Appendix 3-2

Forest and Water Balance Study, an Exploratory Study

Forest and Water Balances, an Exploratory Study:

Concepts of the Upper Feather River Basin Uplands Hydrology

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Introduction

“Upland” - land above the level where water flows or where flooding occurs

Background

The objective of this study is to present a conceptual framework to help understand the forest and water relationships in the Feather River Basin (FRB) in the context of the current technical literature. It will be applied as a basis for informed discussion when developing integrated water management opportunities for the Upper Feather River (UFR) Integrated Regional Water Management (IRWM) Plan Update of 2016. Throughout this document, references to the “Feather River Basin” or “FRB” refers to the upper FRB above Lake Oroville, unless explicitly noted otherwise.

Water is one of the most valuable resources coming out of forested watersheds. Currently, forested lands (including about 2,100 large basins) covering 23 percent of the continental United States contribute a disproportionately higher fraction of 43 percent of the total water yield (Sun et al., 2015).

FRB hydrology is often perceived as a two-dimensional surface water conveyance system that receives precipitation, returns some moisture to the atmosphere as evapotranspiration (ET), and conveys remaining water (runoff) into Lake Oroville. The seasonality of precipitation and streamflow adds a time element to the picture. But the mere fact that the larger FRB streams are perennial is an indication that a large part of summer streamflow is maintained by baseflow, suggesting a groundwater reservoir that is replenished annually. This requires visualizing a three-dimensional system. To add complexity, some of the more recent scientific publications suggest that runoff data in the FRB contain signals of long-term climate trends that are “hidden” inside the seasonal fluctuations of annual runoff.

Looking under the land surface requires applying concepts of groundwater hydrology to the FRB. Groundwater (GW) hydrology was originally developed in alluvial aquifers (sand, silt gravel), such as the Sierra Valley or the California Central Valley (Theis, 1940). Due to limited accessibility, GW studies in mountain terrain are rare and many questions about mountain GW hydrology remain unanswered. Groundwater hydrology in fractured bedrock aquifers, as in the FRB, is a recent development in hydrology.

This makes developing a conceptual model of the FRB difficult. Technically, for reasons provided throughout this report, we are not yet ready to develop a conceptual model of the FRB. However, we are able to apply the physical laws that govern GW flow to mountain settings to assist in developing hypotheses that may help set the direction for further research. This monograph is meant to:

- Inform about the basic hydrologic features in order to help facilitate an informed discussion about long-range water resources planning in the FRB; and
- Identify unresolved questions based on field observations and monitoring data.

It is noteworthy that, although the bulk of FRB precipitation is seasonal, the larger streams in the FRB are perennial; indicating that a significant portion of streamflow is baseflow. Baseflow is an indication of a groundwater reservoir (storage) large enough to provide streamflow during more than 40 percent of the year when little precipitation and snowmelt is available. Based on the modeling results of Koczot et al. (2004), 99 percent of the FRB's annual streamflow volume originates from subsurface flow (73 percent) and GW flow (26 percent). Only about 1 percent enters the streams as surface runoff.

Most hydrologic data and analyses in the uplands are focused on streamflow (possibly due to ease of access). Nevertheless, the subsurface hydrology comprises by far the largest portion of the watershed area/volume. Out of necessity this monograph focuses on groundwater (GW) storage and flow to provide a more comprehensive framework for further understanding of uplands forested watershed management. GW hydrology is usually focused on aquifers in valley-fill settings such as Sierra Valley or the Central Valley. It is only in the past two decades that the science of GW hydrology has focused on uplands hydrology.

Purpose and scope

The objective of this study is to develop a conceptual model based on a literature review of the hydrologic and geologic processes that govern the streamflow regime in FRB uplands watersheds. Specific tasks include:

a) To conduct a water budget analysis for the Upper Feather Basin based on available stream flow data records in the key sub-watersheds (based on Koczot et al., 2004, in a separate report).
b) To facilitate an improved understanding of hydrologic processes in uplands forested landscapes, including the connectivity of groundwater and surface water.
c) To provide a conceptual model as a basis for integrated water and forest management of the forested uplands in the Upper Feather River (UFR) basin.
d) To develop data collection protocols to monitor the hydrologic impacts of forest management projects that may significantly change the water balance at the forest stand level.

In summary, the intent of this study is to create the framework needed to develop useful data gathering programs and help facilitate data analysis and interpretation. Additionally, the study intends to identify candidate areas for forest enhancement projects where hydrologic monitoring protocols for forested uplands can be developed and tested.

Report organization

The reader will be guided along the pathways that moisture follows from precipitation to stream flow; a short review of the hydrologic processes involved in transferring moisture from precipitation into the stream channel. The report is organized as follows:

- A brief description of hillslope hydrology to explain processes leading to GW recharge, including canopy interception and evapotranspiration.

- Description of shallow and deep percolation leading to stream flow.
- Description of bedrock hydrology, groundwater flow, and storage.
- Highlight issues in watershed management relevant to water resources.

The journey begins with precipitation, passing through vegetation cover and the soil and root zone, into the unsaturated zone, and into the water table. The last section includes a short discussion of the implications for watershed management of dry season stream flow regimes in the FRB.

The Water Balance

A focus of watershed hydrology is to understand the relationship between precipitation and runoff. What fraction of precipitation is returned to the atmosphere and what is left for streamflow? How does the watershed respond to certain human activities? What watershed management policies can be applied to mitigate adverse effects of certain human activities?

These concerns can be conveyed in the water balance equation:

$$Q = P - ET$$

Q = stream flow
P = precipitation
ET = evapotranspiration

This equation is valid on the long term. It also implies that all groundwater eventually becomes streamflow. However, on the short term (month, season or year), each term is variable and to maintain the balance it requires some water to be stored or released from storage:

$$Q = P - ET +/- S$$

S = storage

Applying this concept for the late summer when practically no precipitation occurs, then P=0, and GW is released from storage, then the balance becomes:

$$Q = G - ET$$

G = baseflow

It is helpful to keep these water balance relationships in mind while reading this report.

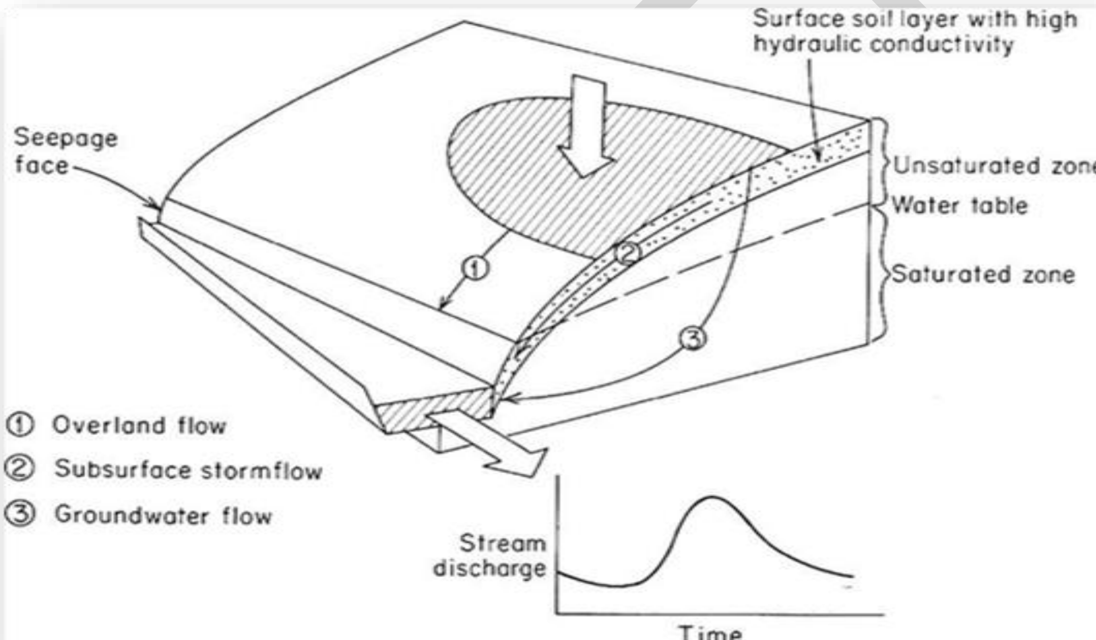
Climate, Vegetation, Interflow and Baseflow

Based on the modeling results of Koczot et al. (2004), most if not all stream flow in the FRB comes from underground sources, some of which enters a stream channel after migrating only a short distance as **interflow**, and some after it has percolated deep and over a long distance as **groundwater flow**. Whatever the subsurface pathways are, in the end both components end up in a stream channel combined as **runoff**. Most hydrologic data are collected from “runoff,” which is the water that is easily accessible in the stream channels. But far less specific information is available from the subsurface flowpaths water occupied while migrating from its source to a discharge point in the channel.

Hillslope Hydrology and GW Recharge Processes

Groundwater recharge is the fraction of precipitation that remains after ET and interflow have been subtracted; that which is left for infiltration into the aquifers. Based on data from Koczot et al. (2004,) an estimated 41 percent of the precipitation entering the FRB is returned to the atmosphere as evaporation and transpiration.

It is at the land surface where prevailing conditions of climate, vegetation, soil, and regolith[1] set the conditions where the precipitation input is partitioned into evapotranspiration, infiltration, subsurface flow, and groundwater recharge. In other words, besides climate, it is the land surface characteristics (i.e., vegetation, soil conditions) that determine volume and timing of runoff and the Basin's hydrologic balance.



Canopy Interception, Evaporation and Transpiration

Forest canopy interception is the fraction of intercepted precipitation which evaporates from the forest canopy. Evaporation loss from forest canopy interception can be substantial and has been studied repeatedly; losses range between 22 and 28 percent of annual precipitation (see Table 2). By comparison, data collected in a coniferous forest throughfall study conducted in

[1] Regolith is the layer of unconsolidated rocky material covering bedrock.

eastern Plumas County at 4300 feet elevation during the winter of 2005/2006 indicated that about 24 percent of total precipitation was returned to the atmosphere through forest canopy interception (Bohm, 2008).

TABLE 1: Common Terminology

TERM	SYNONYMOUS	EXPLANATION
runoff	streamflow, surface water	interflow and baseflow combined
interflow	subsurface flow, subsurface storm flow	localized shallow GW discharge into a stream shortly after advent of a major storm.
ground water flow		water in the aquifer
overland flow	surface runoff	water on the land surface that did not infiltrate and flows directly into the channel
baseflow	groundwater, groundwater flow	component of runoff derived from groundwater
groundwater recharge		water that’s left after ET and interflow
evapotranspiration	ET	combined evaporation and plant transpiration
sublimation		evaporation from snow
aquifer	groundwater reservoir	porous rock formation storing water

Stable light isotope data indicate that small amounts of the intercepted moisture drips off the canopy or becomes stem flow, and reaches the forest floor together with throughfall (Bohm, 2008). Some of this throughfall and stem flow evaporates from the soil and if sufficient moisture is left, water will percolate through the soil and root zone, and into the unsaturated zone. The amount of transpiration loss from the root zone depends on the type of vegetation and the season. Forest vegetation water use can be substantial, up to 70 percent of ET (Schlesinger and Jasechko, 2014 in Vose et al. 2016), but at this stage no attempt has been made to obtain forest vegetation transpiration and water use data from the literature. Further development of the conceptual model data on vegetation and other uses of water in forests needs to be incorporated.

Interflow and GW Recharge

The processes involved when precipitation enters the forest floor in a small tributary watershed are illustrated in the diagram on page 6 (Freeze and Cherry, 1979; page 218). The illustration portrays three precipitation migration routes that reach

Table 2: Canopy Interception in coniferous forests:
(as percentages of annual precipitation)

Dunne & Leopold (1985), median values:		
Rainfall only	11 studies	22%
Rain and Snow	26 studies	28%
Miralles, et al. (2010) globally, using satellite data		22%

(EOS, Vol. 91, No. 43, page 404, 26 Oct., 2010.)

the forest floor near a stream (the riparian zone):

- Overland flow (called “surface runoff” by Koczot et al., 2004) constitutes only about 1 percent of the total basin runoff (streamflow).
- What is commonly called “interflow” in the hydrologic literature (Freeze and Cherry, 1979) is referred to as “subsurface flow” in Koczot et al. (2004). Interflow does not imply a specific depth of infiltration, distance of flow, or residence time. Rather it refers to localized shallow groundwater discharge into the channel, which increases streamflow within a few hours after the advent of a major storm. It may even maintain increased streamflow for several days after a storm event. In the FRB this constitutes 73 percent of the total basin runoff (Koczot et al., 2004).
- On the other hand “groundwater flow” eventually discharges into the channel as baseflow, arriving at a stream channel several months, years, or decades after infiltration, depending on depth of infiltration and distance of flow. Baseflow affects streamflow on an annual scale, if not over several years. In the FRB this constitutes 26 percent of the total basin runoff (Koczot et al., 2004).

In other words, proximal (near stream) groundwater recharge is the source of most spring runoff, whereas the distal (upland) recharge governs the long term baseflow patterns in a stream. In the basin model of Koczot et al. (2004), the total of surface runoff, subsurface flow and groundwater flow merge in the stream channel as “streamflow” (runoff). The terms “interflow” and “groundwater” gives the false impression that there are two distinct types of water, when there is actually a continuum of GW “ages”; depending on how far it has migrated underground.

Land Surface Disturbances and Runoff

It is possible that interflow in the developed areas of the FRB upland watersheds is affected by man-made structures that tend to enhance interflow at the expense of GW recharge. Such structures include road-cuts and ditches, which cause shallow GW to “daylight” and flow into a stream instead of slowly percolating into the underlying aquifer. Similar can be said about degraded stream channels. The same applies to impermeable urban areas such as parking lots and large roof areas. In short, anything that decreases the time it takes water to reach the stream channel reduces GW recharge. Roads are particularly effective at intercepting shallow soil water in road-cuts and diverting it into culverts and stream channels, as can be observed every spring. No attempt was made to find studies in the literature that have attempted to quantify this flow, but it seems to be significant enough to make it worth measuring.

Groundwater Flow in Fractured Bedrock

The prerequisite of groundwater storage and flow in any geologic rock formation are interconnected fractures or intergranular spaces (porosity and permeability), which depends on rock type and tectonic history.

Porosity, permeability and Darcy’s Law

In unconsolidated sedimentary deposits (gravel, sand, silt) groundwater is stored in the intergranular void spaces (porosity). Porosity in consolidated (“bedrock”) formations is comprised of joints which are discrete brittle fractures along which there has been slight movement perpendicular to the plane of the joint (Allaby and Allaby, 1999). The permeability (or “hydraulic conductivity”) is a measure of how well the void spaces are interconnected, and how well water can migrate through a porous geologic formation (Fetter, 1988).

Groundwater flow in unconsolidated sedimentary deposits is subject to Darcy’s Law, which states that the amount of groundwater discharge “Q” (volume per time) through a permeable medium is proportional to the hydraulic conductivity “K”, multiplied by the hydraulic gradient “I” and the area “A” perpendicular to the direction of flow:

$$Q = K \times I \times A$$

On a small scale groundwater flow in fractured rock formations is governed by a flow pattern more complex than Darcy’s Law, and depends on occurrence and direction of faults and fracture zones. However, it is probably safe to say that on a large scale (landscape scale) groundwater flow in fractured bedrock is also subject to Darcy’s Law.

The 0.1 and 1 percent (by volume) fracture porosity in the igneous and metamorphic rocks comprising the FRB upland aquifer formations is much smaller than the 10 to 50 percent porosity in the sedimentary formations. That is the reason why the sedimentary aquifer formations in the large groundwater basins of Sierra, Indian, and American Valleys store such high volumes of GW although they cover much smaller areas than the upland bedrock formations.

