, volcanic aquifers are excluded from the narrow definition of a groundwater basin incorporating alluvial rock material. It may be possible to change the formal designation in the future, but at present there are few options other than returning volcanic aquifers to basin status through Bulletin 118, the document which lists groundwater basins in California. A grassroots effort is needed to build a stakeholder community and funding to improve the area's groundwater hydrology.

California's Cascade aquifers are located in relatively underpopulated areas, but there are still several potentially threatening land-use changes underway. The water and beverage bottling industry around Mount Shasta has grown recently to take advantage of abundant spring water. This concerns local residents since the total amount of water extracted for bottling is not known or required to be made public, making it impossible to evaluate impacts on the aquifer. As another example, in the Medicine Lake Highlands, large-scale geothermal development has been proposed for more than 20 years and the enhanced geothermal techniques needed to make use of the geothermal heat would require large scale water use and potentially polluting methods including geothermal fracking and acid leaching. Forestry practices also impact on watersheds in this region, but much remains unknown about their impact on groundwater. Research is needed to better understand the connections between forest management practices and volcanic aquifer recharge and storage and annual spring flow.

Without a formal groundwater management authority to address these concerns, the aquifers are essentially left unprotected. If Groundwater Sustainability Agencies existed for the volcanic aquifers in California, then a formal process of new groundwater use could be initiated and a weighed against the needs of other uses and environmental concerns.

Although it is clear that California Cascade aquifers are important sources of water supply and storage, much remains unknown. More research and monitoring is needed to answer baseline questions about how these aquifers function and establish long-term data sets on recharge, discharge, and climate change impacts.

We propose the following as a strategic plan for understanding, protecting, and recognizing California Cascade Aquifers:

Objective: Preserve and protect abundant, pristine volcanic source waters for human and environmental needs

Maintain the current flow of the estimated 3000 cubic feet/second from California Cascade Aquifers to:

- Ensure a drought and climate change-resilient water supply to the Central Valley Project and State Water Projects
- Maintain adequate flows and habitat for cold-water fish and wildlife in spring-fed streams and rivers as drought and climate refugia

- Secure reliable water supply for Northern California water users (agriculture, hydropower, cultural, recreational, fish and wildlife)

Strategies

1. *Research, Assessment and Baseline Evaluation:* Establish existing conditions and measure changes over time
2. *Groundwater Policy and Management*: Developing groundwater management priorities and objectives for currently unmanaged volcanic aquifers
3. *Protection of Recharge Areas*: Identify land conservation strategies to protect priority recharge areas for California Cascade Aquifers

Introduction and Background

Northeastern California is one of the most remote areas in the state and unique in its geology. This area is home to three major volcanic centers belonging to the southern end of the Pacific Northwest Cascade Ranges. The landscape is dominated by remnants of volcanic eruptions that have transpired over the past several million years, forming large expanses of contiguous permeable rock. Nowhere else in California does rock of this type cover such a large geographic region.

In this unique geologic environment, rain and snowmelt can rapidly seep deeply into these permeable rocks and become groundwater. The groundwater eventually emerges as large volume spring flows that form the rivers feeding Shasta Reservoir. In contrast, in other parts of the state rivers are generated by the familiar rain and snowmelt runoff and have very small contribution from spring flow. Furthermore, most groundwater in the rest of California is stored in alluvial aquifers (made of eroded sediments), but in northeastern California, the volume of groundwater stored in permeable volcanic rock is nearly equal to the volume stored in the region's alluvial aquifers. This makes northeastern California a unique and somewhat challenging hydrologic environment to investigate and monitor.

Volcanic aquifers in northeastern California, defined here as California Cascade Aquifers, supply spring-fed rivers that contribute significantly to California's water supply and are resilient to drought. Despite their importance, these volcanic aquifers have never been systematically studied, and are not officially recognized as aquifers. The aim of this work is to highlight the role of California Cascade Aquifers, the need for further study and monitoring, and most importantly, the need for effective policy to ensure sustainable management of this groundwater.

As shown on the map in Figure 1, the region includes the aquifers surrounding Mt. Shasta in the northwest, Medicine Lake Volcano in the northeast, and Lassen Peak in the southeast. Aquifer storage is replenished by annual snow and rain on the flanks of these volcanic systems and the groundwater discharges as flowing springs, forming most of the rivers in northeastern California. This includes the Shasta River, fed by Big Springs on the northwest flank of Mount Shasta, the Upper Sacramento River generated by a series of springs emerging along much of its southwestern flank, and the McCloud River on the southeastern flank fed by some of the largest individual spring flows. Further east, Fall River a major tributary of the Pit River, originates from the largest spring system, Fall River Springs, which are fed by aquifers in the Medicine Lake Volcanic highlands. Volcanic aquifers associated with the Lassen Volcanic Center emerge to form spring-fed Hat Creek to the

Volcanic Aquifers of the US

The northernmost part of California is home to the southern reaches of the Cascade Volcanic Range, one of the major mountain chains of western North America, stretching from British Columbia through Washington and Oregon and into northeastern California. Many of the mountains in the Cascades have had historical eruptions, such as Mt. St. Helens, but also earlier ones in Mount Lassen, Medicine Lake Volcano, and Mount Shasta. The US Geological Survey Water Resources Division refers to groundwater aquifers in the Cascade region as the Northwest Volcanic Aquifer Province, a highly permeable hard rock groundwater system providing water resources to multi-billion dollar agricultural and industrial enterprises in the Pacific Northwest.

north and Lake Almanor in the south. Lake Almanor receives nearly half of its water from springs beneath and upstream of the lake and supplies flow to the North Fork of the Feather River. Figures 2 and 3 show several of the springs emerging from California Cascade Aquifers.

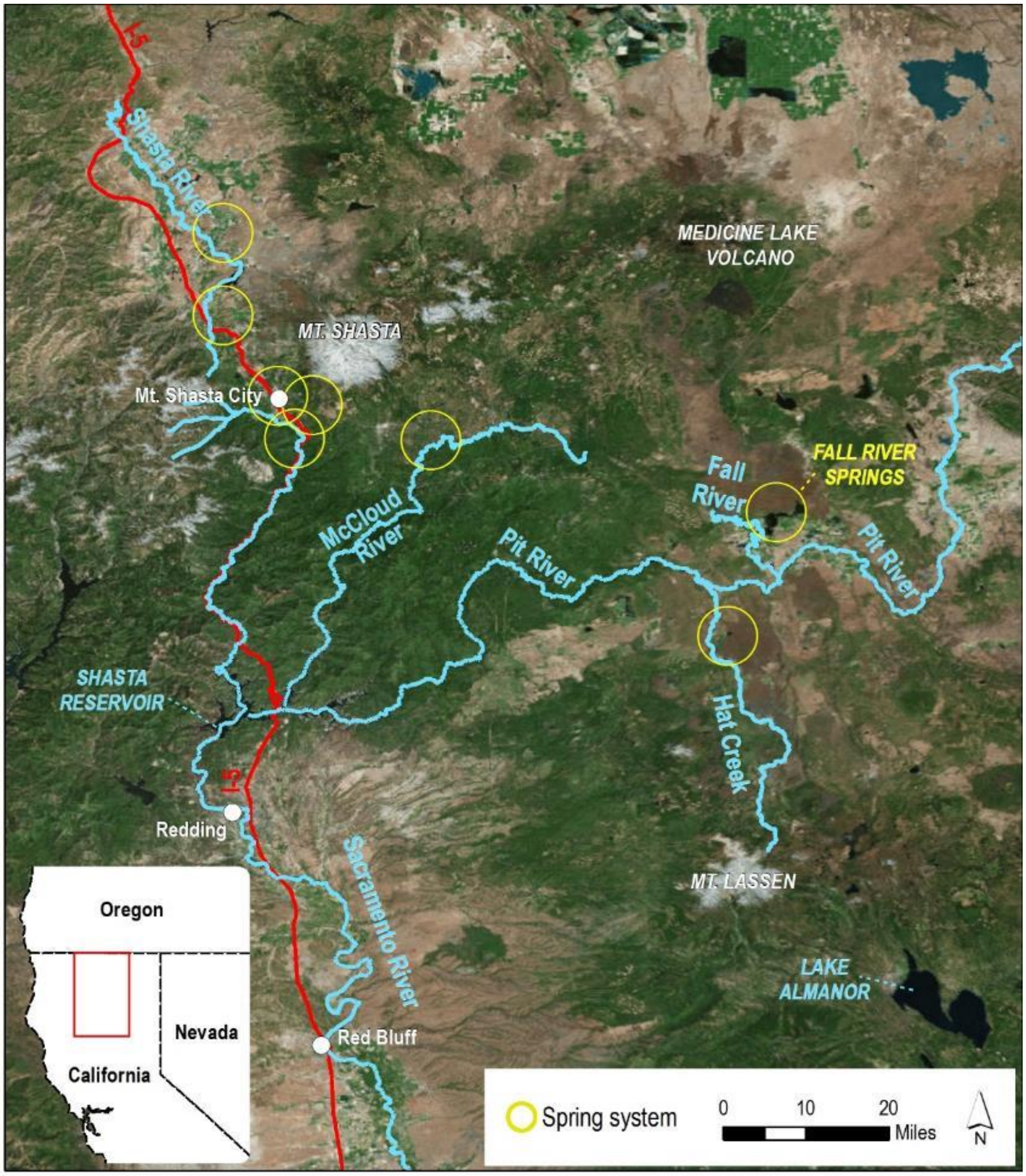

FIGURE 1: MAP OF CALIFORNIA CASCADE AQUIFERS REGION (MAP BY URI GILAD, 2015)