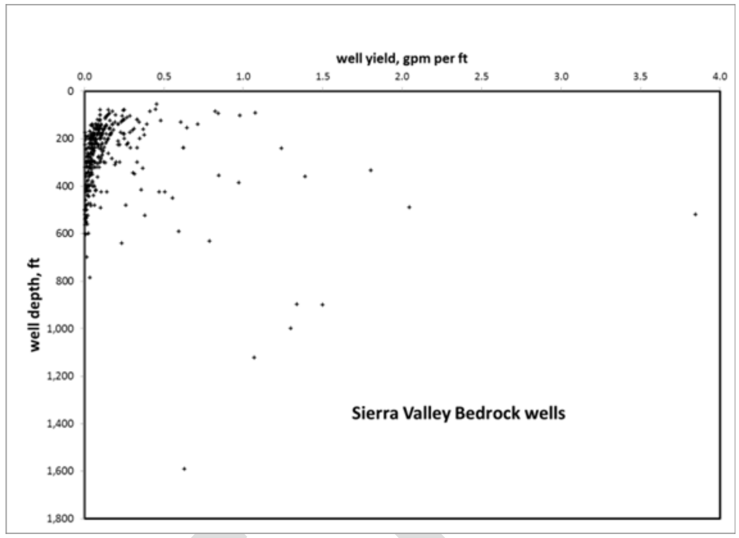
Typically, all water entering the landscape in the bedrock uplands as GW recharge eventually discharges into an upland meadow aquifer or a larger stream flowing into a basin fill aquifer.

GW Flow in Fault Zones

Linear topographical features observed on topographical maps and aerial photos are often associated with faults. These are high permeability zones in bedrock that have become preferential pathways of GW flow. This enhances subsurface weathering and erosion, leading to the formation of linear topographic patterns such as quasi-linear ridges, valleys and stream channels. An excellent example may be the topographic patterns on the southwestern shoreline of Lake Davis.

Depth of GW Circulation

The total amount of water stored in a volume of fractured rock depends on how well it is fractured, and the average depth to which the fractures remain open under the prevailing overburden pressure. Fractures are formed due to elastic expansion of a rock formation (exfoliation) as the land surface is eroded and the overburden pressure at depth gradually decreases. This depth where fracture permeability becomes zero depends on the rock type (e.g. granite, volcanic or metamorphic rocks) and the formation's geologic history.



The approximate depth of groundwater circulation in metamorphic and igneous rocks has been discussed by several authors (e.g. Davis and DeWiest, 1968; Freeze and Cherry, 1979, pages 152-163). Manning and Solomon (2005) state that a permeability decrease with depth has been commonly observed in bedrock aquifers (e.g. Ingebretsen and Manning, 1999).

Assuming that well yield in bedrock aquifers is an indication of permeability this seems to be largely corroborated by an overall decrease of well yields with depth in many bedrock wells drilled in the FRB. This indicates a depth below in which only minimal groundwater circulation occurs. On the other hand, well yields plotting in the upper 20 to 50 feet provide an indirect measure of the specific yield (S_y). The specific yield is an indication of how much water per unit area is stored and yielded annually by the upland aquifers, within the bounds of the highest and lowest annual water levels.

Well data from eastern Plumas County were plotted in the diagram, showing a plot of well depth against well yield. The yield was calculated as yield-per-feet of well depth (gpm per ft).

The low yield wells (less than 0.3 gpm per ft; i.e., the majority of data) plot in a triangular area that indicates the yield decreases with depth, as is expected. However, the higher yield wells plot in a random fashion, which does not seem to correlate between yield and depth. These could be overly optimistic yield estimates arrived at by not testing a well long enough, or they could be "outliers". A more likely possibility is that these high yield wells are associated with fractures that are the result of seismic activity. Northeastern California is part of a seismically active region.

In our interpretation of these data the depth of circulation due to fractures formed by elastic expansion under decreasing overburden pressure reaches as far down as 600 ft, and possibly as much as 800 ft. Wells deeper than that have a small chance of yielding water unless they encounter a water-bearing fracture formed by seismicity, in which case water yield may be significant. This observation has been made in many drilling projects in the FRB and elsewhere. Evidence of discrete fractures has been found at depths greater than 2000 ft at several locations in northeastern California (e.g., Wendel in Honey Lake Valley or Alturas in Modoc

County). The ongoing seismicity in the region may be the cause of a unique feature affecting the flow regime emerging from the FRB bedrock aquifers.

Mountain Block GW Circulation

The depth of circulation defines the lower boundary of the GW bearing geologic formations. If this depth and the average porosity were known, the volume of GW in storage and the GW mean residence time (MRT) could be estimated.

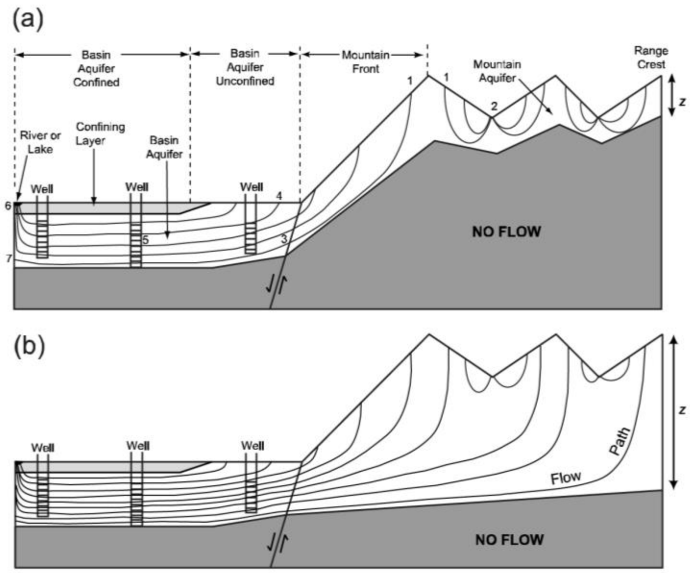


Figure 1. Schematic cross section showing conceptual model of groundwater flow in a mountain block and adjacent basin fill aquifer. (a) Major recharge and discharge components include 1, mountain recharge, which may become either mountain stream discharge or MBR; 2, mountain stream discharge; 3, MBR; 4, valley recharge, including infiltration from streams, precipitation, etc.; 5, discharge to wells; 6, discharge to basin river or lake or evapotranspiration by associated vegetation; 7, water that underflows river or lake and discharges at a location off of cross section. The shallow circulation case shown (small z) results in lower MBR rates, and nearly all MBR originates on the mountain front. (b) Deep circulation case (large z), which results in higher MBR rates; some MBR originates between mountain front and range crest.

The greater the circulation depth, the larger the volume of high altitude recharge stored in the fractured mountain block formations; the recharge eventually flows towards and discharges at depth into a GW basin or a mountain meadow. This is called **"mountain block recharge**" (Manning and Solomon, 2015). On the other hand, the shallower the depth of circulation, the larger the fraction of GW that discharges into the mountain streams, eventually also discharging into the basin infiltrating into the alluvial fans and recharging the basin's shallow aquifers as **"mountain front recharge" ("MFR"),** e.g. Carling et al. (2012).

The implications for streamflow are that one would expect larger mean subsurface residence times in the uplands aquifers, the larger the volumetric ratio of MBR to MFR.

Manning and Solomon (2005) examined GW circulation in a mountain block adjacent to the Salt Lake Groundwater Basin; methodology was based on an integrated environmental tracer approach using tritium, helium and temperature data in GW discharge in the basin.

The two schematic cross-sections below (from Manning and Solomon, 2005, Figure 1) illustrate what is meant by mountain block GW circulation. Mountain block circulation cannot be viewed isolated from the GW sinks constituted by Sierra, Mohawk, American, and Indian Valleys, etc., which are recharged by streams and deep GW percolation from the surrounding uplands mountain blocks. This conceptual model has been most successfully applied in the GW basins of the Great Basin (e.g. Maxey, 1968), and a similar conceptual model has been applied to the northeastern California groundwater basins by Ford et al. (1963). They hypothesize that the shallow aquifers in these basins are recharged by streamflow infiltration into the alluvial fans, and the deep aquifers are recharged by discharge from the fractured volcanic and granitic upland aquifer formations on the basin periphery. Further development of the conceptual model requires more fieldwork and analysis for separating MBR and MFR contributions based on an integrated environmental tracer approach using tritium, helium and temperature data in GW discharge in the basin.

GW Flow Systems

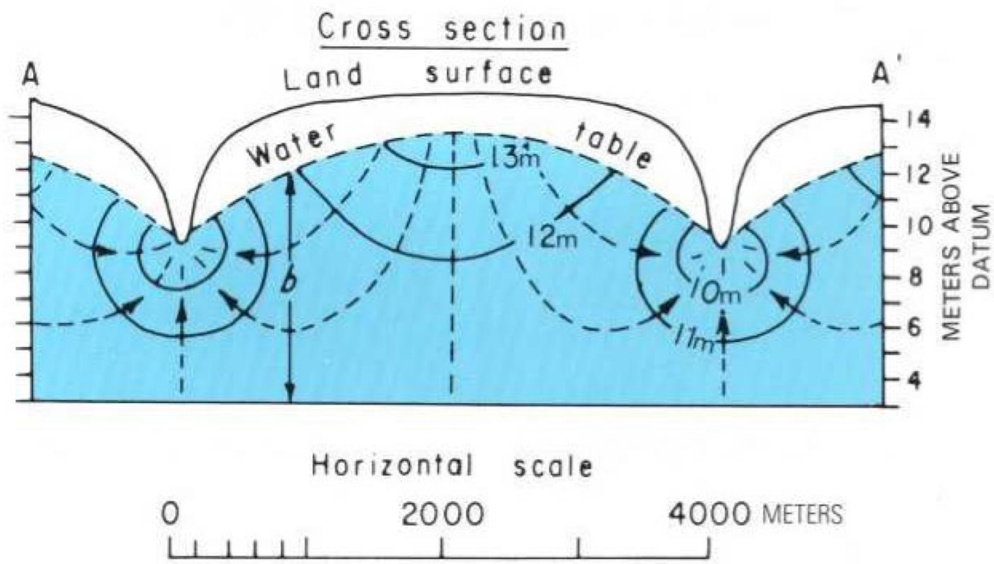
The permeable geologic formations saturated with GW which underlie the uplands comprise the groundwater flow system of the area. The upland area flow system serves two functions: 1) to store groundwater, and 2) to transmit groundwater from recharge areas to discharge areas. Therefore GW flow systems serve both as reservoirs and conduits. In general, water saturated geologic formations serve more as reservoirs than as conduits. Water enters the flow systems in recharge areas and migrates, as a conduit, following the hydraulic gradients and zones of highest hydraulic conductivities to arrive at the discharge areas.

GW Flow Nets

A groundwater flow net is an illustration of how groundwater travels through the subsurface. The uplands are comprised of ridges separated from each other by ravines occupied by streams. The ridges are the recharge areas and the stream channels are the discharge areas (gaining streams). The above diagram (from Heath 2004, p. 22) depicts an idealized cross section of three ridges separated by two upland gaining streams. The unsaturated zone (between GW table and land surface) is thickest under the ridge.

The intent is to show the principal patterns of how GW migrates through the subsurface. The migration paths of groundwater from the ridge to the streams are shown as “dashed” flow-lines. (The solid lines crossing the “dashed” flow lines show the GW flow potential). The most important features are:

- The flow-lines that start at the highest elevations penetrate to the greatest depth and travel the longest distance.



- Because the ridgetop is a recharge area, the hydraulic gradient is directed downward, and GW flows down.
- Under the stream channels, being in a discharge area, the hydraulic gradient is directed upward, and GW flows up.

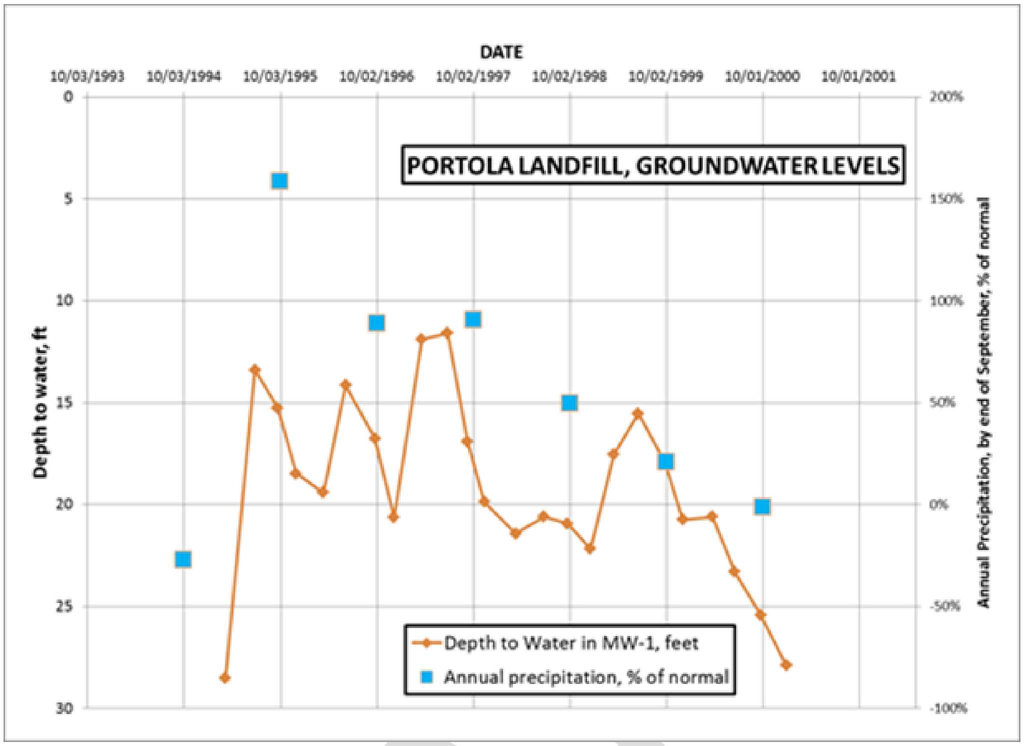
The interested reader may want to read more about flow nets in Heath (2004, p. 22) and Freeze and Cherry (1979).

GW Recharge

Patterns of Uplands GW Recharge

The Precipitation Runoff Modeling System (PMRS) modeling study (Koczot et al., 2004) concluded that the amount of surface flow contributing to streamflow is very small. This is supported by the observation that the hill slopes are seldom covered with a network of erosion rills and snowmelt is observed to percolate into the ground, leading to rising water levels in wells, and increasing spring and streamflow. These observations are indications of groundwater recharge.

An example of how groundwater levels rise in response to annual uplands recharge is shown in the following diagram. The data were measured in a 35 ft deep monitoring well at approximately 5500 ft elevation. The well has been drilled in fractured and weathered granite, uphill from the Portola Landfill in eastern Plumas County, and is far from and not affected by any streams or pumping wells. The geographic setting is on a ridge.



Depth to GW on the vertical axis is plotted versus time in units of water year (October 1 to September 30) on the horizontal axis. Due to the three-month sampling intervals the desired detail cannot be captured very well. Nevertheless, the data permit identifying the approximate seasonal timing of uplands GW recharge at this location, as can be determined by the following:

1. The water levels (colored orange) are at their lowest between March and June and the highest in September. In other words the upland aquifer is recharged in the interval from March to about August.
2. Recharge does not become apparent until several months after onset of the precipitation season since it has to infiltrate through the unsaturated zone before arriving at the water table.
3. Apart from the seasonal patterns, the annual minimum water-levels follow the trend of the total annual precipitation, plotted as percentage of normal (colored blue). The water level was at its lowest by late winter 1994, after several drought years and then recovered rapidly in the above normal wet 1995 water year. Thereafter, water levels mimicked the declining total annual precipitation.

These seasonal patterns are an indication of winter/spring recharge stored in the uplands aquifers, which is then drained for the remaining year until onset of the next recharge season. The long-term trend is an indication of how GW storage that accumulated in the very wet year of 1995, beneficially affected the GW table (and the water budget) for several years afterwards.