FIGURE 2: RAINBOW SPRING, PART OF THE FALL RIVER SPRINGS SYSTEM (PHOTO BY LEE DAVISSON)

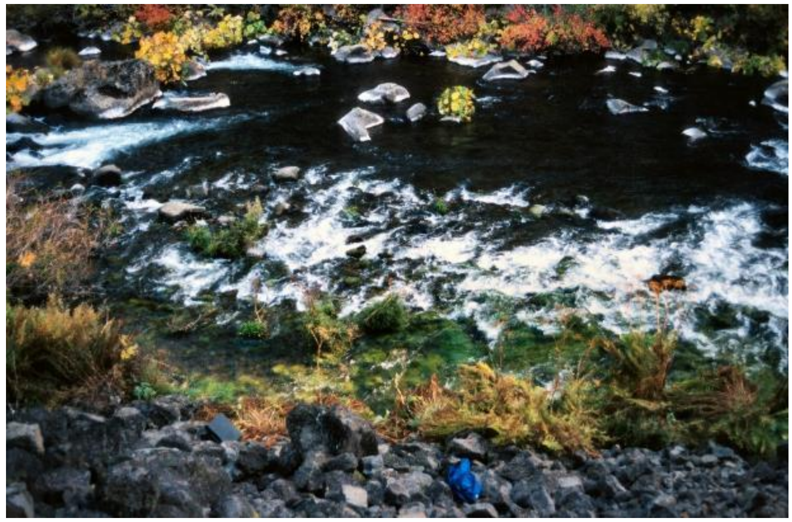

FIGURE 3: MCCLOUD BIG SPRINGS ON THE MCCLOUD RIVER (PHOTO BY LEE DAVISSON)

Volcanic Aquifers Drive the Economy and the Natural Environment

California Cascade Aquifers and the associated spring-fed rivers supply water for domestic and agricultural uses in California, and sustain refuge habitat for cold-water aquatic species. They also provide ecological and economic resilience to drought and projected climate change. On average, the total spring discharge is about 3000 cubic feet per second, or nearly 700 billion gallons per year. Flowing downstream, this water is captured as storage in Shasta Reservoir and supplies water to the Central Valley Project. The water emerging from these springs equates to approximately 20% of the volumetric summertime flow in the Sacramento River measured at Freeport, located at the northern end of the Sacramento-San Joaquin Delta. At a market value of $500 per acre-foot, for example, this spring flow represents a one billion dollar asset annually.

Critical Supply for the Central Valley Project and the State Water Project

Spring-fed rivers originating from California Cascade Aquifers are major sources of inflow into Shasta Reservoir, the largest in California, and a key part of the Central Valley Project. Spring water flows from the Fall River and Hat Creek into the Pit River, which forms the eastern arm of the lake. The Upper Sacramento and McCloud Rivers form the other two major arms (see Figure 2). In total, over two million acre feet per year flow from California Cascade Aquifers into Shasta Reservoir accounting for about one-half of its approximately 4.5 million acre-ft storage capacity.

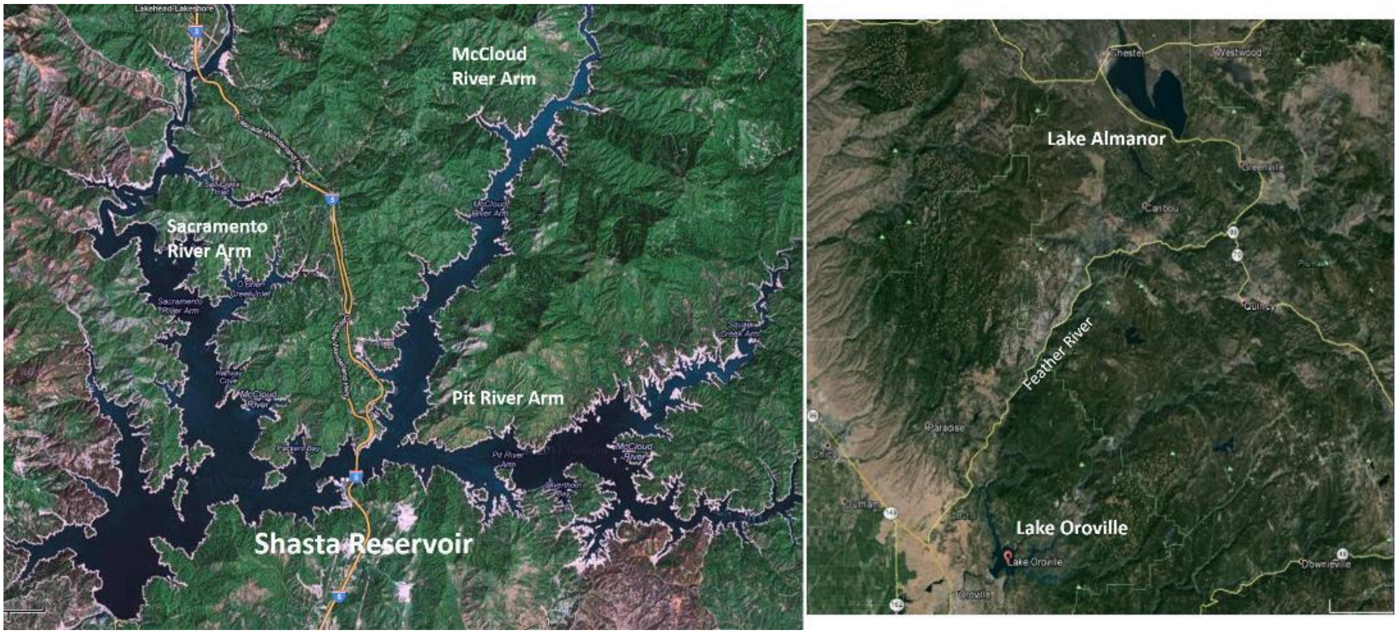

Figure 4: Shasta Reservoir and Lake Almanor-Lake Oroville Connection

The State Water Project (SWP) operated by the California Department of Water Resources collects Feather River flow into Lake Oroville and manages the 3.5 million acre-ft storage for water delivery to urban and agricultural contractors. Spring-fed Lake Almanor is the source for the North Fork of the Feather River supplying over 300 cubic feet per second of flow originating from discharge of volcanic aquifers on the south side of Mt. Lassen. During normal water years this supplies up to 7% of Lake Oroville storage.

Shasta Reservoir provides 40% of the water that flows into the Central Valley Project (CVP), managed and operated by the US Bureau of Reclamation. The CVP is designed to deliver an average of seven million acre feet of water for agricultural irrigation, municipal consumption, and sustainability of wildlife habitat through a complex network of reservoirs, canals, and tunnels. The project stretches more than 400 miles from Shasta Reservoir to Bakersfield at the southern end of the Central Valley (Figure 3). Water from the CVP is used to irrigate three million acres of farmland in the San Joaquin Valley contributing to a multi-billion dollar agricultural economy that supplies nearly a quarter of the nation’s food.

The SWP supplies 2.4 million acre-ft per year to 25 million California consumers and farmers. Approximately 70% of water contracts are for urban centers of San Francisco Bay Area and greater Los Angeles managed through 700 miles of canals and pipelines. SWP deliveries to water-scarce southern California fuel a diverse and rich economic base for California.

FIGURE 5: CENTRAL VALLEY PROJECT AND STATE WATER PROJECT MAP

Although the California Cascade Aquifers contribute a minority of the total water harnessed in California each year, their critical role is realized during late summer months when snowmelt runoff has ceased and water delivery from the CVP and SWP banks on the presence of a reliable base flow input to the reservoirs. During times of drought this base flow component becomes a more important asset at hand during the critical summer months.

Spring-Fed Rivers Provide Flows for Hydropower Generation

In addition to consumptive use, water from these aquifers is used to generate hydropower. Spring-fed water from California Cascade Aquifers generates 40% of the state's hydroelectric power and is integral to reaching California's renewable energy goals. From 1983 to 2014 large and small scale hydroelectric power generation accounted for greater than 50% of all renewable energy production in California (CEC, 2015). In total, hydroelectric comprises 10 to 15% of all power generation in the State, with the exact amount depending largely on annual precipitation.

The Pit River supplies approximately 820 megawatts (MW) of generating capacity. Of the approximately 3.2 million acre-ft of historical average flow in the Pit, nearly half comprises base flow from springs emerging from volcanic aquifers (Freeman, 2007). One quarter of this flow comes from the Fall River Springs alone. Furthermore, the James B. Black power plant on the Pit River derives its 172 MW power generating capacity from water diverted through tunnels from the McCloud River. The intake on the McCloud River is at a point downstream of Big Springs, a large volcanic aquifer discharge estimated at 800 cubic feet per second flow. Another 120 MW of capacity is generated on the North Fork of the Feather River by flow supplied by spring-fed Lake Almanor. Spring-fed river flow captured in Shasta Reservoir also contributes a portion of the Shasta Dam Power Plant generating capacity of nearly 700 MW delivered to the Sacramento Valley.

The economic feasibility of hydroelectric power generation depends heavily on the availability of adequately flowing water. This makes power generators keen observers of long-range precipitation and river flow, particularly in runoff dominated watersheds. The large volume spring discharge emerging from the California Cascade Aquifers provides a somewhat steady and reliable discharge rate. The spring discharge typically does not experience immediate decrease in a low water year but requires cumulative years of poor precipitation to show an effect (Freeman, 2014). Decadal-scale climate effects are recorded in spring output in the Pit River system, making long-range forecasting feasible under current environmental conditions. However, in order to sustain the current hydroelectric power generation in the northeastern California, the source of that power, namely the spring-fed rivers, need to be managed and better understood into the future to prevent inadvertent negative impacts to spring flow.

----Insert image of one of PG &E's facilities in the region ----

Resilience to climate change and drought

California Cascade Aquifers store and release large amounts of groundwater that keeps rivers flowing even when there is little rain or snow to generate runoff. This has important implications for both water supply and cold-water fish species as climate change is predicted to increase the frequency and severity of drought in California, shift precipitation regimes to less snow and more rain, and increase temperatures.

During the 20th and early 21st centuries northern California has experienced three major drought periods. From 1928-1934 river outflow measured in the northern California showed a persistent 40% reduction over long-term averages. Similar, but worst on record for reservoir storage the 1976-1977 drought resulted in a >40% drop compared to average. The 1987-1993 drought caused a 26% average decline in storage, and its persistence heighten awareness for the State of needed measures for long-term drought planning and forced the settlement and reclamation of endangered native fish species dependent on wintertime and late summer Delta flows. Our current drought situation has registered similar declines exceeding in some cases those measured in 1928-1934.

California Cascade Aquifers provide a dependable base flow supply even under predicted climate change scenarios driven by persistent wintertime high pressure and increased frequency and severity of drought (Francis and Vavrus, 2012). Under conditions of increasing temperatures (as predicted by climate models), aquifers would maintain cold water temperatures from spring discharges and provide stable spawning ground for cold-water fish species and similarly dependent aquatic life.

The impacts of drought and changing regional climate on Northern California's water resources leading into the 2014 drought included 15-years of generally declining wetness, apparently causing volcanic aquifer storage to decline from high mid-1990s as reflected in late summer base flow river discharge (Freeman, 2014). Up to 50% decrease in spring output in Hat Creek Valley was observed in in the 1987-1992 drought (Rose et al., 1996). Other studies on Cascade watersheds show that spring-fed rivers can resist variation in volume and temperature better than watersheds that support mostly surface runoff (Tague, et. al 2008). If snow pack melts earlier in the year or decreases in volume, spring-fed rivers continue to flow year-round while runoff and snowmelt-dependent streams may dry up during summer (Tague, et. al 2008).

Although storage levels in Shasta Reservoir fell well below their historical averages during the current drought, inflows from the Upper Sacramento, McCloud, and Pit Rivers were sufficient and supplied about 10% percent of total year's storage behind Shasta Dam, staving off potentially disastrous losses of downstream endangered fish and agricultural productivity (California Department of Water Resources, 2015). During the 1987-1993 drought spring discharge supplied a similar proportion of Shasta's storage during that period, whereas in the 1976-1977 drought spring flow accounted for up to 30% of the needed supply in Shasta (Figure 4).

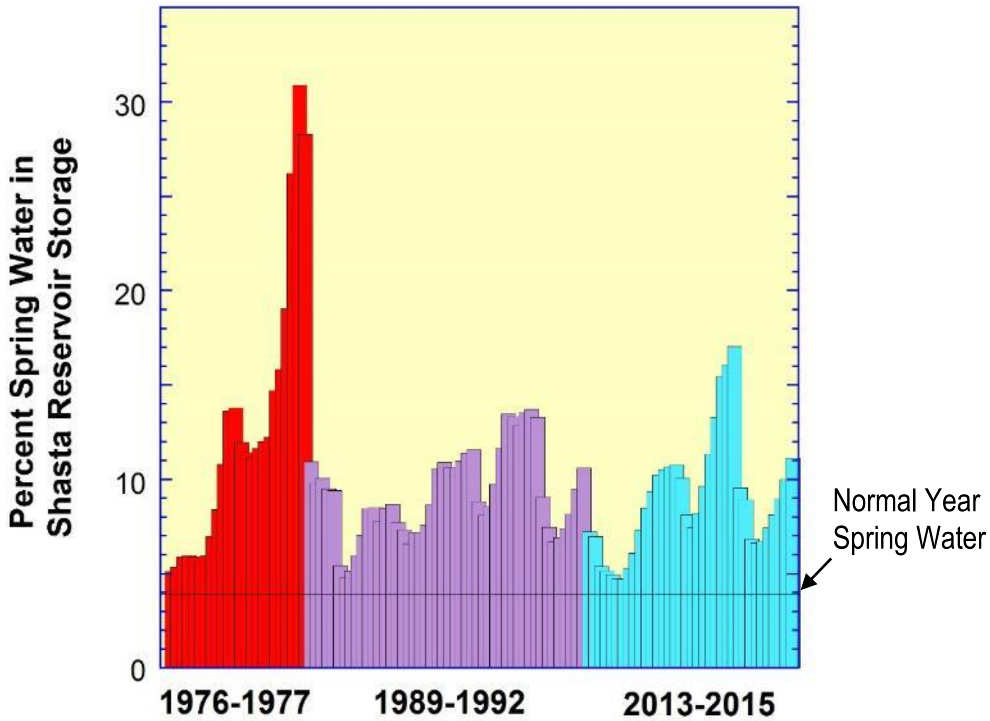

FIGURE 6: SPRING WATER CONTRIBUTIONS TO SHASTA RESERVOIR

During a normal water year, the volcanic spring-fed Lake Almanor derived from Mt. Lassen recharge releases to the Feather River approximately 6-7% of the water that is stored in Lake Oroville. But during the 2015 very dry water year the volcanic aquifer outflow from Lake Almanor contributed approximately 14% of Lake Oroville's total water storage, providing enough State Water Project flow to sustain downstream demand during critical months (G. Freeman, personal communication, December 14, 2015).

Runoff and reservoir storage in the volcanic region differs from streamflow collection and storage in the remainder of California. Recent observation has shown that unimpaired flow for California Rivers since 1977 have annually increased for rivers south of the Yuba River, whereas to the north flows are either stable or decreasing (Freeman, 2012). Furthermore, peak snowmelt runoff has been shifting more frequently to March compared to typical month of April for the same time period, signaling an ongoing changing climate dynamic.

Spring-fed river base flow is essentially immune to these climate affects, but can be impacted where the amount and possibly timing of annual recharge changes. Despite resilience to the impacts of changing climate, many questions are left unanswered about California Cascade Aquifers and the spring-fed rivers.

Spring-Fed Rivers Provide Habitat and Refugia for Cold-Water Fish Species and Invertebrates

The Shasta, Upper Sacramento, McCloud, and Pit rivers as well as Hat Creek are important streams for endangered fish species which thrive in the cold, often nutrient-rich spring water emerging from volcanic aquifers. Spring flows help ensure that even during dry periods, these rivers do not completely dry up. They also help maintain the cold water temperatures that many fish species need to thrive and remain healthy.

Spring-fed aquatic ecosystems receive a constant source of cold water with very little inter-annual variation. These sources of cold water are expected to become increasingly more important for cold-water fishes as climate warms and precipitation-derived and shallow groundwater systems become less reliable sources of surface water. As climate changes and temperatures warm, cold-water species will be threatened and required to adapt, migrate, or face extinction. One exception to the scenario of warming freshwater environments is spring-fed rivers. Volume and temperature in spring-fed rivers are more resilient to inter-annual and long-term variation in precipitation and warming than surface run-off watersheds (Tague et al. 2008, Tague and Grant 2009). Spring-fed rivers will act as cold water refugia for cold water species as climate changes and surface water-fed rivers at the edges of species distributions run low and warm.

Along with the importance of temperature, spring-fed systems often have unique water chemistry that contributes to ecological productivity. The nutrients are incorporated into the water while traveling through underlying geology. The chemical makeup of the underlying rock will ultimately determine the natural productivity potential in the downstream spring-fed river. Two common nutrients incorporated into spring waters are nitrogen (N) and phosphorous (P). Nitrogen and P concentrations can have varying effects on lotic ecosystems. When nutrient-rich spring-fed systems remain cool, primary production and subsequent invertebrate and fish production can be appreciable.