Other data from wells collected in eastern Sierra Valley indicate that the time-lag after which well water levels respond to major recharge events increases with increasing depth to water in a well, due to the time it takes recharge to migrate through the unsaturated zone. Since depth to

GW in the uplands can be variable depending on location, the response of stream flow to uplands recharge events can become quite complicated.

It is important to understand that this recharge setting is quite different compared to the riparian zone setting referred to earlier as “hillslope hydrology.” In this ridge setting there is no stream that receives interflow and the water table is tens or hundreds of feet below land surface.

The recharge affecting this upland monitoring well does not discharge into the stream in the same year. Water recharged in that year is stored in the upland aquifer by filling the pore space above the previous year’s late season GW table. The ‘new’ water table declines throughout the remaining year to “make room” for next year’s recharge. True to the flow net concept referred to earlier, GW migrates from the uplands (high) water table, following a deep penetrating flow-line, into the stream at lower elevation.

The GW recharge discharging into the stream has entered the mountain many years before. The time interval it takes a specific parcel of recharge to reach a stream channel depends on distance, elevation difference and the hydraulic properties of the bedrock formations. However, it is not clear to what extent the bedrock aquifer’s elastic response (‘storativity’) causes a lag between time of recharge and discharge.

The difference between highest and lowest annual uplands water tables delimits the seasonal GW storage volume, which drains until arrival of the next “recharge season.” In simplified terms (for illustrative purposes), for a limited area, the volume of annually available GW in upland storage can be estimated as follows:

$$\text{Volume of recharge} = S_y \times \text{Area} \times (\text{seasonal WL decline}),$$

The variable S_y is the specific yield of the uplands aquifer formation, which ranges between 0.1 and 1 percent.

Prerequisites for GW Recharge

The prerequisites for upland GW recharge are that:

- The underlying bedrock formations have sufficient porosity and permeability to receive and store water.
- The formations are unconfined, i.e. they are not covered by a low permeability “cap-rock”.
- There must be a sufficient amount of precipitation-intensity (depth per time) to exceed the short-term evaporation demand, and to meet the needs of the unsaturated zone.
- The soils in the recharge area permit recharge to percolate through and into the underlying unsaturated zone.

Geologic formations and their hydrologic properties

The FRB is characterized by a very complex geology as is well documented by Durrell (1987), Brooks et al. (2000), and the State's geologic maps (Grose, 2000; Grose and Mergner, 2000; Grose et al., 1990; Saucedo and Wagner, 1992). Following is a short qualitative evaluation of the ability to store and release groundwater in the most prevailing FRB geologic formations.

In the absence of a map that shows geologic formations in terms of their GW storage properties, we have to rely on the traditional geologic maps. From a hydrologic standpoint, five types of upland geologic formations with highly variable GW storage capacities are deemed important for GW storage in the FRB:

1. **Lava flows**. Lava flows make some of the best aquifers. The term 'lava,' as often used by well drillers, is a volcanic rock which, when formed in the molten stage, spreads out across the landscape and cools off comparatively rapidly. Cooling joints, buried soil-zones, and lava caves provide high porosity for GW storage, which provides good GW storage particularly when enhanced by secondary porosity (fracturing). A good example is the Lovejoy Formation in an outcrop west of Lee Summit on Highway 70, and formations in the Lake Almanor area.

2. **Granite**. Granite is a very hard rock with practically no primary (intergranular) porosity. In order to store and transmit water granite needs to be fractured. Granite is fractured by exfoliation, i.e., due to elastic expansion under decreasing overburden pressure when the overlying formations are eroded. Often granite contains highly weathered zones, which are probably formed near faults. The rock near faults is usually stressed, allowing increased GW circulation and more intensive weathering. Well yields in these weathered zones can be very good. However, the bulk of granitic formations provide only a limited GW storage medium. Excellent outcrops of weathered granite can be observed along Highway 49 on Yuba Pass, in southwestern Sierra Valley.

3. **Metamorphic rock**. The metamorphic rocks are usually sediments, volcanic lavas, and pyroclastic formations deposited in a deep-sea setting, and which are slightly metamorphosed. Consequently, these formations of Paleozoic age are also called 'meta-volcanics'. They are usually sufficiently hard enough to hold open fractures, but not much is known about their ability to store and release GW.

4. **Pyroclastic**. Pyroclastic formations typically contain abundant rock fragments embedded in fine-grained material (fine-grained volcanic tuff) and is usually rich in clay, which makes poor aquifers. Even when pyroclastic formations are fractured, the soft clay-rich matrix material is ill-suited to keep fractures open; as a result, well yields are low. Examples are the Ingalls Formation in Clover Valley and the Bonta Formation (notorious for poor well yields) near County Road 15 southwest of Portola.

5. **Shale/Slate**. Although part of the Paleozoic metamorphic formations, the slates of the Shoo-Fly formation (locally called "shale") are considered a hydrostratigraphic unit by itself. The slates were also formed by deposition of fine-grained sediments in a deep sea

setting. They are distributed from the area around American Valley and along the North Fork Feather River Canyon and along the Quincy-La Porte Road. These “shales” are notorious for poor well yields, and therefore do not provide for much GW storage.

These formation characteristics alone may not completely characterize the recharge conditions without the overlying soils. Soil characteristics are primarily determined by the underlying source rock, secondarily by climatic conditions. For further development of the conceptual model, characterizing the soils and geology in the FRB in terms of permeability and porosity would be advised.

For a more objective assessment of the hydrogeologic formation characteristics, it is also advised to conduct a quantitative analysis by means of well yield frequency plots, and by cross-plotting well-yields against well depths using data of wells drilled in bedrock areas obtained from well drillers logs and consulting reports (as was demonstrated in the preceding plot).

Recharge and Discharge Areas

Compared to the closed basins in the nearby Great Basin, the Sierra Nevada watersheds are “flow-through” systems where water is continuously moving from “sources” to “sinks” due to hydraulic gradients that are the result of recharge induced differences in GW table elevation. The annual amount of precipitation is elevation dependent; the depth of precipitation per unit area increases with elevation and most precipitation occurs in the high elevation areas, infiltrating to become groundwater or stream water after a fraction has been returned to the atmosphere. The key characteristics of GW recharge and discharge areas are as follows (Freeze and Cherry, 1979):

- Most GW recharge occurs in high elevation areas and diminishes with decreasing elevation.
- GW discharge occurs at low elevations.
- GW recharge areas are usually much larger than GW discharge areas.
- GWr flow occurs only when there is recharge. When recharge diminishes, the high GW table areas will decline, and discharge decreases in the valley (and vice versa).
- Based on the concepts of GW flow nets, water that is recharged at the highest elevations tends to follow the deepest and longest flow paths.
- The farther and deeper a volume of GW migrates the greater the temperature and dissolved mineral content (TDS) and certain ion-ratios. These values are lowest in the recharge areas.

Total Dissolved Solids (TDS), temperature, and ion ratios can be very useful to qualitatively identify GW flow systems and would inform further development of the conceptual model

GW Subsurface Residence Time

The distinction between interflow on the one end and baseflow on the other end depends on how long it took a specific "parcel" of GW to migrate from a recharge area to a particular discharge point in a stream channel:

- Subsurface flow (or interflow) is usually confined to the soil zone and the underlying regolith (colluvium), reaching the channel in a short time.
- GW flow occupies the bulk of the bedrock formations underlying most of the upland areas. It reaches the channel after much longer time spans, migrating along flow-paths that penetrate deep into bedrock and covering long distances.

The time frames and migration distance for both interflow and baseflow are non-specific. However, the "age" of stream water and GW has increasingly become a subject of debate, since it can be used to distinguish various water components in hydrograph separation. Many literature publications pertaining to groundwater and stream water interactions state that on average two thirds of streamflow is "old water", i.e. more than 30 years old.

Due to the porous nature of subsurface flow media, any recharge becomes part of a mixture with "older" groundwater. **Therefore groundwater flow is a mixture of water of a range of "ages," measured as the "mean residence time" (MRT).** The residence time depends on the GW reservoir volume and the rate at which recharge is added:

Residence time = (aquifer water volume)/ (recharge rate)

This is an important concept that needs to be further elaborated upon. Since the aquifer formation's pore volume is larger than the average annual volume of recharge, the average GW residence time is always more than just a year.

For example, Turner et al. (1987) studied the interaction between stream flow and bank storage in a small watershed, using stable isotopes and chloride in rainfall, deep and shallow GWs, and streamflow. It was found that 60 to 95 percent of streamflow is shallow groundwater, derived from rainfall events continually recharging and mixing with the shallow GW in the stream-banks, indicating streamflow originated primarily from preceding rainfall events after a short residence time in shallow groundwater.

A similar conclusion was reached by Liu et al. (2004), finding that GW flow contributed to more than two thirds of streamflow. Rademacher (2001) found the mean residence time of baseflow in a high altitude stream to be about 28 years, which shortened to about 15 years during snowmelt (indicating recharge). The implications for hydrograph separation studies are that groundwater is not a single, well-mixed component but a variable parameter depending on mean residence time, which needs to be accounted for in baseflow studies. Using CFC's and tritium-helium dating techniques, Rademacher et al. (2005) determined that GW ages in the high elevation Sagehen Creek catchment were ranging between 5 and almost 40 years. Major cation[2] levels, pH, and spring water conductivity were found to correlate with spring water age, suggesting additional tools for hydrograph analysis, which would inform further development of the conceptual model.

Singleton and Moran (2010) used noble gas and isotopic tracers to determine that groundwater residence times in a small, high-elevation Sierra Nevada watershed (Olympic Valley near Lake Tahoe) range from less than a year to several decades. The groundwater ages indicate that the valley-fill aquifer, recharged by annual snowmelt, is replaced annually and is thus most vulnerable to climate change compared to the surrounding bedrock aquifer. Since these studies were conducted in high altitude small watersheds, one would expect significantly larger MRT's in the larger watersheds that these sub-watersheds flow into. **This makes one wonder whether the 73 percent interflow of total FRB stream flow modeled by Koczot et al. (2004) may possibly be smaller in favor of a larger groundwater flow component.**

Unresolved Issues

Indications of GW Flow between FRB Watersheds

It is possible that GW flow occupies both stream channel (baseflow) and subsurface routes, the relative contributions of which can change over time. Although by definition baseflow is GW emerging in a gaining stream, that same stream water (formerly GW) may return to GW at a point downstream in a losing stream, from where it may re-emerge in channel sections downstream.

The complex structural geology of the FRB lends itself to much speculation about its effect on the movement of both ground and surface water. It is conceivable that in some geologic settings some stream reaches may receive baseflow contributions from sources outside a sub-watershed. Evidence for such situations may have been found in the stable light isotope data from Clover Valley, north of Portola (Bohm, 2009).

Some of the light stable isotope data generated in local GW studies seem to hint at the existence of GWs the origin of which transcends the watershed boundaries defined by the hill-crest. For example, stable light isotope data indicate that some geothermal waters in Sierra Valley may have originated from outside the Sierra Valley Basin (Bohm, 2016, in progress.). High TDS sodium-bicarbonate GW originating from great depth (Barnes et al., 1981) can show up in unsuspected places, as some of the GW studies in American Valley have shown (Bohm, 2005). Further studies of the MRT of GW discharged into various locations in the FRB could be used for further development of the conceptual model.

[2] A cation is a positively charged ion.

Watershed management issues

Based on the hydrologic literature, including numerous government publications (USFS, USGS, CA-DWR), watershed management in the FRB will have to face at least three water resources related challenges in the coming decades:

1. Overstocked forest vegetation management and catastrophic wildfire.
2. Land surface disturbances due to catastrophic wildfires, roads, urbanization, and other activities.
3. Changed precipitation and runoff regime due to climate change.

Each of these three challenges adversely affects the hydrologic balance and timing of streamflow, implying that it is desirable to reduce evapotranspiration and reduce early year streamflow in favor of increasing late year streamflow. In short, this would imply the need for two watershed management “policies”:

1. To reduce forest vegetation density to help prevent catastrophic wildfire (forest thinning). An additional benefit is reduction of evaporation and transpiration from the forest canopy in overstocked forests and enhanced GW recharge.

2. To minimize uplands infiltration from becoming interflow, in favor of groundwater recharge by diminishing (mitigating) land surface disturbances which shorten the “time of concentration.”

Additionally, it is will be prudent to collect data to verify whether implementation of such outcomes will have the desired effect.

Vegetation and GW Recharge

Since the landmark publications by Bosch and Hewlett (1982) and Sahin and Hall (1995), the connection between stream flow regime and vegetation has become a commonly accepted hydrologic concept, leaving little doubt about the impact of vegetation on watershed water yield. In numerous field experiments conducted in the past 100 years with vegetation manipulation around the globe, it has been established that watershed yield can be significantly affected by forest thinning (Andreassian, 2004), depending on vegetation type, climate, topography and other factors.

Forest Canopy Density and Water Yield

An excellent overview of the current state of knowledge about the established link between forested watershed yield and vegetation cover can be found in Sun et al. (2015), an extract of which is given as follows:

> *Knowledge about how watershed hydrology responds to forest cover change and climatic variability has further expanded (Amatya et al., 2011; Sun et al., 2011a, b; Vose et al., 2012a, b). But uncertainties remain because of the high variability of the*

watershed conditions (climate, type, and density of vegetation cover and magnitude of change). This will determine how much a watershed will respond (e.g. Edwards and Troendle, 2012). It also remains uncertain if and how changes in water yield in small experimental watersheds can be extrapolated to larger watersheds.

Forest water use (ET) very much correlates with the leaf area index (a measure of ecosystem biomass) in addition to several other biophysical factors such as age, species, and climate (Sun et al., 2011a,b). Sun et al. (2015) puts it simply: "the higher the leaf and basal area of a forest, the more water it uses". They continue, saying that "Over 60% of the variability in monthly ecosystem-level ET can be explained by leaf area index (LAI) (Sun et al., 2011a)." As the leaf area is reduced by forest thinning the total water use from tree transpiration and canopy interception at the stand level will also decrease, resulting in an increased watershed yield (stream-flow) due to increased GW recharge and subsurface-flow.

To determine the possible ranges of water yield response to certain forest canopy thinning scenarios under anticipated climate change scenarios, the interactions between thinning and climate at the large basin scale were modeled across the entire United States including about 2100 large basins, employing the Water Supply Stress Index (WaSSI) model (Sun et al., 2015). The modeling results are summarized from the abstract of Sun et al. (2015):

- As a whole, the modeled water yield increased by 3 percent, 8 percent and 13 percent when leaf area index (LAI) was reduced by 20 percent, 50 percent and 80 percent, respectively.
- Water yield decreased by 3 percent when LAI increased by 20 percent.
- A 2^oC temperature increase, decreased water yield by 11 percent.
- A 10 percent and 20 percent precipitation reduction could result in a yield reduction of 20 percent and 39 percent, respectively.

Of course these are averages for the entire modelled region, whereas yields are significantly smaller in the semi-arid watersheds of the Western United States. However, the modeling results suggest that forest thinning does have a significant positive effect on the water balance. To be clear, this is not to advocate aggressive vegetation management for the narrowly focused objective of maximizing water yield from the FRB uplands watersheds, but to promote a balanced and science-based approach to watershed management. Any proposal to thin overstocked forests should aim at re-establishing a balanced ecosystem, similar to the situation that existed before introduction of fire suppression.

Forest Density and Wildfires

The quest beginning in the early 1990's to diminish the looming danger of catastrophic wildfires in the overstocked forests in the FRB has triggered a debate about the connection between forest canopy density and runoff among hydrologists involved in stream and watershed restoration on public and private land. One key observation is that the geomorphic features of many FRB ephemeral streams and their riparian surroundings seem to hint that at one time these were populated by beavers, implying that these were once perennial streams. Why would the flow regime have changed in these streams? Several factors could have contributed to this, including changing climate and land use.

Some research in the published literature hints that some sub-basins in the FRB and other basins in the Sierra Nevada are already experiencing declining streamflows. For example Freeman (2010) observed up to 40 percent declines of 30-year moving average spring streamflows, beginning in 1964. Since this effect is most prominent in sub-basins affected by topographic ridges along their windward boundary, Freeman (2010) attributes these changes to climate change. **However, the fact that it can be observed in 30-year moving averages, but not in 8-year moving averages, gives reason to speculate whether this data may contain baseflow trends 'hidden' in the spring-runoff data. If so, that may convey a signal that recent baseflow trends are due not only due to climate change but also the growing impact of vegetation density, which will be important to differentiate in the further development of the conceptual model.**

Climate Change and GW Recharge

There are reasons to believe that climate change will significantly diminish snow-water content and thinning snow packs. Under these circumstances, uplands GW recharge is expected to decrease (USGS, 2007; Berghuijs et al.; 2014). Snowmelt volume and distribution is expected to significantly change under a warming climate regime. Mean streamflow is likely to decrease in watersheds that experience significant reductions in the fraction of precipitation falling as snow. The mountains of the western United States are deemed particularly vulnerable because so much GW recharge is derived from snowmelt.

On the other hand, climatic warming could also result in a portion of GW recharge shift into upland streams, which eventually flow into the large alluvial GW basins, thereby adding to shallow aquifer recharge at the expense of deep recharge. On the other hand, streambed infiltration may be enhanced by increasing streambed permeability due to rising stream water temperatures. Also, increasing air temperatures associated with climate change are believed to result in increased ET and decreasing streamflow (Krakauer and Fung, 2008).

Clearly, there are reasons to be concerned that a shift from snow to more rain may result in a decrease of GW recharge. Therefore, long-term monitoring of GW recharge should become a topic of discussion for FRB watershed management.as an early warning system (Earman and Dettinger, 2008).

The dilemma is that there is no track-record of experience in long-term GW recharge monitoring, although there is no lack of tools to measure GW recharge and estimates have been conducted in many places. It is not clear if by now (in 2016) we are any closer to developing experience in long-term GW recharge monitoring. Nevertheless, this matter should be further explored.

Data collection for:

Verifying the Impact of Forest Thinning on GW recharge

As was shown in the preceding discussion, the general consensus in the literature is that overstocked vegetation adversely affects the water budget, indicating the need for further study. A way to verify the efficacy of reducing canopy interception and transpiration would be to monitor GW recharge in areas treated with forest thinning.

Although measuring GW recharge is one of the more challenging problems in hydrology, its feasibility has been documented in the technical literature (e.g., DeVries and Simmers, 2002; Johnson et al., 2007; and others). Techniques based on GW data generally provide more accurate estimates than those based on surface water data (Scanlon, 2002).

Verifying the Impact of Land Management on the Timing of Streamflow

Verification would require identifying signals that measure the ratio of groundwater flow to subsurface flow (GW flow versus interflow) in the stream channel. At this stage our literature search has not included research into characterizing how forest and fire management, including roads, affects the timing of streamflow.

Methods to Monitor Long-term GW Recharge Trends

Studying GW conditions in upland watersheds poses significant challenges, including difficult site access (physical and weather conditions), permitting issues and site security. Test and monitoring wells are expensive to drill, and application of automated data collection instrumentation is an absolute necessity over a sufficient period of time without confounding factors

During a 2007 workshop held jointly in Sacramento by the CA Energy Commission and the USGS in 2007, the workshop participants agreed upon five categories of methods suited to monitor GW recharge in mountain terranes (Earman and Dettinger, 2008):

1. methods based on water levels measured in wells,
2. chemical and isotope methods,
3. geophysical methods,
4. stream based methods, and
5. biological methods.

Of these five categories, the first three are deemed feasible for the proposed application in the FRB. Two of these three categories will be outlined based on local experience with their applications. The first two have been applied in the FRB, though not necessarily for the dedicated purpose of estimating GW recharge as envisioned by Earman and Dettinger (2008).

Monitoring Methods Based on Water Levels Measured in Wells

Because of its simplicity, the water table fluctuation method is probably the most commonly used technique for estimating GW recharge; all that is required are the specific yield and changes in water levels over time. Advantages of this approach include its simplicity and no need to understand the mechanism by which water moves through the unsaturated zone. A disadvantage is that the aerial distribution of specific yield at a particular monitoring site may lead to a wide range of recharge estimates.

Recharge is defined as water that infiltrates through the soil, into the unsaturated zone, and into the water table. Per this definition, recharge does not necessarily result in a water table rise; when the moisture content in the unsaturated zone has to reach a minimum level before recharge can reach the water table. In short, recharge includes water necessary to meet the moisture requirements of the unsaturated zone (Sophocleous, 1991).

The method to estimate recharge by means of water table fluctuations assumes that water table rises are caused by recharge that reaches the water table. Knowing the water table rise and the specific yield, recharge can be calculated:

$$\text{Recharge} = \text{delta h} \times S_y$$

delta h = the rise in water table height
S_y = the specific yield

A number of corrections have to be applied since precipitation is not the only cause of water table rises. The causes of water table rises that have nothing to do with recharge need to be filtered out, otherwise recharge will be overestimated. A more detailed description of this method is included in Attachment A.

Implementation will require some careful planning, including site selection and year-round access, hydrogeologic setting, absence of site disturbances and vandalism, etc.

The method will require some initial planning, including (but not limited to) the following steps:

1. Selection of monitoring sites where thinning projects will be implemented.
2. The sites should be undisturbed, permit year-round access, and be protected against vandalism for specified periods of time before and after treatments.
3. The properties of the soils and underlying geologic formations should be suited for installing monitoring wells and for GW storage.
4. The site should have the most suitable hydrogeologic setting, not affected by GW flow from/to adjacent areas.
5. The data from the control site can be augmented by “scavenging” several monitoring wells at the two closed landfills, or any other abandoned wells in the uplands (not affected by nearby pumping).
6. Selection of a control monitoring site with comparable geologic and hydrologic characteristics, but which will not be treated.
7. Selection of environmental tracers collected for site characterization and annual/seasonal monitoring.

8. Selection and installation of automated precipitation gauges and temperature database management and barometric pressure recording devices. To be installed at both sites.
9. Installation of small diameter monitoring wells.
10. Selection and installation of automated data collection equipment for water level measurements.
11. Monitoring protocols and durations to be specified in a monitoring plan, and revised as needed based on a science review.

A monitoring plan will need to be formulated, sufficient financial resources acquired to retain qualified field personnel and personnel for database management, and resources made available for data analysis, reporting, and review. Details would have to be worked out once a project is funded.

Monitoring Methods Based on Chemical and Isotope Tracers

Data of light stable isotopes (deuterium (^{2}H) and Oxygen 18 (^{18}O)) and GW chemistry have been collected routinely for most GW resource projects in the upper FRB since the late 1990's. Most of these projects are located in the basins of the Upper Middle Fork Feather River (MFFR) and a few in the East Branch of the North Fork Feather River.

These projects, one in Mohawk Valley (between the Upper MFFR and Johnsville) and an ongoing project in Sierra Valley, have generated comprehensive isotope and geochemical datasets useful to help conceptualize the prevailing GW recharge processes. However, a GW recharge estimate has been attempted in only one data-set from the Chilcoot-Sub-basin in eastern Sierra Valley, which used the chloride balance, hydrologic balance, and elevation-recharge correlations developed in the adjacent Great Basin.

Promising new approaches have been developed in the past two decades using light stable isotopes in combination with tritium and helium isotopes. These studies have enhanced our understanding of mountain block GW circulation. Unfortunately, these approaches are estimates of regional recharge estimates, with significant margins of uncertainty in mountain block recharge (MBR) estimates (e.g. Manning and Solomon, 2004, 2005; and others). One such study has recently been conducted in Martis Valley, immediately south of the Upper MFFR Basin (Segal et al. 2015).

Due to the significant margins of uncertainty, the environmental tracer methods would not be suited to monitor recharge at a particular site, unlike the water level method. Environmental tracers are probably best applied in combination with well water level monitoring.

Monitoring with Geophysical Methods

These methods are very promising in the right setting. One method that comes to mind is gravity measurements. A monitoring protocol could be designed and tested in the FRB.

Recommendations

1. It would be beneficial to use one easily applied measure or comparable measures of vegetation density. Currently there are three different measures of vegetation density in use: leaf area index, basal area, and canopy density. Another measure used is taking canopy pictures with a fish-eye lens.
2. Characterize stream hydrographs in the FRB's sub-basins with environmental tracers to understand GW sources and ages.
3. Classify FRB upland meadows to understand their genesis and original functions in order to test the hypothesis of possible implications of land use impacts on the water balance.

Bibliography

Amatya DM, Douglas-Mankin KR, Williams TM, Skaggs RW, Nettles JE. 2011. Advances in forest hydrology: challenges and opportunities. Transactions of the American Society of Agricultural and Biological Engineers 54(6): 2049-2056.

Andreassian V. 2004. Waters and forests: from historical controversy to scientific debate. Journal of Hydrology 291: 1-27.

Barnes I, RW Kistler, RH Mariner and TS Presser, 1981: Geochemical evidence on the nature of the basement rocks of the Sierra Nevada, California. US Geological Survey Water-Supply Paper 2181.

Berghuijs, WR, RA Woods and M Hrachowitz, 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. Nature Climate Change, Letters, Published online: 18 May 2014. DOI: 10.1038/NCLIMATE2246

Bohm B, 2005. Ground water exploration in American Valley, Plumas County, California: Drilling in Nugget Canyon, Boyle Ravine, Goodwin Ravine, and the western floodplain. Prepared for Quincy Community Services District. Plumas Geo-Hydrology, September 2005.

Bohm B, 2008. Canopy interception in a coniferous forest in eastern Plumas County, California. Technical Summary Report. Prepared for Plumas County Flood Control and Water Conservation District. July 2008.

Bohm B, 2009. Red Clover Creek Base Flow monitoring 2005-2008 using Environmental Isotopes. Prepared for Plumas County Flood Control and Water Conservation District. December 2009.

Bosch, J.M. and Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegeta- tion changes on water yield and evapotranspiration. J. Hydrol., 55: 3-23.

Bridget R. Scanlon BR, RW Healy, PG Cook, 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal (2002) 10:18–39 DOI 10.1007/s10040-0010176-2.

Brooks, LR. and Dida, LX, editors, Field guide to the geology and tectonics of the northern Sierra Nevada: California Division of Mines and Geology Special Publication 122, p. 155-172. Wakabayashi, J., and Sawyer, T.L., 2000, Neo-tectonics of the Sierra Nevada and the Sierra

Carling GT, AL Mayo, D Tingey, J Bruthans, 2012. Mechanisms, timing, and rates of arid region mountain front recharge. Journal of Hydrology 428–429 (2012) 15–31.

Crosbie, R. S., P. Binning, and J. D. Kalma (2005). A time series approach to inferring groundwater recharge using the water table fluctuation method, Water Resource. Res., 41, W01008, doi:10.1029/2004WR003077.

Davis SN and LJ Turk. 1964. Optimum depth of wells in crystalline rocks. Ground Water, v. 2, pp. 6-11.

Davis and Dewiest, 168.

De Vries JJ and I Simmers, 2002. Groundwater recharge: an overview of processes and challenges. Hydrogeology Journal (2002) 10:5–17 DOI 10.1007/s10040-001-0171-7.

Durrell C, 1987. Geologic History of the Feather River Country, California. Univ. California Press, Berkeley. 337 pages.

Durrell, Cordell, 1966, Tertiary and Quaternary geology of the northern Sierra Nevada: California Division of Mines and Geology Bulletin 190, p. 185-197.

Earman S, M Dettinger, 2007. Monitoring networks for long-term recharge change in the mountains of California and Nevada. A Meeting Report. PIER Workshop Paper, July 30, 2007. CA Energy Commission, CEC-500-2008-006.

Edwards PJ, Troendle CA. 2012. Water yield and hydrology. In 2012. Cumulative Watershed Effects of Fuel Management in the Eastern United States. Gen. Tech. Rep. SRS-161. Asheville, LaFayette R, Brooks MT, Potyondy JP, Audin L, Krieger SL, Trettin CC (eds). Department of Agriculture Forest Service, Southern Research Station: NC: U.S; 229-281.

Essaid, H. I., and B R Hill (2014), Watershed-scale modeling of streamflow change in incised montane meadows, Water Resource. Res., 50, 2657–2678, doi:10.1002/2013WR014420.

Fetter CW. 1988. Applied Hydrogeology. Second edition. Macmillan Publishing Co. 592 pages.

Ford, et al., 1963. Northeastern Counties Ground Water Investigation. California Department of Water Resources.

Freeman, GJ, 2010. Tracking the impact of climate change on Central and Northern California's spring snowmelt subbasin runoff. Paper presented at Western Snow Conference 2010.

Freeze A, and JA Cherry, 1979. Groundwater. Englewood Cliffs, N.J. 604 pages.

Freeze RA and PA Witherspoon. 1967. Theoretical analysis of regional groundwater flow: 2. Effect of water-table configuration and subsurface permeability variation. Water Resources Research, 3, pp. 623-634.

Grose, T.L.T. and Mergner, M., 2000, Geologic map of the Chilcoot 15' quadrangle, Lassen and Plumas counties, California: California Division of Mines and Geology Open-File Report 2000-23, scale 1:62,500.

Grose, T.L.T., 2000, Geologic map of the Portola 15' quadrangle, Plumas County, California: California Division of Mines and Geology Open-File Report 2000-22, scale 1:62,500.

Hammersmark CT, MC Rains, JF Mount. 2008. Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA. River Research and Applications 24: 735–753.

Healy, R.W., Cook, P.G., 2002. Using groundwater levels to estimate recharge. Hydrogeol. J. 10, 91…109.

Hoffman J, K Roby, B Bohm, 2013. Effects of Meadow Restoration on Stream Flow in the Feather River Watershed. A Review Based on Monitoring Data and Pertinent Research. February 2013.

Huntington, J. L., and R. G. Niswonger (2012), Role of surface-water and groundwater interactions on projected summertime streamflow in snow dominated regions: An integrated modeling approach, Water Resour. Res., 48, W11524, doi:10.1029/

Ingebritsen, S. E., and C. E. Manning (1999), Geological implications of a permeability-depth curve for the continental crust, Geology, 27, 1107-1110.

Johnson AC, RT Edwards, and R Erhardt, 2007. Ground-water response to forest harvest: Implications for hillslope stability. J. American Water Resources Association, Vol. 43, No. 1.

Koczot KM, AE Jeton, BJ McGurk, MD Dettinger, 2004. Precipitation-Runoff Processes in the Feather River Basin, Northeastern California, with Prospects for Streamflow Predictability, Water Years 1971–97. Scientific Investigations Report 2004-5202. U.S. Department of the Interior, U.S. Geological Survey.

Krakauer NY, Fung I. 2008. Mapping and attribution of change in streamflow in the coterminous United States. Hydrology and Earth System Sciences 12: 1111-1120.

Liu, F., M. W. Williams, and N. Caine, 2004. Source waters and flowpaths in a season-ally snow-covered catchment, Water Resources Research, Vol. 40, W09401.

Manning, A. H., and D. K. Solomon (2003), Using noble gases to investigate mountain-front recharge, Journal of Hydrology, 275 (2003) 194-207. Elsevier Science B.V.

Manning, A. H., J. S. Caine, P. L. Verplanck, D. J. Bove, and G. P. Landis (2004), Insights into groundwater flow in an alpine watershed provided by a coupled heat, mass, and fluid transport model, Handcart Gulch, Colorado, Geol. Soc. Am. Abstr. Programs, 36(5), 539.

Maxey GB, 1968. Hydrology of desert basins. Ground Water, v. 6, No. 5.

Mayo, A. L., T. H. Morris, S. Peltier, E. C. Petersen, K. Payne, L. S. Holman, D. Tingey, T. Fogel, B. J. Black, and T. D. Gibbs (2003), Active and inactive groundwater flow systems: Evidence from a stratified, mountainous terrain, Geol. Soc. Am. Bull., H5, 1456-1472.