Spring-fed rivers and streams originating from the southern California Cascade Aquifers provide important habitat for cold water species such as trout, steelhead, coho salmon and Chinook salmon. The constant temperature and high productivity has resulted in novel life history strategies that are unique to spring-fed rivers. The diversity of life history strategies present in spring-fed systems provides a foundation for resiliency in a changing climate. To date, the importance of these spring-fed rivers in the larger context of the fishes that reside within them has yet to be fully appreciated.

An example of a well-studied spring-fed river is the Shasta River, which is fed from a large spring complex on the northwest flank of Mount Shasta. The Shasta River highlights the benefits that volcanic aquifers confer on aquatic ecosystems, and especially for cold water species such as salmonids. Historically, the Shasta River, a tributary to the Klamath River, was one of the most productive salmon streams in California relative to its water volume. In the early 1900s the Shasta River contributed about 1 percent of the Klamath River's outflow, yet supported approximately 50 percent of Klamath River's Chinook salmon population (Wales 1951, NRC 2004). The constant 55° F water is the suitable year-round habitat for trout, steelhead, and salmon. This high productivity is due in part to the geologically derived nutrients in the spring-fed water that allow for high primary productivity (plants), which facilitates abundant secondary productivity (invertebrates), ultimately providing a food source for fish. Moderate spring temperatures also minimize either cold or warm water stress conditions and generally sustains an optimal growth range. These conditions promote rapid juvenile salmon growth and increases the chances that they will return from the ocean to spawn. Figure 5 shows a salmon spawning in the Shasta River.

Federal Protection and Restoration

- *Restoration since 2009 (mainly excluding cattle from streams) has improved habitat quality and led to cooler summer water temperatures and more aquatic vegetation, which provides a food resource and structural habitat for aquatic insects.*
- *The spring-fed portions of the Shasta River have more suitable salmon and steelhead habitat. Over-summering juvenile coho salmon have been observed in multiple locations or tens of kilometers compared to the single pool they were observed in 2008*

The UC Davis Center for Watershed Sciences and its many partners are conducting research to measure and compare ecological productivity and food-web dynamics in these three spring-fed streams compared with those of rivers that receive mainly snowmelt and surface water derived runoff in the same watershed.

Other spring-fed rivers important for both resident and anadromous salmonids in California include Hat Creek, Fall River, McCloud River, Upper Sacramento River, Mill Creek and Battle Creek. Spring systems are expected to become increasingly more important for the survival for salmonids and other cold-water fishes as the climate changes and runoff-fed rivers run low and warm.

Spring-fed rivers are also important refugia for invertebrates. The endangered Shasta crayfish population endemic to Shasta County also thrives in cold water pools supplied by springs emerging from volcanic aquifers. The Shasta crayfish feed on rock surfaces having thin mats of rich primary growth, and consequently they have a small range. They are at risk from dissection of their habitat and invasive competitors, namely the signal crayfish. Shasta crayfish are unable to survive without the constant flow of spring water.

FIGURE 7: SALMON SPAWNING IN THE SHASTA RIVER (PHOTO BY CARSON JEFFRES)

State Groundwater Policy Excludes Volcanic Aquifers from Sustainable Management Requirements

In 2014, California passed the Sustainable Groundwater Management Act (SGMA) to further address the problem of over extracted and polluted groundwater throughout the state. The legislation aims to encourage local water authorities to sustainably manage groundwater in their local basin. The SGMA process ranks State designated groundwater basins based on the degree of impact measured by a number of ranking variables. Those basins found to be in a medium or high impacted state are required to form a Groundwater Sustainability Agency within two years of SGMA enactment, develop a sustainability plan within 5-7 years, and have that plan fully implemented with 20 years. Failure to meet these deadlines invite State Water Resource Control Board management instead. Basins found to be in a low priority condition have the option to develop and follow a groundwater sustainability management plan but it is not required.

SGMA is a commendable achievement for California and for its need to better manage its water resources. However, the downside of SGMA from the perspective of the California Cascade

Aquifers arises from the fact that the definition of groundwater basins in California are based on those listings in DWR's Bulletin 118. A strict definition of groundwater basin according to DWR is that it is made up of alluvial material. Accordingly, the map of groundwater basins in northeastern California show a sparsely distributed picture of small pockets of groundwater basins in small valleys and low-lying areas. None of the volcanic aquifer terrain is included in DWR's basin boundaries (Figure 6).

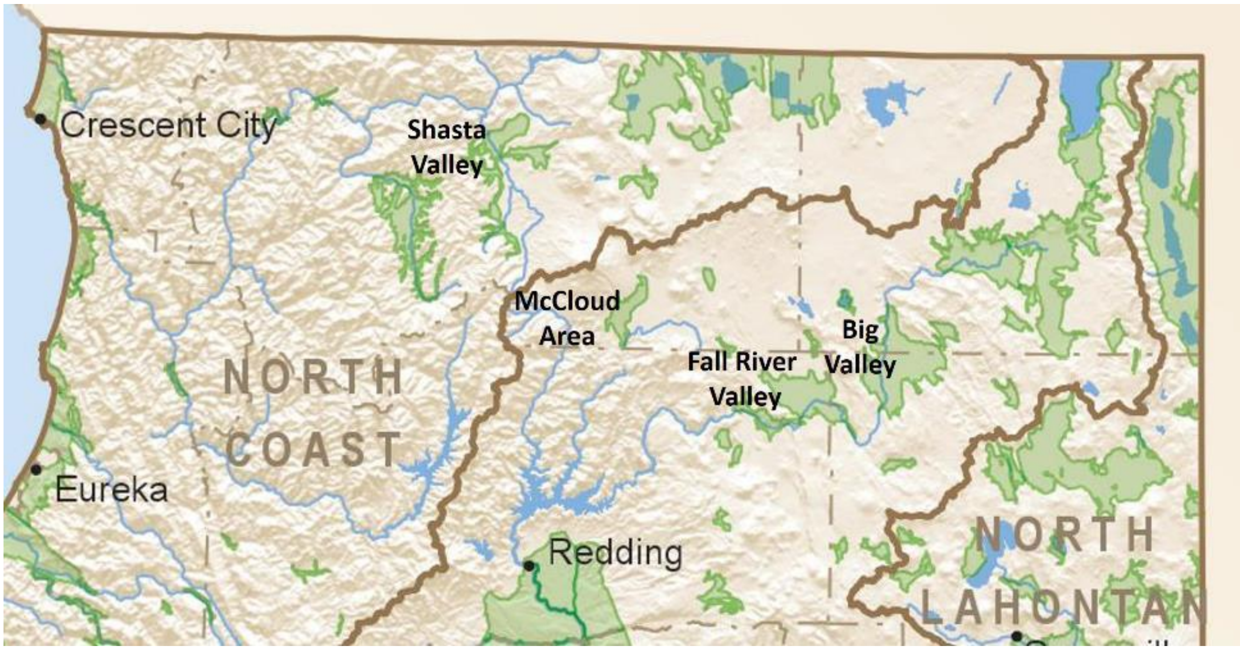

FIGURE 8: GROUNDWATER BASIN BOUNDARIES NEAR CALIFORNIA CASCADE AQUIFERS (CALIFORNIA DWR)

In order for SGMA to include California Cascade Aquifers, basin boundaries would have to be modified from the current alluvial-based ones. Basin boundary expansion would require encompassing most of the volcanic highlands throughout northeastern California, a dramatic shift from current boundaries. Alternatively, these broad volcanic rock areas surrounding the current basins could be designated as recharge areas for the alluvial systems.

DWR has recently instituted a formal process to petition a change in basin boundaries and is currently accepting proposals. On March 31, 2016 the current window for basin boundary modification proposals will close. Only resource agency with legal authority over water may submit a request. The formal submission process requires prior notice within 15 days of consideration, notification and public outreach of proposed changes, production of a scientific technical report for the change along with a hydrogeological conceptual model of the basin.

As shown on Figure 6 above, listed basins in Bulletin 118 relevant to California Cascade Aquifers are the Big Valley, Fall River Valley, Shasta Valley, and McCloud Area basins. Shasta Valley and Big Valley received medium priority ranking, while Fall River Valley and McCloud Area are ranked low and very low priority, respectively. However, note that Hat Creek Valley has no associated alluvial system, even though it supplies nearly 400 cubic feet per second of spring discharge to the Pit River, feeds two PG&E hydroelectric projects, and provides important fish habitat. Nevertheless, it disconnection from any currently recognized basin makes it a challenge to petition a changed status.

Ultimately, management of the California Cascade Aquifers will require engaging in stakeholder outreach and developing an improved understanding of their extent and sensitivity to land use change. Formal designation as a basin status may be challenging, but the formation of regional stakeholder groups and a fluid communication process may encourage informal management instead in the event that formal status change is elusive.