Mifflin MD, 1968. Delineation of ground water flow systems in Nevada. Technical Rpt. Ser. H-W, Hydrology and Water Resources Public. No. 4, Desert Research Institute, Reno, Nevada. July 1968.

Rademacher, L. K., J. F. Clark, D. W. Clow, and G. B. Hudson (2005), Old groundwater influence on stream hydrochemistry and catchment response times in a small Sierra Nevada catchment: Sagehen Creek, California, Water Resour. Res., 41, W02004, doi:10.1029/2003WR002805.

Rademacher, L. K., J. F. Clark, G. B. Hudson, D. C. Earman, and N. A. Earman (2001), Chemical evolution of shallow groundwater as recorded by springs, Sagehen Basin, Nevada County, California, Chem. Geol., 179, 37- 51.

Robinson, C. S., F. T. Lee, J. H. Scott, R. D. Carroll, R. T. Hurr, D. B. Richards, F. A. Mattei, B. E. Hartmann, and J. F. Abel 01974), Engineering geologic, geophysical, hydrologic and rock-mechanics investigations of the Straight Creek Tunnel site and pilot bore, Colorado, U.S. Geol. Survey. Prof. Pap., 815.

Saucedo, G.J. and Wagner, DL., 1992, Geologic map of the Chico quadrangle, California: California Division of Mines and Geology Regional Geologic Map Series Map No. 7A, Sheet 1, scale 1:250,000.

Schlesinger, W.H.; Jasechko, S. 2014. Transpiration in the global water cycle. Agricultural and Forest Meteorology. 189: 115-117.

Segal DC, JE. Moran, A Visser, MJ Singleton, BK Esser, 2015. Characterization of Seasonal Variation of High Elevation Groundwater Recharge as Indicator of Climate Response. In preparation.

Singleton, M. J., and J. E. Moran (2010), Dissolved noble gas and isotopic tracers reveal vulnerability of groundwater in a small, high - elevation catchment to predicted climate changes, Water Resour. Res., 46, W00F06, doi:10.1029/2009WR008718.

Sophocleus, M., 2002. Interactions between groundwater and surface water: the state of the science. Hydrogeology Journal (2002) 10:52–67.

Sophocleus, M.A., 1991. Combining the soil water balance and water-level fluctuation methods to estimate natural groundwater recharge: practical aspects. J. Hydrol., 124: 229-241.

Summers WK, 1972. Specific capacities of wells in crystalline rocks. Ground Water, 10, no. 6, pp 37-47.

Sun G, Alstad K, Chen JQ, Chen SP, Ford CR, Lin GH, Liu CF, Lu N, McNulty SG, Miao HX, Noormets A, Vose JM, Wilske B, Zeppel M, Zhang Y, Zhang ZQ. 2011b. A general predictive model for estimating monthly ecosystem evapotranspiration. Ecohydrology 4: 245-255.

Sun G, Caldwell PV, Noormets A, Cohen E, McNulty SG, Treasure E, Domec JC, Mu Q, Xiao J, John R, Chen J. 2011a. Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model. Journal of Geophysical Research 116: G00J05. DOI: 10.1029/2010JG001573

Sun G, PV Caldwell, SG Mac, 2015. Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States. Published online in Wiley Online Library (wileyonlinelibrary.com) DOI: 10.1002/hyp.10469

Theis CV, 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Transactions of the American Geophysical Union, v. 16, p. 519-524 .

Tiedeman, C. R., D. J. Goode, and P. A. Hsieh (1998). Characterizing a ground water basin in a New England mountain and valley terrain, Ground Water, 36, 611-620.

Troendle CA, JM Nankervis, A Peavy. 2007. The Herger-Feinstein Quincy Library Group Project — Impacts of Vegetation Management on Water Yield. Prepared for Plumas National Forest. US FS. By METI Corporation, Fort Collins, CO. May 2007.

Troendle, C.A., and R.M. King. 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. Journal of Hydrology 90: 145 – 157.

Turner, J.V., D.K. MacPherson, and R.A. Stokes (1987), The mechanisms of catchment flow processes using natural variations in deuterium and oxygen-18. J. Hydrol. 94: 143-162.

USGS, 2007. Trends in snowfall versus rainfall for the Western United States, 1949-2001. PIER Project Report. Prepared for California Energy Commission. April 2007. CEC-500-2007-032.

Vose JM, CF Miniat, CH Luce, 2016. Ecohydrological implications of drought. Chapter 10.

Vose JM, Ford CR, Laseter S, Dymond S, Sun G, Adams MB, Sebestyen S, Campbell J, Luce C, Amatya D, Elder K, Heartsill-Scalley T. 2012b. Can forest watershed management mitigate climate change impacts on water resources? Book Chapter In: IAHS red book "Revisiting Experimental Catchment Studies in Forest Hydrology" (Proceedings of a Workshop held during the XXV IUGG General Assembly in Melbourne, June-July 2011) (IAHS Publ. 353, 2012).

Vose JM, Peterson DL, Patel-Weynand T (eds.). 2012a. Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector. USDA Forest Service, PNRS Gen. Tech. Rep. ENW-GTR-870

Wagner, D.L., Saucedo, G.J. and Grose, T.L.T., 2000, Tertiary volcanic rocks of the Blairsden area, northern Sierra Nevada, California in Brooks, E.R. and Dida, L.T., editors, Field guide to the geology and tectonics of the northern Sierra Nevada: California Division of Mines and Geology Special Publication 122, p. 155-172.

Wakabayashi, J. and Sawyer, T.L., 2000, Neo-tectonics of the Sierra Nevada and the Sierra Nevada-Basin and Range transition, California, with field trip stop descriptions for the northeastern Sierra Nevada in Brooks, E.R. and Dida, L.T., editors, Field guide to the geology and tectonics of the northern Sierra Nevada: California Division of Mines and Geology Special Publication 122, p. 173-212.

Attachment A: Monitoring GW recharge using water levels measured in wells

Sophocleus (1991) used a simple and practical approach to calculate GW recharge in semiarid plain and shallow water table environments. By combining a storm-based soil water balance (lasting several days) with the resulting water table rise, effective storativity values are obtained. This 'hybrid water-fluctuation method' is used to estimate groundwater recharge. Examples based on field-measured data from Kansas show that the proposed methodology gives better and more reliable results than other well-established approaches.

Healy and Cook (2002) conducted a review of methods to estimate recharge from changing GW-level data. Because of its simplicity the water-table fluctuation method is probably the most commonly used technique for estimating recharge. All that is required are the specific yield and changes in water levels over time. Advantages of this approach include its simplicity and no need to understand the mechanism by which water moves through the unsaturated zone. Uncertainty in estimates relate to the limited accuracy with which specific yield can be determined and the validity of the underlying assumptions.

Crosbie et al. (2005) used a time series approach to estimate groundwater recharge using a water table fluctuation method for determining groundwater recharge from precipitation and water table measurements was combined with a multi-event time series approach, incorporating specific yield based upon soil moisture and other variables.

Attachment B: Initial applications of this Study: the work of the Uplands and Forest Workgroup

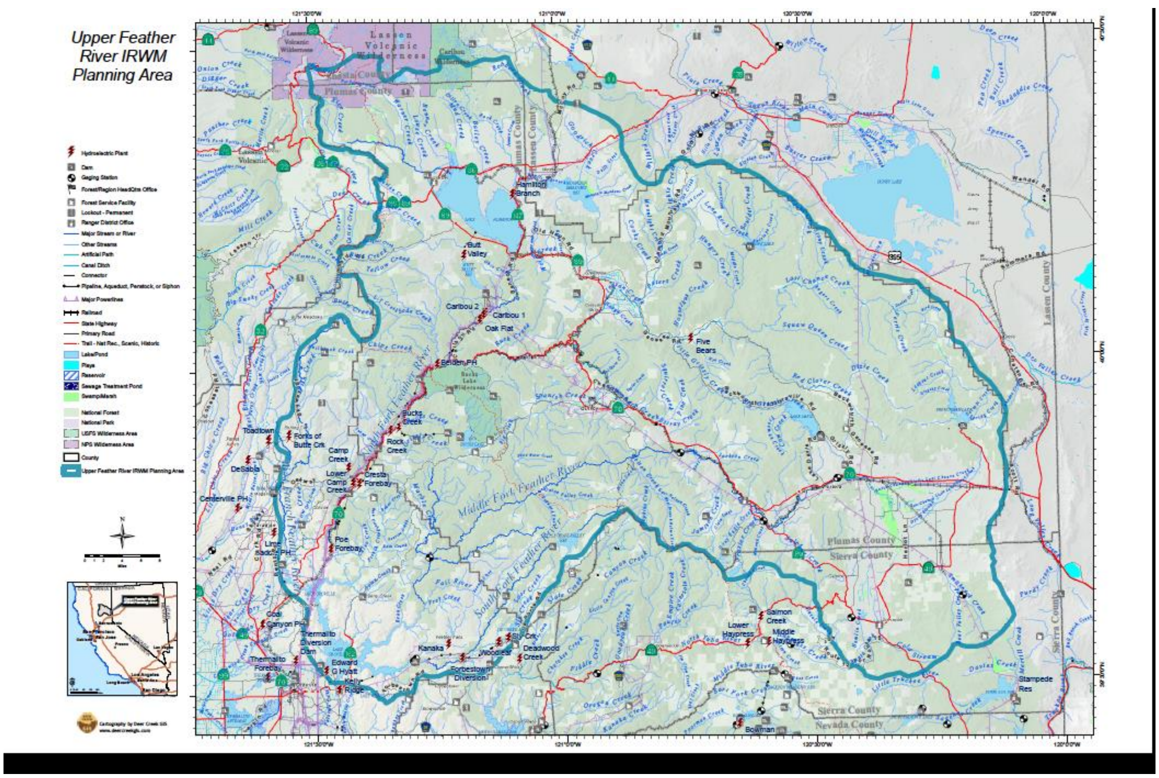
Forest Management through a Water Lens

Respectfully submitted by Leah Wills, Uplands and Forests Management Workgroup Coordinator for the UFR IRWM Plan, June 30, 2016.

The work of the Uplands and Forest Management Workgroup for the Upper Feather River IRWM Plan 2014-2016 follows.

1: The Process:

A Regional Water Management Group (RWMG) of water management entities in the Upper Feather River (UFR) is responsible for developing the 2016 Integrated Regional Water Management (IRWM) Plan for the region.



A consultant team assists the RWMG with updating the 2005 UFR IRWM Plan to comply with new IRWM planning standards. Over the past 18 months, planning participants have developed policies and projects for local water needs in the UFR region that align with the state-level water management priorities in the 2013 California Water Plan (CWP). CWP priorities include forest management, groundwater management, and water services for economically disadvantaged communities (DAC).

The consultant team includes coordinators for five workgroups charged with building the new UFR IRWM Plan "from the ground up" based on local priorities. The Uplands and Forest (UF) Management Workgroup (Appendix A) is providing input to the RWMG on projects and policies that are needed for improving forest conditions for the 75 percent of the UFR region that is covered by forests. The other

IRWM planning workgroups are the Agricultural Lands Stewardship Workgroup, the Municipal Services Workgroup, the Floodplain and Meadow and Waterbodies Management Workgroup, and the Tribal Advisory Committee. Please see the website (featherriver.org/workgroups) for more information about the Workgroups and the planning process.

The Uplands and Forest Workgroup relies primarily on the extensive and collective knowledge of its members. Planning and implementing the forest management aspects of the Plan over the next 20 years relies the application and testing of an extensive body of recent "reference" science on forest ecology and on forest trends that is collected and shared by Workgroup members. But, above all else, it has been direct and dramatic experience with the effects four years of record drought that has elevated restoring and sustaining the forest hydrograph in a more variable precipitation future, as the dominant theme for developing a shared understanding of forest-water interactions and "forest management through a water lens" in the Upper Feather River (UFR) region.

Over the past 18 months, the Uplands and Forest Workgroup discussed specific aspects of sustaining forests in a more variable precipitation future including:

- Catastrophic wildfire behavior
- Drought-related forest mortality
- Watershed enhancement
- Forest ecosystem restoration
- Groundwater recharge and storage in forest lands
- Flood risks with intensifying rain and runoff events
- Water quality
- Reintegration of managed fire into the forest ecosystem
- Reintegration of Maidu tribal Traditional Ecological Knowledge (TEK) into forest and fire management
- The changing hydrology in the UFR with declining snowpack reserves and increasing temperatures
- Investment challenges and partnership opportunities for forest conservation and stewardship

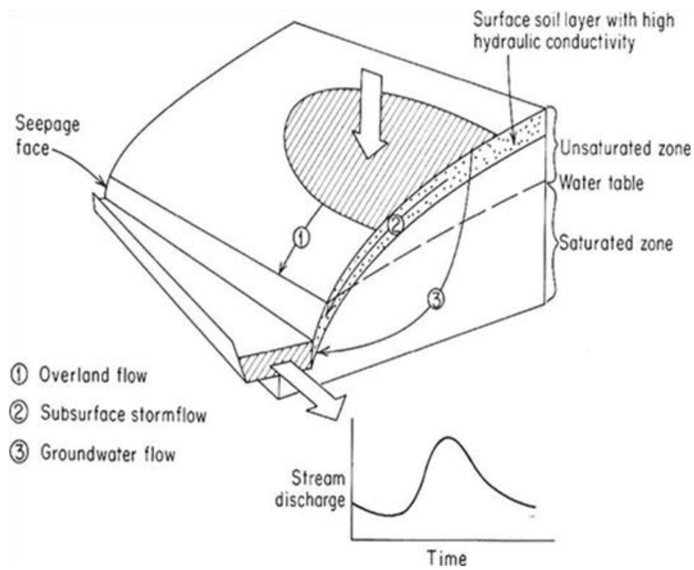
The UF Workgroup's achievements include:

1. Integrating "best available science" with the deep experience of local forest management professionals was essential for thinking about "forest management through a water lens"- especially where the science is spotty. For example, some Workgroup members had experienced forest mortality during past droughts that became important for exploring relationships between the forest hydrograph and forest health during this epic "warm" drought. Updates to the Workgroup on the Forest Water Balance Study (Study) were important for shaping the workgroup's thinking about interactions between groundwater and surface water, forest moisture stress and mortality, catastrophic wildfire, and drought.
2. Another workgroup achievement was developing objectives, strategies, and priority projects that, when implemented, will demonstrate a suite of forest management actions for reducing catastrophic wildfire risk and for conserving forests in a changing precipitation future. These objectives, strategies, and projects also reflect the workgroup's paradigm shift away from conventional thinking about forest management for increasing water yields.
3. Identifying appropriate coordination with other municipal and agricultural water workgroup strategies and projects was an important planning milestone for the Workgroup.

4. Coordinating with tribal water management strategies and projects was another noteworthy Workgroup achievement.
5. Aligning regional forest and watershed policies and priorities with state and federal forest management direction was important for the Workgroup because "buy in" at all governmental levels was seen as essential for effective and timely implementation of forest management priorities across the different forest ownerships in the region.

Financing regional-scale forest health remains elusive for the Workgroup and has not been achieved. This has been especially frustrating because Workgroup members feel that planning without implementation becomes, in the end, merely an exercise in wishful thinking. Throughout the process, the Workgroup members returned to investment partnership opportunities and barriers.

As more information has become available about the UFR hydrograph, conventional "fee-based" financing for increasing water yields, or "avoided cost" payments for water treatment began to look too narrow. Especially in a record drought, recharging groundwater reserves could help the Workgroup achieve priorities like moderating catastrophic wildfire and sustaining forests. Groundwater recharge could become a significant byproduct of reducing dangerous forest fuels. A broader forest investment framework that includes restoring the groundwater component of the forest hydrograph as "added value" to other public benefits from forest management such as retaining large trees and key ecosystems, reducing black carbon greenhouse gas (GHG) emissions, and conserving forest carbon stocks.