California Groundwater Management

Most groundwater in California is not regulated except where a basin has been adjudicated. A land owner has a right to produce groundwater under their property, equivalent to a streamflow riparian right. Because of this long-standing legal precedence, California legislature has a passed a number of bills in the past 25 years that create incentives for local agencies to manage their groundwater basins in a sustainable fashion The following are key bills enacted:

AB3030 1992

Formalized process of developing a groundwater management plan

SB1938 2002

Additional requirements included in groundwater management plan in order to receive State funds

SBX7 6 2009

Established groundwater elevation monitoring network of cooperating agencies (CASGEM)

AB359 2011

Enhances groundwater management plan implementation including identifying recharge areas and coordination with land use planning

Sustainable Groundwater Management Act 2014

Creates a mechanism to form groundwater sustainability agencies (GSAs) and sustainability plans, and requires them in designated impacted basins

Development Impacts on Volcanic Aquifers

California's Cascade aquifers are located in relatively unpopulated areas, so while they are unlikely to face pressure from rapid urban development, they eventually undergo increased pressure from development or large-scale land use changes.

Urban/industrial development initially impacts environmental ecosystems by dissecting lands that cross ecosystem ranges. For small scale urban expansion or rural development, impacts to water resources have less to do with quantity of water than potential water quality compromises. Spring water emerging from the volcanic aquifers has very low dissolved salt content and a delicate balance of nutrients. Spills of contaminating chemicals or leakage from underground storage tanks and septic systems have untold impact to downstream aquatic ecosystems. Land movers and removal of large tracts of forest generate loose sediment that in typical watersheds cause silting of streamflow. However soil is sparse and the shallow subsurface can be quite porous in many of the volcanic areas, potentially allowing sediment to travel deep into groundwater flow.

Around Mt. Shasta there has been a growing water and beverage bottling industry eager to bottle under a spring water label. At present there are three bottling plants current operating and two in various stages of preparation, one of which is scheduled to open soon. These plants all draw their water from springs or wells drilled into volcanic aquifers flowing down from Mount Shasta. The total amount of water being extracted for each plant is currently not known nor required to be made public. The difficulty has to do with the lack of groundwater management authority and a framework in which to assess water development impacts. The quantity of water used for beverage bottling is not regulated by the State of California or Siskiyou County. Only companies that rely on municipal water supplies have limits on the amount of water they can pump or use.

The growth of the water and beverage bottling industry in this region could result in cumulative effects that impact some spring flow dynamics around Mt. Shasta. In this particular case a basin designation for the affected areas and the implementation of a Groundwater Sustainability Agency would provide an oversight and review mechanism for future proposed development. In the meantime, the issue pits local communities against developers and limits the chances of responsible management with unbiased information. CalTrout has been active in a cooperative effort of baseline monitoring of groundwater and springs around one of the plants that is scheduled to begin operations soon in Mount Shasta in order to evaluate the impact of water extraction once the plant is operating. Collecting reliable monitoring data of groundwater in a transparent manner is the only way to evaluate the impact of the water and beverage bottling industry on volcanic aquifers.

Geothermal energy development is another industry that has the potential to impact California Cascade Aquifers. Since the 1980s, Medicine Lake Volcano has been a target of geothermal exploration and development and has had leases in the Glass Mountain area for this purpose. After a controversial Environmental Assessment Period in the late 1990s, where no potential negative impact was determined, the Bureau issued the leases for exploration and development of 48 MW scale projects. Recently, the energy company has petitioned for change in the lease agreement terms to develop a 480 MW generating capacity instead because of the now available enhanced development and recovery processes that have evolved in the past 20 years. Enhanced geothermal development is an analogue of the oil and gas industries fracturing technologies known in the popular press as “fracking”. This type of resource enhancement is water use intensive because of the need to inject a fluid to induce rock fracturing. In this case, the energy company on Medicine Lake Volcano would require the production of a large scale water source to support the 480 MW generating capacity using the enhanced geothermal recovery methodologies. There are also potential risks to water quality from spills in the surrounding aquifer from hydrofluoric acid used to break up the rock.

Once again the potentially affected area downstream, namely the Fall River Valley, does not have a formal groundwater management authority to turn to for a thorough vetting and a formal process of stakeholder input. If a Groundwater Sustainability Agency existed that had jurisdiction in both the Fall River Valley and the associated recharge areas of the Medicine Lake Highlands, then a formal process of evaluation could be initiated and a responsible plan for impact assessment could be implemented.

Forest Watershed Management and Spring Function in the California Cascades

The mixed conifer forest watersheds of the higher precipitation regimes of Mounts Lassen and Shasta play a major role in the overall hydrologic functioning of this region. These forests collect, store and transport water, providing a critical step-function in the hydrological mass balance picture that is largely understudied. This northern California mosaic of forested stands, meadows, streams, and springs have a symbiotic and complementary relationship. In these forest watersheds springs feed streams and rivers which the flora and fauna of the forest draw upon for day to day biological functioning, while forests collect and hold precipitation that streams and springs depend on for vital recharge. Accordingly, forest watershed management practices could potentially have a major impact on spring production and function.

Pre-1900, forest structure was characterized by many larger trees spaced out well with a grass dominated under-layer (Youngblood et al. 2004).. Fire regimes –initiated both by lightning and Native Americans—shaped these forests through regular, relatively frequent, low-intensity fires in this region (Stephens et al. 2007; Van de Water and Safford 2011). With a variety of soils and elevations, the area has the most biodiverse conifer types globally, and amongst the most productive (California State Wildlife Action Plan, 2015). The volcanic soils near Mount Shasta, combined with relatively high moisture and milder winters produced the largest, tallest ponderosa pine found in North America (Fattig, 2011).

Forest structure and composition affect how precipitation is captured and stored (Bales et al. 2011). Over a century of timber production, grazing and fire exclusion has altered this region’s forest composition and structure (Collins et al., 2011), simplifying the forest types, narrowing the age classes to those largely under 60 years of age, and potentially impacting water production (Podlack et al. 2015). In addition, the landscape has been fragmented by various forms of ranching, agriculture and development as well as intensive timber production. These varying land use patterns between different ownerships further compromise watershed integrity and function.

Water quality and quantity may be enhanced by managing forests to restore and maintain more natural structure. Snow catch, timing of runoff, reduction in sediment yield and preservation of soil moisture longer into the summer season can be achieved using recent developments in forest management and restoration techniques. In addition, recent monitoring and research in many of the forests of California is generating new and novel approaches to managing forest hydrology, and these approaches are likely to be very important to the volcanic systems. Forest restoration improves water quality through reducing sediment and agricultural pollutant loads as well as temperature. The restoration and sustained natural forest management of forested watersheds above volcanic aquifers can help to protect the both the quality and quantity of water that provides their vital recharge supply.

Investigations are needed to better understand forest management practices and volcanic aquifer recharge and storage and ultimately how that affects annual spring flow. An example of an integrative study in Mt. Lassen watershed has been conducting recharge studies of snowmelt in three different forest stands undergoing alternative management approaches (Gaffney, et. al., 2014). Ultimately, studies understanding the links between forest management, recharge rate and spring production in different areas of variable precipitation rates would enhance our understanding of forest land use practice and water production.

Baseline Knowledge is Lacking on Volcanic Aquifers

The volcanoes of the Cascade Range originate from the subduction zone where the Pacific tectonic plate moves beneath the North American continent, leading to a continuous arc of volcanic centers spanning from British Columbia in the north to northern California in the south. The three volcanic centers Mt. Shasta, Lassen Peak, and Medicine Lake volcano are part of a volcanic arc stretching from northern California to southern British Columbia. The shallow groundwater in these volcanoes recharged by high-elevation snowmelt distributes geothermal heat away from the volcanic centers where it is concentrated (Ingebritsen and Sorey, 1985, Ingebritsen et al, 1992). This enhanced recharge also feeds the large-volume cold springs found at the lower elevations of the volcanoes. The springs in northern California are the primary source of the Pit, McCloud, and Upper Sacramento rivers. They vary in rate with seasonal snow melt and drought cycles, and the largest have been traced to recharge areas over 30 miles away (Rose, et al. 1996; Davisson and Rose, 2014). Their water quality is generally excellent, and as their recharge areas remain largely undeveloped, the aquifers do not yet have any issues with contamination from the surface.

Although it is clear that California Cascade aquifers are significant sources of water supply and storage for multiple purposes, there is much we don’t know about them. For instance, can the effect of warming influence the proportion of snowpack to rainfall in recharge areas? How dependent is aquifer storage on the accumulation of melting snow packs versus distributed percolated rainfall? How extensive are the volcanic aquifers in their geography and depth? How much water is actually stored in the aquifers?

Even though some initial assessments have been made (Rose et al., 1996; Nathanson et al., 2003; Davisson and Rose, 2014), no consistent efforts have been made to determine aquifer depth and porosity of permeable layers, or even measurements of the largest spring discharge rates. How sensitive is recharge to land use change? Do the forested watersheds promote replenishment, and does human manipulation of the land cause a decrease? All these questions and other equally important ones need addressing in order to better understand those variables that have direct negative consequences to the water accumulation and storage capacity of these aquifers.