The Forest-Water Balances Study (UFR 2016) concludes that 1 percent of streamflow in the UFR region originates directly from precipitation runoff. Some 73 percent of streamflows originate from shallow and moderate groundwater storage, and 26 percent of streamflows derive from deep groundwater storage of which 6 percent is "lost" to groundwater storage outside of the region. Based on the Study, the groundwater hydrograph determines over 98 percent of the surface water regime in the UFR basin. Quoting from the Study,

> "Proximal (near stream) groundwater recharge is the source of most spring runoff, whereas the distal (upland) recharge governs the long- term baseflow patterns in a stream…. If the average mean residence times in the UFR are in the same range (between 5 and 40 years) as nearby Sagehen and Martis Valley catchments, this may indicate that the 73 percent of interflow portion of the Upper Feather River streamflow that was calculated by Koczot et al. (2004) might be smaller and the deeper groundwater component may be larger."

The deeper portions of the groundwater hydrograph have significantly different economic implications-especially in multiyear droughts. Deeper groundwater that discharges into the Feather River closer to Lake Oroville is important for downstream California as both hydroelectric and water supplies and for sustaining the flows in Sacramento Valley rivers in dry years. If deep groundwater percolated during the wetter water years reaches the stream channels during drier precipitation years, steamflows may be augmented for statewide environmental and economic benefits.

Shallow groundwater that discharges into headwater streams of the UFR is especially important for sustaining key upland forest ecosystems such as meadows and springs. Headwater streamflows originate from more recent precipitation that is released from shallow groundwater, generally within a year. The Upper Feather River is rich in headwater meadows and alluvial valleys. Meadows and valleys that are rimmed by water-bearing uplands and that are underlain by low permeability substrates; are able to store and discharge water over longer periods. In summary, the value of groundwater storage and discharge in the UFR region depends on the timing of water and the age of water, and ambient water conditions across the landscape. These are factors that are generally beyond the "water on demand" requirements for conventional water sales.

Delivering water from a treated forest area to a downstream water buyer becomes further complicated in the UFR because of its size (more than 2.3 million acres), its variable precipitation zones (10 inches to 90 inches/yr.), and for other reasons:

- Distances to water consumers in Southern California can exceed 500 miles.
- Identifying and tracking what volume of additional water flow derives from what forest project and when, becomes even more complex as waters pass through large surface reservoirs and "bypass" multiple river diversion and conveyance systems.
- Baseflows in the lower portions of the Upper Feather River are highly regulated but measured in only specific places for regulatory compliance at a resolution that may not account for intermittent enhanced flows.
- The Federal Energy Regulatory Commission (FERC) allocates baseflows in the North Fork Canyon of the Feather River through lengthy hydroelectric licensing processes. "Instream flows" become enforceable (and rigid) operating conditions for PG&E's and the Department of Water Resources' 35 to 50 year hydroelectric licenses.
- Diversions of surface water for other "beneficial uses" are also regulated by lengthy water rights and water quality evidentiary processes before the State Water Resources Control Board that are often followed by decades of litigation in state and federal courts over "balancing beneficial uses of water."
- Some instream flows and agricultural diversions in the UFR are also governed by Superior Court decrees.

"Avoided treatment cost payments" also fail to attract interest in the UFR because the largest water purveyors in California such as the DWR's State Water Project (SWP) at Lake Oroville convey and sell "raw" water rather than treated water. Water agencies in the Bay area and in Southern California already treat their SWP raw water deliveries as part of the specific mix of water sources that are delivered to their customers.

Finally, forest managers in the UFR region are not in the business of developing water for transfers and sales. They are in the business of growing trees and maintaining forest productivity. As overlying landowners, forest landowners in California have well established legal water rights to groundwater underlying their lands for "lawful and beneficial uses" on their lands such as growing trees and sustaining forest productivity.

In summary, restoring the surface and groundwater hydrograph provides a more relevant economic framework in the UFR region for defining water values, including surface and groundwater interaction zones with significant ecological importance such as forest streams, meadows, springs, wetlands, black oak and aspen forests, riparian forest corridors, etc.

Based on the Forest-Water Balances Study, the economic values of waters originating from forests in the UFR derive from groundwater hydrologic processes such as:

- Groundwater flow nets, where water that is recharged at the highest elevations tends to follow the deepest and longest flow paths to stream channels.
- Subsurface (or "interflow") dynamics where the fastest groundwater inputs to streams are confined to the soil zone and the underlying regolith (colluvium), and thereby reaching the channel in a short timeframe.
- Significant groundwater flow volumes that occupy the bulk of the bedrock formations underlying most of the forested upland areas in the UFR. Groundwater flows under most of the regions' forest lands reach stream channels after much longer time spans, migrating along flow-paths that penetrate deep into bedrock and that migrate long distances before discharging into surface waters."

The hydrology of the UFR region leads to an unconventional economic paradigm where waters originating from forests in the region are "public goods" that are sustained by public and private investments into forest conservation and stewardship.

In this record "warm" drought with its scant snowpack, the UFR's waters and living forests are even more dramatically dependent on adequate soil moisture and upon the recharge of shallow aquifer reserves from deeper recharge in the uplands. However, the science for documenting forest and groundwater interactions is just becoming available. And state and federal policies for conserving groundwater in forests are still in their infancy. Therefore, acceptance of the full dimensions of the forest hydrograph and its economic implications will be slow. The Forest-Water Balances Study is a beginning step. A landscape-scale investment program that is based on the broad range of public values from sustaining forests such as drought resiliency, carbon storage, black carbon pollution reduction, and appropriately scaled biomass utilization (especially in economically disadvantaged communities) is a vision that inspires both persistence and resistance.

2: The Presumptions:

The Workgroup began its deliberations by reviewing local information and articulating some initial hypotheses about forest-water interactions for guiding the Forest Water Balances Study (UFR) and for honing the Workgroup's search through the scientific literature. The initial assumptions are:

2.1: Waters and forests are important to the UFR region and for the rest of California.

Agricultural and municipal users within t(sp) of the Upper Feather River region consume less than 14 percent of total watershed runoff (UFR 2016).

County	Total Size (Acres)	Acres in Watershed	% in Watershed	% of Watershed
Butte	1,072,692.12	341,476.18	31.83	14.9
Lassen	3,020,394.37	118,954.05	3.94	5.2
Plumas	1,673,682.02	1,651,084.83	98.65	72.1
Shasta	2,460,536.78	11,616.40	0.47	0.5
Sierra	615,880.38	164,979.02	26.79	7.2
Tehama	1,893,613.69	932.52	0.05	0.04
Yuba	411,972.86	1,333.06	.32	0.06
Total (Acres)		Feather River Watershed 2,290,376.07		100

Table 5.1. County acreages of the Upper Feather River Watershed

*Acreages derived from CASIL's county shapefile and watershed shapefile

Surface runoff from the UFR is stored in Department of Water Resources' Lake Oroville reservoir and then released for augmented water supplies for over 23 million Californians, for aquatic habitat flows, for flood protection, and for the irrigation of around 600,000 acres of farmland in the Central Valley.

The North Fork of UFR has significant hydroelectric generation and storage capacity. At 1.5 megawatts, the hydroelectric values in the North Fork of the Feather River are the highest in the Sierra (Podolak et al. 2015).

The Middle Fork of the Feather River is designated a "California wild and scenic river" for 70 miles.

Lake Almanor, the Upper Feather River's second largest reservoir, attracts more than one million visitors per year, and is the second most popular recreational lake in the Sierra Nevada after Lake Tahoe (at three million visitors per year).

Major River Drainage	Mean Daily CFS	Mean Gallons Per Day (1000's)	Average Yearly Inflow to Lake Oroville (Acre-Feet)	% of Inflow
West Branch Feather	345.51	223308.6	250137.74	6.47
South Fork Feather	261.60	169074.6	189387.92	4.90
North Fork Feather	3227.6	20860.53	2336679.2	60.48
Middle Fork Feather	1502.3	970987.7	1087645.2	28.15
Total	5337.0	1384231	3863850.1	100.00

The UFR Watershed produces runoff into Oroville Reservoir from three major drainages, and runoff is affected by watershed size:

Major River Drainage	Acres	% of Watershed Area
West Branch Feather River	106985.60	4.64
South Fork Feather River	81071.44	3.51
North Fork Feather River	1380108.00	59.82
Middle Fork Feather River	738877.10	32.03
Total	2307042.14	100.00

Table 4.2 Major River Drainages area

Drainage areas for the four major rivers in the Upper Feather River Watershed

2.2: Forest composition and fire are interconnected:

Interactions between tree crowns, forest fuel loads, and vegetation flammability affect fire severity. Vegetation flammability and fuel load ignitions are also affected by vegetation type, fire history, and also by soil moisture and moisture stress in forest vegetation:

Table 3. Fire resistance of Sierra Nevada Tree Species, adapted from Agee 1993.

Species	Bark thickness	Rooting habit	Branching habit	Canopy cover	Foliage flammability	Most vulnerable to
Douglas-fir	Very thick	Deep	High and dense	Dense	High	Crown fires
Lodgepole pine	Very thin	Deep	Moderately low and open	Open	Medium-low	Scorching cambium, crowning
Ponderosa pine	Thick	Deep	Moderately high and open	Open	Low	Crown fires
White fir	Medium	Shallow	Low and dense	Dense	Medium	Root char,

Table 1. Fire Frequencies in Sierra Nevada Forests. Source: SNEP 1996

Forest Type	Fire – Return Interval (Years)	
	Pre-1900	20th Century
Blue oak	8	78
Ponderosa pine	11	192
Mixed conifer-pine	15	185
Mixed conifer-fir	12	644
Red fir	26	1,644

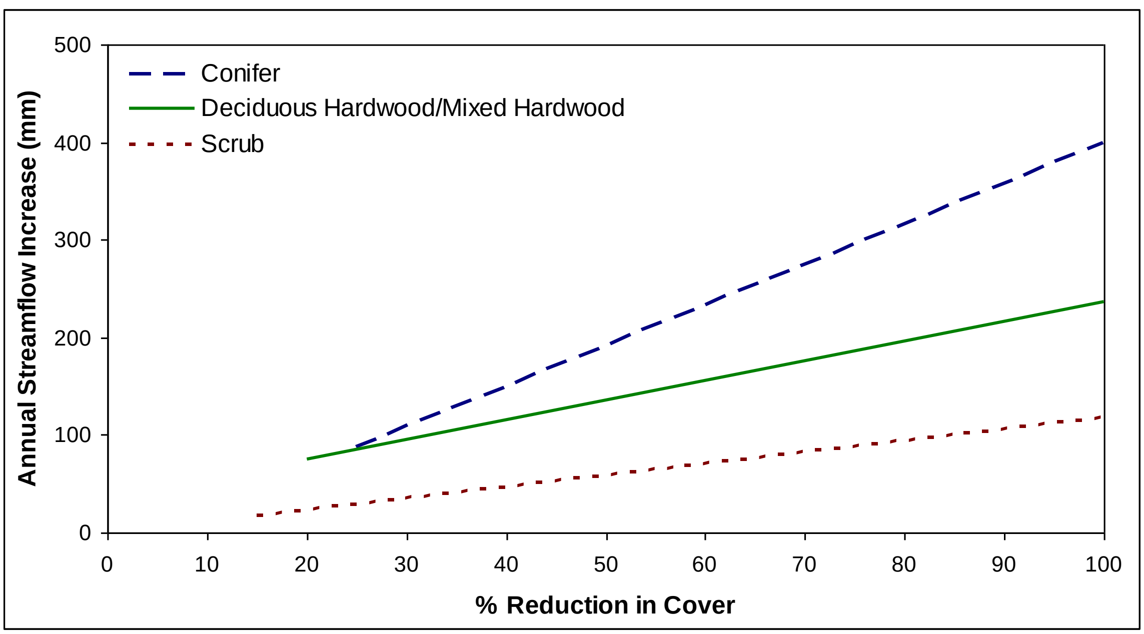
2.3: Forest-water interactions in the UFR region depend on the interplay between precipitation, land forms, and vegetation:

The forest species mix, forest canopy cover and root structure, fire history, subsurface soils and geology, along with the surface topography and elevations are all factors that affect forest-water interactions. From an early Forest-Water Balances Study literature update, the Workgroup learned that,

> "Singleton and Moran (2010) found that recharge is more likely to occur in vegetated areas on the lower slopes, instead of recharge through the higher elevation bedrock fractures. " strengthening the Workgroups' assumption that vegetation "drives" forest-water balances in the UFR. Hypothesis development began in 2012 at the close of the HF-QLG pilot project. The Workgroup adopted the following hypotheses based on regional studies. The authors for the science for the hypotheses were Dr. K. Miriam and Dr. H. Safford (forest ecologists) and Dr. G. Freeman, a senior hydrologist for PG&E Company.

2.3.1.: Hypotheses about interactions between increasing temperatures, increasing forest evaporation and transpiration (ET), and declining streamflows:

- Winter average minimum nighttime temperatures have risen by as much as 9 degrees F in parts of the Feather River region over the past 50 years, compared to a more common range of 2-3 degrees F increases across the rest of the Sierra Nevada. A shift to more rain instead of snow and the declining hardness of the snowpack due to the rising winter temperatures (block ice melt compared to crushed ice melt) results in additional soil moisture being available to upland vegetation earlier in the spring.
- Warmer temperatures and earlier snowmelt may result in the forest emerging from dormancy earlier in the spring season, so there is less time to allow water to percolate into the deeper storage below the root zone.
- The combination of overstocked forest stands and rising temperatures may result in more forest uptake of springtime water that otherwise would have entered the stream systems as surface runoff or percolated into aquifers to become part of the groundwater contribution to summer baseflows.



(Source: Bosch and Hewlett 1982)

2.3.2: Hypotheses about forest thinning, streamflows, and groundwater recharge:

In the spring, streamflows derive predominately through precipitation throughfall in forest canopy openings into hillslope soils. Downslope and lateral migration of underground flows through soils and rock and into streams and downstream aquifers extends local and distant streamflows.

2.4: It is also hypothesized that:

1. Spring pulse flows can be enhanced through forest vegetation treatments that create more precipitation throughfall and more snowpack shading. In the fall, hillslope water storage again produces lateral soil flows from upland forests through the cessation of transpiration. As the forests enter dormancy (beginning in mid-September), the onset of forest dormancy results in measurable increases in stream flow and in higher water levels in hillslope springs.

2. Fall pulse flows can be enhanced through forest vegetation treatments that reduce forest tree densities, reduce seasonal evapotranspiration, and thereby, retain soil and shallow aquifer water for release to streams in the fall for the effective life of the treatments.

3. Leafless and mature aspen, alder, oak and cottonwood hardwoods may capture and infiltrate more winter precipitation into soils and in some cases, into aquifer storage.

4. Groundwater infiltration and storage during the winter storm season, depends on 1) underlying groundwater storage characteristics, 2) forest canopy factors, 3) forest soil conditions, and 4) the connectivity of stand-level soil moisture to underlying bedrock and alluvial formations capable of conveying groundwater to local and/or distant surface waters.

Table 2: Results of streamflow simulations in the FRB, based on the USGS PRMS model.