Baseline studies create benchmark characterization of groundwater systems and establish boundaries of recharge contribution and range of hydrological variability. For instance, spring baseline studies conducted in the Mt. Shasta area provided comprehensive water discharge and water quality variability among the dozens of springs sampled, creating a snapshot of conditions in time (CalTrout, 2009). Similar work performed during drought of high precipitation years further establish range of expected variability. Knowledge of expected variability provides a reference framework in which to compare any perceived impacts due to human activities. Further work of this nature could be performed on groundwater wells where available, establishing drawdown characteristics during and after pumping, interconnectivity among different wells and springs, and variability in water quality. Data of this type can be further used to develop some initial assessments of aquifer hydrological properties.

Monitoring California Cascade Aquifers: A Necessary Challenge

Monitoring these aquifers to allow prediction of the impacts of change on their resource potential is challenging. In contrast to typical alluvial aquifers common in the rest of California, groundwater wells in the volcanic aquifers are rarer. Furthermore, most of the aquifers are located in some of the most remote portions of California where few meteorological or flow discharge stations exist. Measuring changes in aquifer discharge is also difficult, as much of the discharge occurs through diffuse springs, where measurement of flow rates require manpower using traditional methods. A number of straightforward and routine measurements are needed to enhance data collection for just simple hydrologic balance determinations over time. Among these are an 1) expanded remote precipitation collection beyond what is currently maintained, 2) gauging and rating of major spring discharges in the Sacramento, McCloud, and Fall River valley, and in Hat Creek Valley, regular or automated spring discharge measurements, and 3) regular or automated monitoring of groundwater levels in wells completed in volcanic aquifers. This data could be made public, some in real time, as part of stakeholder agreements and public education

In addition, water quality (e.g., pH and electrical conductivity) and temperature monitoring on designated key spring discharge sites would support a baseline measure of natural variability during a water year. Furthermore, regular monitoring of stable isotopes in water of spring discharge has been shown to determine any potential recharge source changes during a water year (Davisson, 2015). Baseline data for important areas of each basin would provide a point of reference in which to compare any suspected impacts from associated land or water use changes.

While previous observation suggests volcanic aquifers are resilient to drought and changing climate, the nature and mechanism of this resilience is not well understood, which is one of the reasons baseline characterization is needed. As part of baseline characterization the identification and establishment of long-term monitoring points will be necessary to understand long-term (decadal and beyond) effects of climate cycles and change over time. Two types of long-term data collection are needed: 1) variables that affect aquifer recharge, and 2) those that affect spring discharge. These two types of variables combined provide an indirect measure of aquifer storage.

Quantifying aquifer recharge

Most regional climate models predict a decrease in snow to rain ratio in annual precipitation for higher elevation terrains. This may induce a change in the timing and magnitude of recharge that penetrates into the aquifer. The effects of this shift on recharge efficiency in these volcanic aquifers is not well understood nor easily predicted in the current sparse level of data availability. Of course complicating the picture is that recharge rate varies in space depending on precipitation rates, surface geology, forest type and density, and industrial/urban development. Given the challenges of this spatial and temporal variability in aquifer recharge, monitoring should focus on measuring proxy data that can indicate the amount and location of recharge such as precipitation, air temperature, vegetation density and type, chemical signatures of recharge conditions preserved in the groundwater and continuous monitoring of groundwater levels, particularly when coupled to shallow piezometers of domestic wells. Much of this data collection can be carried out remotely after initial setup, and automated and transmitted electronically to reduce manpower demand.

Aquifer discharge

Most of the discharge from volcanic aquifers supports base flow conditions in the McCloud, North Fork, Hat Creek, and Fall River, monitoring discharge can be done through monitoring stream flow at or near spring sources. At present, few stream gauges exist in these headwaters regions, and some have been abandoned. A more comprehensive stream-gauging network is needed to accurately record spatial and temporal variability for this high-value region. In particular, key sites need to be identified that have a high probability of remaining in their current state in the long-term. Focus should be on places such as State Parks and protected areas of National Forests. Here dedicated monitoring can be established to record changes in baseline conditions over longer time scales consistent with drought cycles and predicted climate change.

Measuring aquifer chemistry and temperature can more easily be measured, and when compared with historical measurements can be valuable to observe changes in aquifer recharge or changes in flow paths. Temperature records of discharge can also be used to infer storage volumes and recharge rates. Routine chemical analyses of spring discharge will be important to estimate residence time in the aquifer, recharge rates, and recharge areas.

Aquifer storage

Measuring the total water stored in these volcanic aquifers will require knowledge of aquifer geometry, porosity, and permeability. Estimates of aquifer properties and storage can be developed based on limited drilling and monitoring well program, which will also be important for other monitoring.

Changes in storage can be inferred from changes in water levels in monitoring wells and spring discharge rates. GRACE satellite remote sensing of temporal changes in the earth's gravitation field have been used to monitor changes in California's alluvial aquifers, since changes in gravity are directly related to the total water storage beneath the satellite's tracks. For the larger volcanic aquifers in California, GRACE analysis may be appropriate for estimating annual changes in aquifer storage, however it may be too large scale to monitor any smaller aquifers.

Along with any monitoring program, modeling of the aquifer with existing data must be conducted to help guide the monitoring program and to develop confidence in the conceptual model of the aquifer responses to climate and potential land use changes including forest restoration or intensive forest harvest. Although the volcanic systems will be challenging to model, recent work on the Columbia Plateau and Snake River Aquifers have shown that numerical modeling, particularly when coupled with heat transport modeling, can provide excellent insight into aquifer behavior.

Novel scientific research

The California Cascade Aquifers represent a unique and challenging research field environment to explore the concepts of fluid dynamics, coupled heat transport, and land/water energetics at geographic scales that have relevance to understanding Earth's physical phenomena and to regional and global climate effects. An academic and governmental research community in this area should be encouraged and nurtured to foster novel research and to create new means to better understand the processes governing the area's water balance. This should include deployment of novel instrumentation and remote sensing technologies to study and monitor the hydrological budget using fluid potentials, relationships between forests stands, precipitation, and fate of accumulated water, and atmospheric dynamics that affect precipitation, as examples. The groundwater management challenge can be better met if a cooperative and learning environment is established between the research and stakeholder communities.

A Strategic Plan for Protecting California Cascade Volcanic Aquifers

California Cascade Aquifers make an important contribution to California's water supply, renewable energy supply, and ecosystem health in spring-fed rivers. However they are a largely unrecognized natural resource that remains largely unstudied and currently unprotected by new state groundwater legislation. Much of the discourse on water policy in California commonly operates on the assumption that the state's water supply begins at Shasta Reservoir, ignoring the high-elevation source waters of Mount Shasta, Mount Lassen, and Medicine Lake Volcano. In order to sustain this resource for California water users, a comprehensive and strategic process is needed to recognize the value of these source waters, increase understanding of aquifer function, measure changes over time and manage them to protect and preserve water quantity and quality.

Objective: Preserve and protect abundant, pristine volcanic source waters for human and environmental needs

Maintain the current flow of the estimated 3000 cubic feet/second from California Cascade Aquifers to:

- Ensure a drought and climate change-resilient water supply to the Central Valley Project and State Water Projects
- Maintain adequate flows and habitat for cold-water fish and wildlife in spring-fed streams and rivers as drought and climate refugia
- Secure reliable water supply for Northern California water users (agriculture, hydropower, cultural, recreational, fish and wildlife)

Strategies

4. *Research, Assessment and Baseline Evaluation:* Establish existing conditions and measure changes over time
5. *Groundwater Policy and Management*: Developing groundwater management priorities and objectives for currently unmanaged volcanic aquifers
6. *Protection of Recharge Areas*: Identify land conservation strategies to protect priority recharge areas for California Cascade Aquifers

1. Research, Assessment and Baseline Evaluation

In order to protect a resource, we must first understand it. As an underappreciated resource, California Cascade Aquifers have not been studied nearly as much as non-volcanic headwaters regions such as the Sierra Nevada. The last comprehensive study of surface water resources in this area was carried out a century ago. Consequently, there is a general lack of the groundwater hydrology knowledge in this area.

Long-overdue baseline research is needed to provide a general understanding of aquifer characteristics and function. There is only limited understanding of the rate of aquifer recharge and location of primary recharge areas. There have been no studies of inter-aquifer connectivity, aquifer permeability, storage volumes, and correspondence of surface topography and geology with aquifer geometry.

This poor understanding equates to a large uncertainty of groundwater vulnerability to development pressure and changing climate. A recent study has argued that the current drought experienced in California is related to climate change (Williams, et al., 2015). While some research has shown that volcanic aquifers are resilient to climate change, the nature of this resilience is not well understood. Following baseline research of California Cascade Aquifers, it will be prudent to establish long-term monitoring to observe how these aquifers respond to climate change impacts including drought, increasing temperatures, and shifting precipitation regimes. The technical capacity to do this work exists – what is needed is funding to carry out the work and coordinate research efforts.

2. Groundwater Policy and Management

California Cascade Aquifers are currently not managed by any comprehensive policy framework beyond county ordinances and US Forest Service policies. Recent passage of the Sustainable Groundwater Management Act (SGMA) culminates a 25-year effort by the state to create formal management instruments for local stewardship of groundwater resources. However, this legislation is primarily designed to ameliorate the declining conditions in groundwater basins already recognized as being negatively impacted. SGMA is implemented based on identified alluvial basins, which inadvertently excludes the volcanic aquifers from sustainable management since they are not designated as basins. Including these aquifers into this policy framework through either basin boundary modification or recharge area designation would provide a management approach to ensure sustainability of the resource into the future. To include California Cascade Aquifers in the SGMA process and create sustainability agencies would provide a foundation for proactively managing the groundwater systems in their current pristine state, rather than corrective action after damage or overexploitation has already occurred.

3. Protection of Recharge Areas

Once a baseline assessment has been completed and general recharge areas have been identified, the next stage is to identifying land conservation strategies to protect priority recharge areas. Depending on the land ownership of the recharge areas, this could involve working with private landowners for natural forest management or liaising with the US Forest Service where recharge areas are in National Forests to promote watershed-friendly practices. Looking into the future, if recharge areas are officially designated and associated with volcanic aquifers/basins in the SGMA framework, protection of priority recharge areas can be incorporated into the basin’s Sustainable Groundwater Management Plan.

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Appendix 1. State of Knowledge for Northeastern California Water Resources

The geological setting of the Pacific Northwest has evolved from the actions of subduction of the Pacific tectonic plate beneath the North American continent that has formed a continuous arc of volcanic centers spanning from Bristish Columbia to the north to northern California southward. This volcanism began in late Eocene time around 35 million years ago, although not until late Miocene (5 million years ago) did volcanism and tectonic uplift give rise to the current axis of eruptive centers that form the modern Cascade Ranges (Macdonald 1966). These volcanic eruptions span into modern day and continue to lay down voluminous deposits over a large geographic area.

These aerially extensive volcanic deposits of the Cascade Ranges usually comprise basaltic or andesitic composition and most were surface extrusions. Extensive fractures formed in the rocks when chilled, and along with numerous subterranean lava tubes in the basalt flows, created a highly permeable network of groundwater recharge and transport pathways.

Based on regional geological continuity, much of the Pacific Northwest groundwater has been lumped together into the Columbia Plateau Regional Aquifer System by the US Geological Survey (Kahle et al., 2011), which spans the geographic areas of southeastern Washington, northern Oregon, and southwestern Idaho. Much of this group is defined by the voluminous Columbia River basalt flows laid down during the late Miocene to Pliocene periods. Additionally, similar extensive volcanic extrusions span much of eastern Oregon, particularly of the Deschutes River basin deposits and its associated regional groundwater (Gannett et al., 2001; Gannett and Lite, 2004). Related regional volcanism also formed much of the Klamath Basin groundwater system of southeastern Oregon (Gannett et al., 2010).

The southern end of the Cascade Ranges is formed by the three main volcanic centers of Mt. Shasta, Mt. Lassen, and Medicine Lake volcanoes all located in northern California. Even though these volcanoes are all associated with the same volcanic arc complex, their surface expressions are distinct from one another. Mt. Shasta is an andesite-dacite stratovolcano constructed in four brief eruptive episodes over the past 450 ka, with extended pauses dominated by erosion (Christiansen 1982). The Lassen Volcanic Center contains hundreds of small- to intermediate-volume eruptive centers of mostly mafic composition that surround a few larger volume intermediate- to silicic-volcanic centers (e.g. Clynne 1990). Lassen Peak itself is a large dacitic dome that rests on the erosional remnants of an older stratocone. Just north of Lassen Peak is the Hat Creek Valley, a graben-like feature bounded by northwest-trending normal faults (Muffler et. al. 1994) that is covered by the 15 kyr Hat Creek Basalt flow, which extends from an eruptive center near the base of Mt. Lassen northward for a distance of ~30 km. Medicine Lake Volcano is a broad shield-like volcano with a shallow caldera located near its crest (Donnelly-Nolan 2011). It comprises mostly basaltic to andesitic deposits, with more recent silicic volcanic deposits limited to high elevations on the volcano (Christiansen 1982; Donnelly-Nolan 1988). The summit area is underlain by a young rhyolitic intrusion. The Giant Crater lava field stretching from the southern flank of the volcano southward for a distance of 45 km is a series of basalt flows laid down in a brief eruptive episode ~10.5 kyr (Donnelly-Nolan et. al. 1991).

In northern California, Pliocene-age fluvial lake and stream deposits are exposed in deep erosional incisions below 300 m elevation (Macdonald 1966; Parfitt 1984), and their geographic extent may form a basal boundary to regional groundwater flow in the volcanic deposits in this area and further north.

Groundwater studies in arc volcanoes in northwest United States have also largely focused on determining geothermal potential (e.g. Ingebritsen et al. 1992). Enhanced groundwater recharge from high elevation snowmelt is a proposed recharge source to shallow geothermal systems in north-central Oregon volcanoes, and a mechanism for transporting heat away from modern volcanic arc centers where heat is concentrated (Ingebritsen and Sorey 1985; Ingebritsen et al. 1992).

Enhanced recharge also feeds large-volume cold springs typically found downgradient (Rose et al. 1996; Rose and Davisson 1996; James et al. 2000; Jefferson et al. 2006; Davisson and Rose, 2014). These spring discharges are the predominant source of the Pit, McCloud, and Sacramento rivers, they vary in rate with seasonal snow melt and drought cycles, and the largest have been traced to recharge areas over 50 kilometers away (Rose, et al. 1996; Davisson and Rose, 2014).

Mt. Lassen, Mt. Shasta, and Medicine Lake volcanoes all features limited surface runoff and numerous high volume spring discharges. Dotting the volcanic edifice of Mt. Shasta are a number of cold water spring discharges occurring in the upper Sacramento River and the McCloud River drainages. The largest is Big Springs of the McCloud River estimated at 800 cfs. To the north are additional spring discharges that feed fresh water flows into the Shasta River. Studies to date have only narrowed down specific recharge *elevations* that feed large spring discharges by using stable isotope analysis (Rose et al., 1996; Davisson and Rose, 1997; Nathanson et al., 2003). These analyses provide an indirect measure of the mean elevation of recharge. However, no effort has been made to correlate recharge areas to *geological* and *topographical* controls, based on the numerous individual volcanic deposits that occur on the surface of Mt. Shasta (Christainsen et al., 1977, 1982).

Emerging from the northern end of the Hat Creek Basalt are large volume springs with a combined flow of ~400 cfs, whose recharge source have been shown to be from snow melt at high elevations of Mt. Lassen (Rose et al. 1996). Regionally extensive discharge of magmatic CO_2 in the subsurface has been quantified using radiocarbon measurements in these springs and associated surface waters (Rose and Davisson 1996) and is likely associated with recent centers of volcanic activity. A number of smaller spring discharges are distributed on the flanks of Mt Lassen feeding discharge to Hat Creek to the north and supplying captured runoff in Lake Almanor to the south. Unlike the Sacramento, McCloud, and Pit river drainages, Lake Almanor ultimately supplies water to the State Water Project via Feather River flow.

The Fall River Springs discharges along a 16 km wide zone near the southern terminus of this of the Giant Crater Lava Flow. Combined discharge from the springs averages ~1200 cfs, making it one of the largest first-magnitude spring systems in the US (Meinzer 1927). Majority of spring flow is in the western portion of the discharge zone (Meinzer 1927). It is of note that both Medicine Lake Volcano and the Giant Crater lava field have virtually no surface water drainages, even during the springtime melting of the snowpack. Of further note, both the Lassen and Medicine Lake volcanoes are underlain by relatively shallow geothermal systems (Muffler et al. 1982; Evans and Zucca 1988). However, whereas the Lassen system has numerous surface expressions of geothermal activity, the Medicine lake Volcano geothermal system is relatively tightly sealed. Nevertheless, large volume springs occur downgradient in both and they are associated with regionally extensive basalt flows of Quaternary age (Rose et al. 1996; Davisson and Rose, 2014).

Large volume springs fed by recharge on Mt. Lassen, Mt. Shasta, and Medicine Lake Volcano have a combined flow of ~3000 cfs, which provide virtually all the base flow component to the Upper Sacramento, McCloud, and Pit Rivers. These spring-generated rivers supply nearly half of the 4.5 million acre-ft of storage capacity in Lake Shasta reservoir each year, and are utilized in hydroelectric power generators along the Pit River and Hat Creek to produce >2000 gigawatt-hours annually.