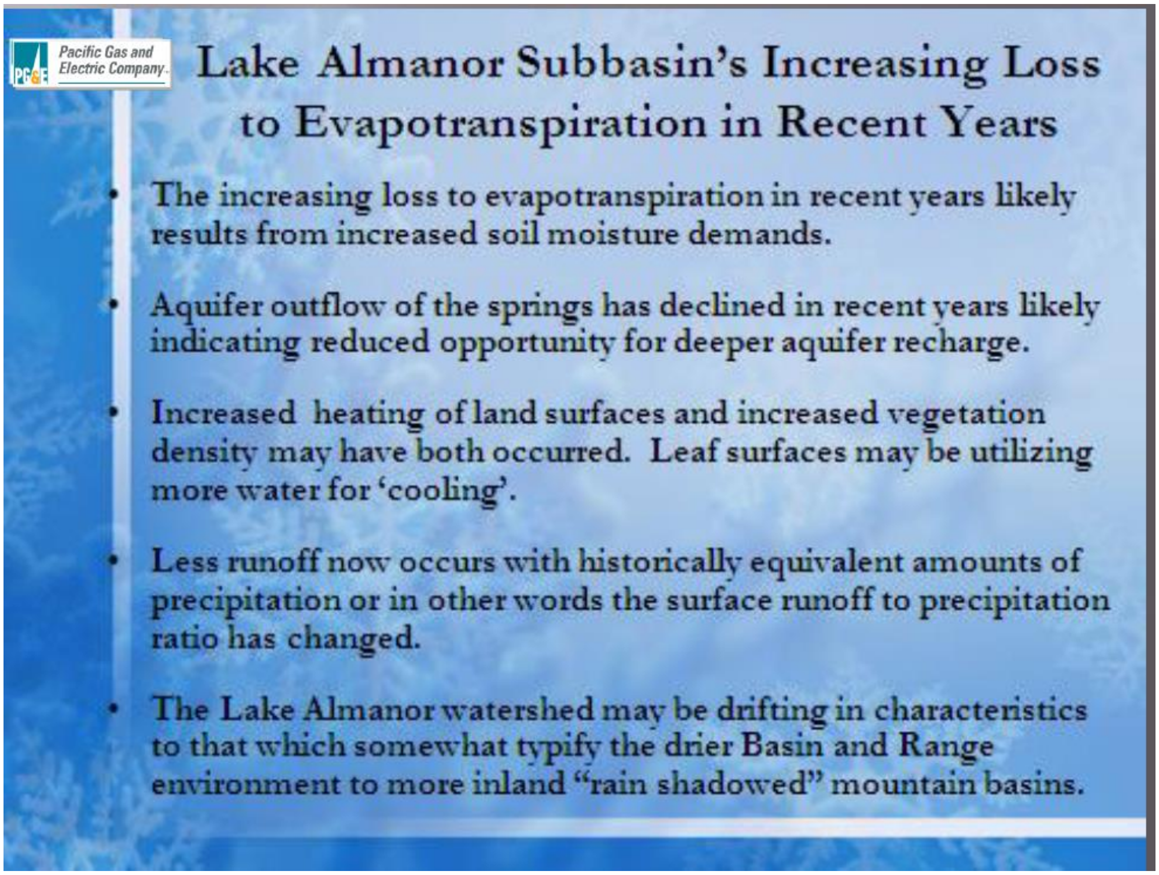
						"young GW"	"old GW"	
Model	**Area**	**Precip., snow & rain**	**ET**	**streamflow (3 components)**	**Surface runoff**	**Subsurface flow**	**Ground-water flow**	**% GW of streamflow**
		simulated	simulated	simulated	simulated	simulated	simulated	
	mill-acres	mill. AFA	mill. AFA	mill. AFA	mill. AFA	mill. AFA	mill. AFA	
Almanor	0.283	1.079	0.413	0.664	0.021	0.411	0.231	96.8%
Butt Creek	0.044	0.144	0.069	0.067	0.002	0.039	0.026	97.3%
East Branch	0.657	1.849	0.974	0.733	0.011	0.574	0.148	98.5%
Lower North Fork	0.186	1.140	0.313	0.825	0.011	0.602	0.213	98.7%
North Fork, Total	1.170	4.213	1.769	2.289	0.045	1.626	0.618	98.0%
Middle Fork	0.670	2.344	0.988	1.032	0.000	0.764	0.268	100.0%
South Fork	0.069	0.367	0.124	0.243	0.017	0.172	0.055	93.2%
West Branch	0.091	0.447	0.174	0.204	0.000	0.182	0.021	100.0%
Oroville	0.201	1.050	0.374	0.678	0.005	0.498	0.174	99.3%
TOTAL for FRB:	**2.201**	**8.421**	**3.429**	**4.446**	**0.067**	**3.244**	**1.136**	98.5%
	percentage of precip:	100%	41%	53%				
			percentage of streamflow:	100.0%	1%	73%	26%	

(Source: The UFR Water Balances Study (Bohm 2016)

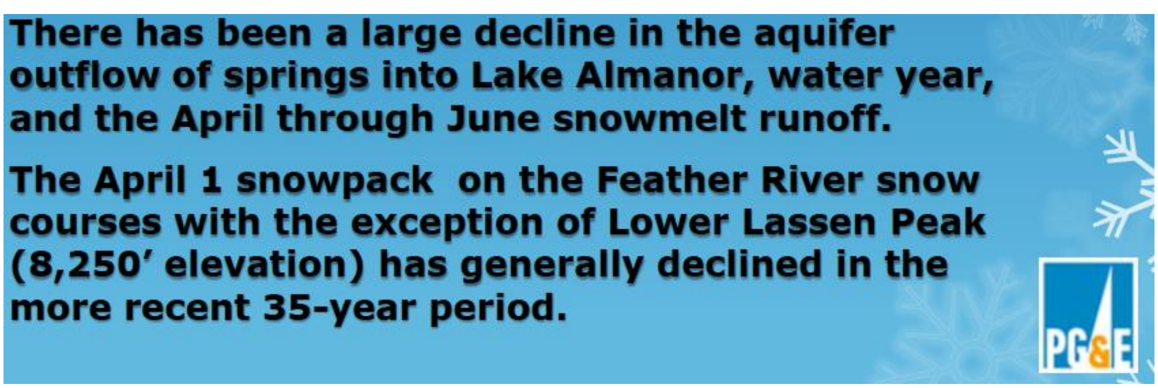
Water balance for the UFR: For the 8.4 million acre-feet of average annual precipitation in the UFR Basin, vegetation growth consumes 3.4 million-acre feet of precipitation through seasonal evapotranspiration. Groundwater storage accounts 4.4 million acre-feet of precipitation which is released in direct runoff and through groundwater inputs to short-term and long-term streamflows.

Water balance trends in the UFR: Stream flows in the North Fork Feather River have been declining since the mid-1960s according to Pacific Gas &Electric Company's data and analysis (Freeman 2009, 2015).

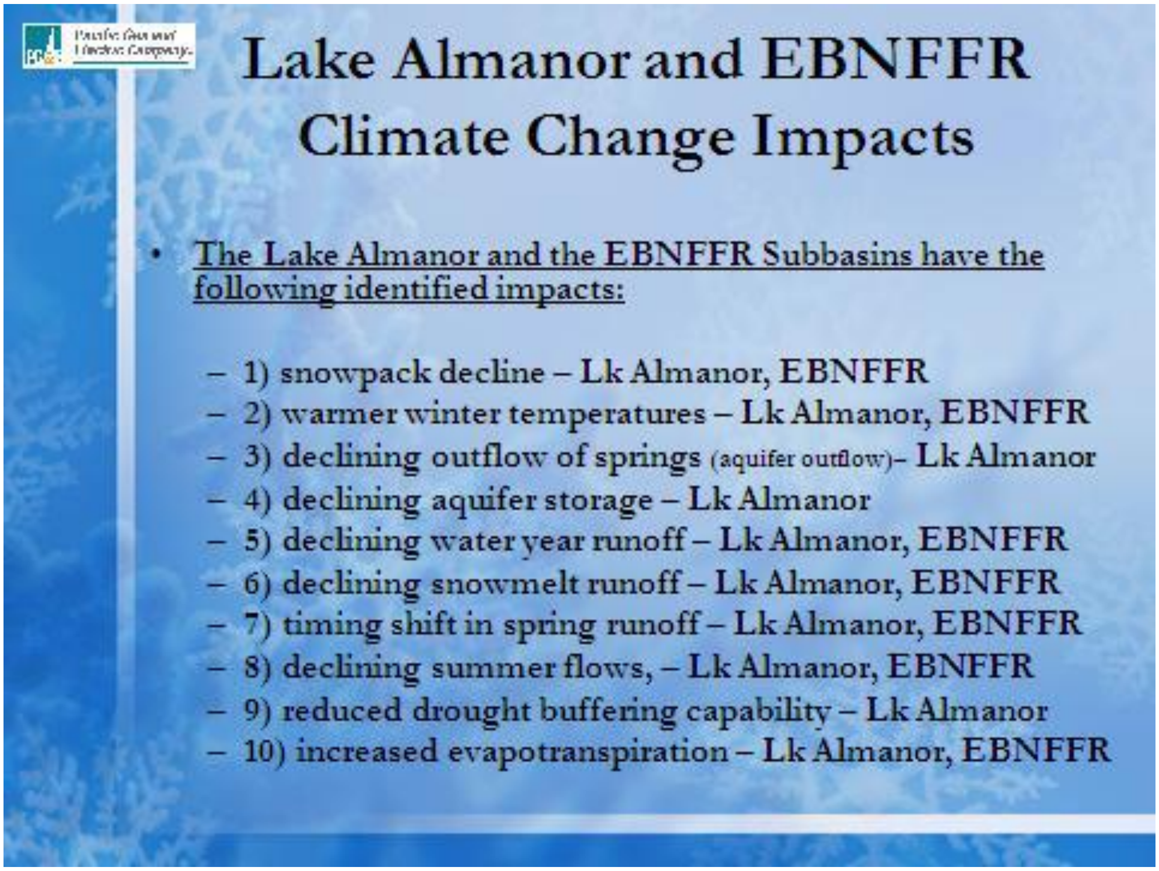
Beginning in 2002 Dr. Freeman began publishing papers on changing runoff conditions in Sierra and Cascade watersheds where PG&E operates hydroelectric generation facilities



(Source: Freeman 2013)



(Source: Freeman 2015)

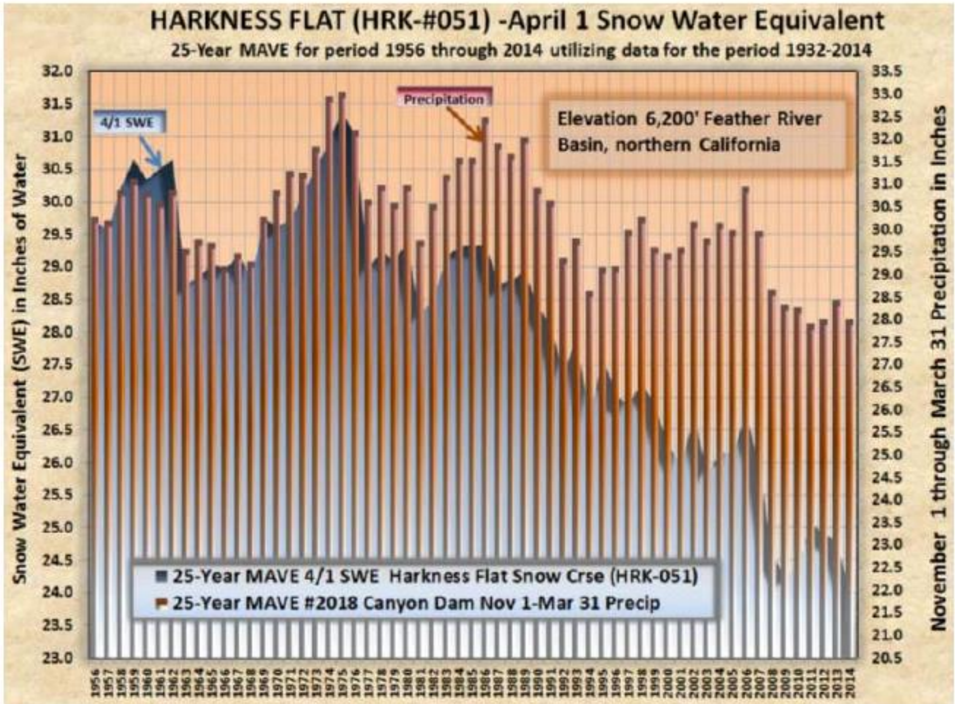


(Source: Freeman 2015)

At the 2015 UFR IRWM climate workshop, participants requested that Dr. Freeman's work be included in the UFR IRWM Plan. And so, it was included in the Climate Chapter excerpts below:

> Figure XX-5 illustrates the 25-year moving average of the April 1 Harkness Flat Snow Course located on the Upper North Fork Feather River utilizing the period 1932 through 2014. This snow course is a permanent site that represents snowpack conditions in snow water equivalent. Snow water equivalent is the depth, in inches, of the water that would form if the snow were to melt. There is a declining trend suggesting a reduced snowpack over time. This matches the conclusion discussed above of a reduced snowpack over time. The figure also charts the 25-year moving average of the November 1 through March 31 precipitation at Canyon Dam (Lake Almanor). This, too, indicates a trend of reduced precipitation over time.

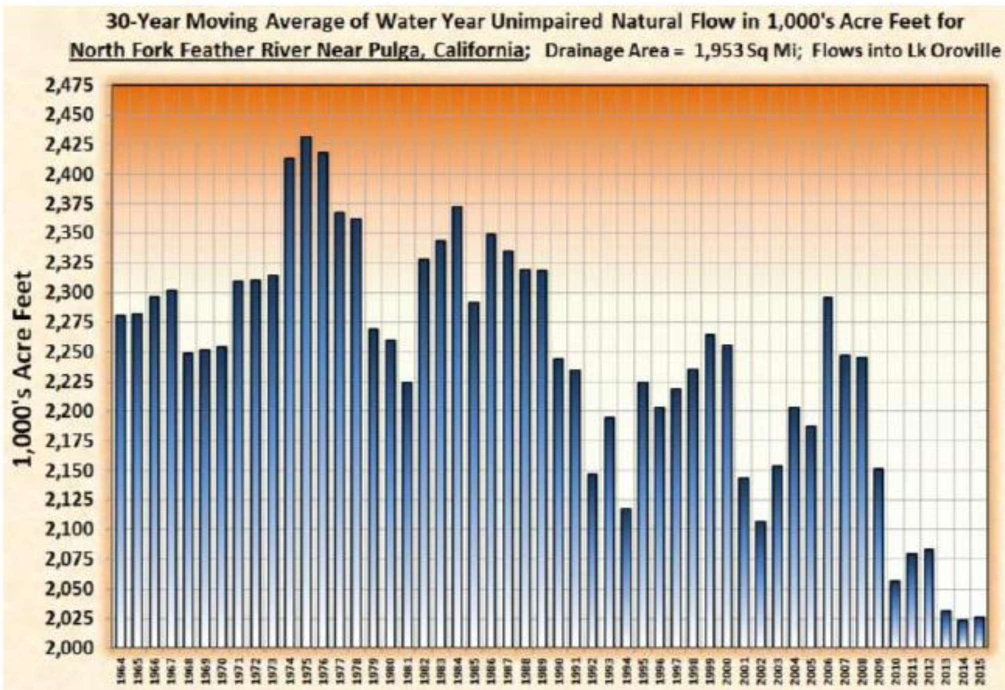
Figure XX-5. Harkness Flat Snow Course April 1 Snow Water Equivalent and November 1 through March 31 Precipitation at Canyon Dam



Source: Freeman 2015.

Figure XX- 3 illustrates the 30-year moving average (ex. data point 1964 is the average of 1935 through 1964) of the Water Year (October 1 through September 30) unimpaired natural flow for the North Fork Feather River near Pulga for the period 1964 through 2015. The declining trend indicates that over this period, 1935 through 2015, the North Fork Feather River has experienced a reduction in annual runoff restricting the ability to meet water demands.

Figure XX-3. North Fork Feather River Water Year (October 1–September 30) Runoff



Source: Freeman 2015.

3: Potential Water Benefits from Enhancing Groundwater Recharge in Forests

The Workgroup had many questions.

Are the water-forest hypotheses and the watershed trends described above connected to “manageable factors” in forest management like reducing forest density, reducing vegetation moisture stress, and enhancing forest productivity?