Precipitation rates are highest at high elevation peaks in northern California. Lassen Peak averages around 90 inches of rainfall equivalent per year, mostly as accumulated snow. Mt. Shasta and Medicine Lake Volcano also have local maximums that average 70 and 40 inches per year, respectively. In the Shasta area, annual precipitation rates of up to 80 inches per year occur at lower elevations south of Shasta Peak. Likewise, local maximums also occur in the Clover Mtn. area (90 inches) on the west side of Hat Creek Valley. Rain shadows occur on the back side of each of the volcanic peaks, where annual precipitation rates can drop as low as 15 inches per year. Large volume spring discharge rates in the Hat Creek Valley are variable in time and have been shown to have direct and near-immediate links to precipitation rates in their recharge areas. For example, Rose et al. (1996) showed that Rising River and Crystal Lake springs decreased in flow as much as ~50% during the drought of 1987 to 1992, which was approximately equivalent to the decrease in the annual snow pack during that time. A 50% decrease in flow from the Fall River Springs is also reported to have occurred in response to the 1987-1992 drought.

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Appendix 2. Monitoring California's Volcanic Aquifers

The volcanic aquifers of California represent a significant water resource for California and the Pacific Northwest . These aquifers are located in young volcanic areas, predominantly in northern California, where thick layers of blocky lava flows have enormous storage capacity and drain slowly. These aquifers are capable of both storing and discharging significant quantities of water and provide consistent and perennial base flow to those California rivers that are sourced in young volcanic regions. Their water quality is generally excellent, and as their recharge areas remain largely undeveloped, the aquifers do not yet have significant issues with contamination from the surface.

These aquifers are largely unstudied, however, with only limited understanding of the rate of aquifer replenishment (recharge), location of primary recharge areas, inter-aquifer connectivity, aquifer permeabilities storage volumes, correspondence between surface topography and aquifer geometry, and finally, the potential for changes in these quantities due to human activities and land use. Under human induced changes, whether from changes in global climate, or land use practices in the recharge zones, the volume of water storage, discharge, and quality can be affected.

Monitoring these aquifers to allow prediction of the impacts of change on their resource potential is challenging. In particular, groundwater wells completed in the volcanic aquifers are rare and contrasts typical alluvial aquifers common in the rest of California. Furthermore, most of the aquifers are located in some of the most remote portions of California where few meteorological or flow discharge stations exist. Measuring changes in aquifer discharge is also difficult, as much of the discharge occurs through diffuse springs, where measurement of flow rates poses challenges. Quantifying the rate of aquifer recharge is often used to estimate the rate of discharge assuming steady state conditions, however recharge into the very fractured and spatially variable surficial lavas is difficult if not impossible to measure accurately. Finally, the storage capacity in these aquifers is strongly controlled by the subsurface geology, which for most of the volcanic systems is not well known and varies widely across large areas.

MONITORING OBJECTIVES

While these aquifer systems are complex, development of an understanding of their primary recharge and storage mechanisms is critical if we are to plan for water resources in the future. While these systems appear static and unchanging in time, significant changes in climate, precipitation and land use may have very large impacts on the ability of these aquifers to provide dependable high quality waters resources.

Therefore, monitoring of these aquifers should follow these broad objectives to allow for accurate resource planning:

1. **<u>Monitoring and Quantifying aquifer recharge:</u>**
   Aquifer recharge is highly sensitive to human change. Changes from a snow-to rain-dominated system, as projected by most climate models, will fundamentally change the timing and magnitude of recharge that penetrates below the active rooting depth of the recharge area's vegetation. It is estimated that current recharge rates from melting snow

packs to the McCloud and Fall River system and Hat Creek may exceed 50% and be as high as 85% of annual precipitation (Rose et al., 1996; Davisson and Rose, 2014). In contrast, recharge in sedimentary aquifers in rain-dominated regions rarely receive more than 20-30% of annual precipitation. The effects of rain-dominated versus snow packs on recharge efficiency in these volcanic aquifers is not well understood.

Recharge will also be widely varying in space depending on precipitation rates, surface geology, forest type and density, and industrial/urban development. While it is expected that most recharge occurs in the upland areas, the very permeable nature of the surface soils can allow significantly deep infiltration far down in the groundwater catchment. The areas of the upland areas of the aquifers that contribute significantly to recharge are also understudied and poorly understood.

Under the current climate, most aquifer recharge occurs during or soon after snow melt for most of the volcanic aquifers. However, under changing climate, it is possible that shifting rain elevations may promote recharge distributed over a greater length of time if temperatures remain above freezing.

Given the challenges of spatial and temporal variability in aquifer recharge, the objective of aquifer recharge monitoring should focus on measuring proxy data that are indicative of recharge magnitude and location such as
Precipitation, air temperature, vegetation density and type, chemical signatures of recharge conditions preserved in the groundwater and continuous monitoring of groundwater levels, particularly when coupled to shallow piezometers of domestic wells.

2. **<u>Monitoring aquifer discharge:</u>**

Groundwater discharge will also be affected by human changes, and given the highly permeable nature of the volcanic rocks, will occur much more quickly than in alluvial aquifers, where porosities are much higher and total storage is likely also to be larger. As most of the discharge from volcanic aquifers supports baseflow conditions in the McCloud, North Fork Feather, Hat Creek and the Fall River, monitoring discharge from the aquifers can be accomplished through monitoring stream flow at or near spring sources. Few stream gauges exist in these headwaters regions, however, and in some cases, gauges have been abandoned (i.e., upper Hat Creek). While analysis of hydropower records can be used to infer aquifer discharge, a more comprehensive stream-gauging network is needed that accurately records spatial and temporal variability for this high-value region.

Aquifer chemistry and temperature can much more easily be measured at or near spring sources, and a number of land management agencies have initiated ad hoc monitoring of these parameters in some areas. Long term changes in chemistry, as historically recorded by temperature, electrical conductivity, and pH but now available through direct ion measurements, will be valuable to observe changes in the aquifer recharge or changes in flow paths. Temperature records of discharge can also be used to infer storage volumes and recharge rates of the aquifers. Chlorinity monitoring of spring discharge has been a useful indicator of thermal water inputs to groundwater (Mariner et al., 1989), and nitrogen content is a key indicator of spring area aquatic productivity and diversity.

Additional chemical analyses of spring discharge for aquifer characterization, on a routine monitoring basis, will also be important to estimate residence time in the aquifer, recharge rates and regions of recharge. For example, the stable isotope ratios of hydrogen and oxygen of the precipitation water are known to vary widely as a function of elevation in the mountainous regions of Northern California. Recharge sources for springs have been but could be more thoroughly correlated to precipitation by comparing stable isotope measurements of spring discharge with measurements from precipitation collection. Furthermore, time-series measurements of spring discharge will also capture any changes in stable isotope ratios that can signify different recharge areas contributing to discharge at different times of the water year. These derived recharge areas can be further verified by measuring the dissolved noble gas concentration in the spring discharge. The relative abundance of dissolved noble gases depend on recharge elevation and temperature and would provide a robust confirmation.

Spring water age-dating provides some quantitative control on aquifer residence times. These residence times can be used to infer potential storage capacity of the volcanic aquifers. Some limited tritium-helium-3 age-dating in the Fall River system suggests surprisingly young ages and suggests limited storage (Davisson and Rose, 2014). However, interferences from volcanic gas emissions prevalent in this area can result in high uncertainty. Additional use of developed age-dating methods such as chlorofluorocarbon ratios or krypton-85 would be warranted. The age-dating would be useful as a characterization tool to establish baseline conditions on groundwater.

3. Monitoring aquifer storage

The measurement of total water stored in the volcanic aquifers will require knowledge of the aquifer geometry, porosity and permeability (to help define the hydraulically active portions of the aquifers). Preliminary estimates of aquifer properties and storage can be developed from a limited drilling and monitoring well program, which will be important for other monitoring.

Changes in storage in the volcanic aquifers can be first inferred from changes in water levels in monitoring wells and spring discharge rates. To further enhance monitoring recent satellite remote sensing using temporal changes in the earth's gravitation field have been used to monitor changes in storage in large alluvial aquifers of California (Famillgleitti get referenes). Changes in gravity are directly related to the total water storage beneath the satellites tracks. The GRACE missions (Gravity Recovery and C E) now routinely process and provide changes in gravity on a gridded 1^{o} scale, representing a downscaling of several degree analyses. For the largest volcanic aquifers of California, the downscaled GRACE analysis may be very appropriate for estimating annual changes in storage in the aquifers. For the smaller aquifers, the GRACE scale may be too large to represent precisely the underlying aquifer, however it may still provide valuable change detection.

4. Development of Models of Aquifer Behavior

Coincident with any monitoring program, modeling of the aquifer with existing data must be conducted to help guide the monitoring program and to develop confidence in the conceptual model of the aquifer responses to climate and potential land use changes. Although the volcanic systems will be challenging to model, recent work on the Columbia Plateau and Snake River Aquifers have shown that numerical modeling, particularly when coupled with heat transport modeling, can provide excellent insight into aquifer behavior.

LIST OF MONITORING TECHNIQUES:
Monitoring wells
Pump tests
Spring discharge
Power plant records

Spring discharge measurements
Spring chemistry, chloride
Spring temperature
Stable isotopes
Noble gases
Chlorofluorocarbons
Krypton-85

GRACE data

Precipitation
Temperature
Humidity
Soil moisture
Rain/snow transition elevation