How does reducing forest canopy cover *affect groundwater infiltration in the UFR?*

The Workgroup asked for an update of an earlier “throughfall” study in the region and requested a memo on the potential relationship between forest canopy cover and precipitation “throughfall” and availability for groundwater infiltration. From the memo (Bohm 2008):

> “To examine effect of forest canopy on the amount of precipitation reaching the forest floor, field experiments were conducted in the winter of 2005/06 on private property near Blairsden) in eastern Plumas County, CA (Bohm, 2008)...Based on these experiments the amount of precipitation evaporated due to canopy interception is 24 percent (average 20station canopy density was 62 percent, ranging between 26 percent and 91 percent), suggesting that canopy interception in overstocked forests has significant adverse impacts on the forest water balance.
>
> The data analysis results indicated that by reducing average canopy closure to 40 percent the amount of precipitation reaching the forest floor can be increased by about 20 percent. The amount of infiltration entering the forest floor depends on annual precipitation –minus canopy interception…For example average annual precipitation in Quincy is about 40 inches. If the moisture lost from canopy interception is 24 percent, precipitation left for infiltration is about 30 inches.
>
> By thinning the average canopy closure from 62 percent to 40 percent, the amount of precipitation reaching the forest floor increases by about 20 percent, thereby increasing infiltration by about 6 inches annually. This translates into a potential gain of 0.5 acre-feet per acre (ac-ft/acre).”

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TABLE 1: Summary	**Estimated GW recharge increase by forest thinning:**					
	after canopy interception and ET.					
Quincy, American Valley	**Feather River Basin**			2/12/2015		
GWR = Precip - Canopy Interc. - Eto						
GWR = throughfall. - Eto						
Forest Conditions:	**Precipitation**	**Throughfall after 24% interception**	**Infiltration after ET from forest floor**	**GW recharge per acre of forest**		
	in/yr	in/yr	in/yr	ac-ft/acre		
Pre-thinnig Forest Conditions:						
Wet Water Year	52.4	39.8	26.6	2.2		
Above Normal Water Year	45.4	34.5	21.7	1.8		
Mean annual precip. (normal)	40.2	30.5	18.2	1.5		
Dry Water Year	29.6	22.5	13.3	1.1		
Estimated GW recharge increase by forest thinning:						
After-thinnig Forest Conditions:			reduction in canopy interception:		20%	
Wet Water Year	52.4	39.8	33.1	2.8	**0.54**	**ac-ft/acre gained**
Above Normal Water Year	45.4	34.5	27.1	2.3	**0.45**	**ac-ft/acre gained**
Mean annual precip. (normal)	40.2	30.5	22.9	1.9	**0.39**	**ac-ft/acre gained**
Dry Water Year	29.6	22.5	17.1	1.4	**0.31**	**ac-ft/acre gained**
NOTE: these annual estimates are based on monthly data of Eto and precipitation in American Valley.						
The estimated infiltration rates (GW recharge depths) are low since Eto and precipitation was						
measured at the valley floor (3400 ft ab. msl), whereas GW recharge occurs at high elevations, up to 8000+ ft.						

Note: In a "normal water year" of 40 inches per year, Quincy receives "average" precipitation for the region. Precipitation varies between 90 inches per year in some parts of the region to 10 inches per year in other parts of the region (Bohm 2015).

The Workgroup also wanted to better understand the full range of water values that could be attributable to currently "uneconomic" fuels reduction projects:

> Environmentally and economically sound surface and groundwater storage, conjunctive use, groundwater management, river, wetland and floodplain restoration and watershed restoration efforts are all tools that can help us weather prolonged drought. These investments in natural and physical infrastructure can be most effective in banking water in wetter years for use during drought periods. In addition, natural infrastructure and healthy watersheds also result in cleaner water supplies. However, those facilities must be operated to preserve stored water for drier years and to avoid further ecosystem impacts.

(Source: Wetter or Not by an Environmental and Equity Water Coalition of 13 California non-governmental (NGO) groups on the Califonia drought (2014) https://www.nrdc.org/sites/default/files/wat_14111701a.pdf)

***What are some of the downstream economic values** from enhancing groundwater storage in UFR forests?*

From the literature:

An October 2104 Research Brief by the Stanford Woods Institute for the Environment and the Bill Lane Center for the American West quantifies groundwater storage benefits:

> "Using a median cost of $1,900.00 dollars per acre foot for new surface water storage, that amount could fund approximately 1.4 million acre-feet of new surface water storage. Conversely if the $2.7 billion from Proposition 1 earmarked for water storage were to be spent on groundwater recharge and storage, California could gain about 8.4 million acre-feet of new groundwater storage capacity.
>
> … For the same amount of money, groundwater storage could provide six times more storage capacity than surface water storage."

The Nature Conservancy quantified enhanced runoff benefits in the North Fork of the Feather River:.

> "The greatest percentage of the watershed acreage defined as "operable area" in the 11 Sierra watersheds was in the {North Fork} of Feather River Watershed at 694,593 acres of additional and available National Forest acres for mechanical forest treatment of 1,380,108 NFFR watershed acres. The BCR (benefit cost ratio) approaches 1.01 for the hydroelectric generation values for increased runoff in the UFR basin" (Podolak et al. 2015).

Supply benefits are estimated for the Sierra Nevada forests by Wesleyan University researchers:

> "Over-forested acreage transpires an additional 2.3 acre-feet of water per year.... Applying low end estimates to the more than 7.5 million acres of Sierra Nevada conifer forests suggests that the uses an excess daily net water loss of 58 billion liters or that 17 million acre feet of water may no longer seep in tor trickle down from the Sierra to thirsty families, farms, or endangered fisheries. Investing $1000 dollars per acre could yield $1,100 to $1,500 of water @$450 to $650/acre foot in current water markets" (Workman and Poulos 2013).

***What are some of the environmental and streamflow values** from enhancing groundwater storage in UFR forests?*

From Bales et al. 2011:

> "Thinning forest cover to 40 percent increases runoff by 9 percent. Yields range from an 8 percent yield increase with a reduction to a 20 percent forest canopy cover, and up to a 16 percent yield increase with a reduction to a 30 percent canopy cover from current density conditions. Thinning 500 to 600,000 acres of forest, on the average yields 100,000 acre-feet of water annually."

The Rocky Mountain Research Station's brief states that

> "Across 95 watersheds in the US, there is a 2.5mm increase for each 1 percent of the watershed harvested (which becomes detectable in streams above a 20 percent basal area removal in the watershed). Yields decline after 20 years in "cold" snow elevations and after 10-30 years in "warm" snow elevations… Reducing chaparral with high severity fire increases water yields from

> between 4 to 14 times…. Streamflows on National Forest lands have declined by 3 inches from 1860-2000 from increasing forest density…" (unpublished data).

A number of researchers have focused on the effects on streamflows associated with continuing the current forest management trends with warming temperatures:

> "The application of "fuzzy" linear regression data from 145 experiments shows that, for a 10 percent reduction in conifer cover, yield increased by some 20-25mm…. A 5mm decrease in yield was associated by conversion to scrub" (Sahin and Hall 1996).
>
> "A 4.1 degrees C warming of mean air temperatures is predicted to increase ET by 28 percent and to reduce streamflows in the Kings River basin by 26 percent" (Goulden and Bales, 2014).
>
> "A 2.4 degrees C increase in mean annual temperatures is predicted to reduce streamflow by 12 percent based on trends in 420 US catchments" (Berghuijs et al. 2014).

A worldwide science synthesis (Sun et al. 2015) focused on projecting current forest-water trends under different forest thinning scenarios in the context of future global climate precipitation and temperature change scenarios.

> "As a whole, water yield increased by 3 percent, 8 percent, and 13 percent when {leaf area index} LAI was reduced 20 percent, 50 percent, and 80 percent, respectively, while water yield decreased by 3 percent when LAI increased by 20 percent.
>
> Temperature increases of 2 degrees C alone could decrease water yield by 11 percent. A reduction of precipitation by 10 percent and 20 percent could result in a decrease of water yield by 20 percent and 39 percent, respectively.
>
> The direction and magnitude of water yield response to the combinations of LAI (+10 percent), climate warming (+1 degree C), and precipitation change (±10 percent) were dominated by the change in precipitation. Climate change projected by the four GCMs (CSIROMK2 B2, CSIROMK3.5 A1B, HADCM3 B2, and MIROC32 A1B) resulted in a large change in water yield (+18 percent to **-** 64 percent) by 2045**–**2055 when compared with the baseline.
>
> Forest LAI under the four GCMs scenarios could greatly mitigate or exacerbate future climate change impacts on water yield in forest- dominated watersheds with high precipitation. This study provides the first quantitative estimate of the effects of forest thinning options on water yield under future climate across the continental US. Effective forest water management for climate mitigation should focus on those watersheds identified"(Sun et al. 2015).

***What are the relationships between** forest mortality and increasing wildfire severity?*

From North 2012:

> "Acreage that would have historically burned each year was estimated using Geographic Approach to Planning (GAP) analysis (Davis and Storms, 1996) and sources summarizing historical regimes (Stephens et al. 2007, Van de Water and Safford, 2001, FEIS 2011)."

Of the Forest Services' 4.8 million forested acres "…approximately 44,800 ac…may have burned each year before the arrival of Europeans. From 1986 to 2010, on average, 51,000 acres /ac/yr. are burned by wildfire… leaving 437,000 acre/yr. to be treated to mimic historical reduction levels"…" (on National Forests in the Sierra Nevada)"(USDA 2013).

> "Fires at the beginning of the record {1984-2007} burned an average of about 17 percent high (stand replacing) severity, while the average for the last ten-year period was 30 percent. Miller et al (2009) found that both climate change and increasing forest fuels were necessary to explain the patterns analyzed" (Merriam et al. 2013).

As the following table shows, the fire adapted forests in the UFR basin, before the European management era, were characterized by "clumpy' and heterogeneous tree spacing and were dominated by large conifers and mature hardwoods intermixed with patches of understory vegetation that was distributed and maintained by frequent and low intensity ground fires.

Study	Study Site	Forest Type	Time period	Trees per Acre[1]	Basal Area (ft^2/acre)[1]	Diameter (inches)[1]	Relative Density[2]
	Yosemite NP	conifer	(ca. 1899)				
Stephens & Gill 2005	N. Mexico: Sierra San Pedro Martir	JP - Mixed conifer	Contemporary Forest with unaltered disturbance regime	59 (12 -130)	87 (25 - 221)	12.8 (1.0 - 44.1)	20%
Taylor 2001, Taylor 2010	S. Cascades: Ishi Wildernes s	Ponderos a Pine - Black Oak	Contemporary Forest with relatively unaltered disturbance regime[C]	47 (29 - 64)	108 (65 - 142)	20.6 (17.6 -23.6)	33%

[1] Ranges are provided in parentheses
[2] Calculation of Relative Density is based on a Maximum SDI of 450 from Long and Shaw's Draft Density management diagram for Pine-dominated Sierran Mixed conifer Forests. Using a maximum SDI of 450 provides a very liberal estimate of density because relative density = current SDI/ maximum SDI. Using higher values for maximum SDI would produce even lower relative densities.
[A] Mean Diameter was calculated using Trees per acre and Basal area per acre
[B] No range provided.
[C] Skinner and Taylor (2006) discuss the applicability of the Beavery Creek Pinery site in the Ishi Wilderness in Sidebar 10.2 (pages 207-209)

(Source: USDA 2013])

4: Applying the Science

The Workgroup members reviewed the extensive body of reference science that was collected by the members (**Section** 9). The science search was member-driven and so it is selective more than comprehensive, and the Workgroup found some science "more useful" than other science. The Workgroup was most interested in "regional science", and then in "agency science" because it more directly linked science to management issues across the different forest ownerships. "Advocacy science" was interesting for the Workgroup because it challenged members' thinking and enabled members to better understand policy and political barriers to implementing landscape-scale strategies and projects. The "popular science" in the media helped the Workgroup understand drought perspectives from forest and water managers and advocates from differen regions in California.

And then there is the "new science." After the Workgroup had developed its priority strategies and projects, a comprehensive science synthesis on droughts and forests was published (Vose et al. eds. 2016) that included findings that specifically relate to Workgroup priorities. Relevant findings from this study are inserted into the following discussions as "postscripts" and in (**Section** 7. Another article was published (Hessberg et al. 2015) after Workgroup projects were submitted; therefore, that material is also referenced as a postscript for future project development.

5: Integrated Forest-Water Strategies: Restoring the Forest Hydrograph by Re-establishing more Fire and Drought-Resilient Forests

The Workgoup adopted "forest fuels hazard reduction" as the general approach for integrating forest and water management in the region. "Variable density thinning" is a forest fuels reduction approach that encompasses the range of canopy cover and forest stand density treatments. Forest fuels reduction includes "managed fire" as a forest conservation and management tool. Both managed fire and forest thinning "keep fire on the ground and out of the tree crowns," and thereby reduce the extent and severity of forest mortality from wildfire and also achieve other objectives such as reduced forest evapotranspiration and moisture stress that are key to maintaining forest productivity.

From Vose et al., eds. 2016:

> "Managers can implement structural changes by thinning or density management of planted forests. Thinned stands require less water and may be less vulnerable to water stress and insect outbreaks. Reduced fuel loads in thinned stands can also reduce wildfire risk." (P.8) For example, warming means that the droughts we have now are more likely to produce tree mortality for a given level of water deficit (e.g., Adams and others 2009). (P.35) Because warmer temperatures elevate metabolism and respiration, a higher productivity will be required to match the demand. As plants shut down during moisture stress, they will exhaust carbon stores more quickly, and survival times between wetting events will shorten. (P.19) An awareness of the declining precipitation… has revealed that the precipitation variability has historically been a more important control on interannual variability in burned area (Abatzoglou and Kolden 2013, Holden and others 2012, Riley and others 2013), and increasing wildfire area is consistent with increasing drought severity as indexed by the lower streamflow quartile (P.34)."

"Variable density thinning" strategies include:

- Fire and fuels management and strategically located firebreaks for ridgeline lightning, roadway, and railroad ignitions.
- Fire and fuels management for the protection of critical habitats.
- Snow zone fuels and fire management.
- Wildfire liability reduction along forest property boundaries.
- Wildland-Urban Interface (WUI) fire and fuels management.
- Traditional Ecological Knowledge to reintroduce historic fire regimes before the "fire suppression" management period and for enhancing tribal "beneficial uses" of water.
- Community recharge area (CRA) management to protect of domestic and agricultural wells and surface water sources from catastrophic wildfire and from reduced groundwater infiltration or excessive siltation.
- "All-scale" biomass utilization including community and tribal biomass projects

- Landscape-scale forest conservation and management that includes multiple (#1-#8) fire and fuels management strategies.

"Managed fire" strategies include:

- Landscape-scale managed burning that will most likely occur by burning downslope from ridgelines on federal lands.
- "Fireshed"-scale managed burning that will occur more intermittently due to prohibitive fire liability risks for non-federal forest owners and managers for the purposes of fuelbreak maintenance or for other landowner objectives, including establishing study plots.
- Understanding re-burning sequences on severely burned land across forest ownerships is important for all forest owners and managers.
- Burning on federal lands in this region could be broadly initiated to follow the retreating snow line as depicted in the "probable snow courses above 5000 ft. and 6000 ft. elevations" map to enhance climate resiliency in the upper elevation forestlands of the UFR region which are also the deeper groundwater recharge areas.

Additional Tribal Advisory Committee "managed fire" recommendations:

- Increase landscape productivity by increasing ecosystem diversity and resilience through low and moderate intensity fire.
- Increase landscape and climate change resilience through low and moderate intensity fire to increase fire succession mosaics.
- Monitor effects of fire succession in reducing invasive species and re-establishing fire adapted native species.
- Implement projects and studies utilizing TEK as a monitoring tool for water quantity and quality over time.

6: Projects and Strategies

Projects implement strategies. Strategies integrate science, management issues, and forest and water interactions through actions for the different precipitation and groundwater forest zones in the UFR region. Project and strategy development is ongoing and is based on adaptive management and learning. Again because the Workgroup is not "chasing water yields", forest management projects would be implemented in high and low precipitation zones

6.1: Applying strategies to the deep recharge portion of the UFR hydrograph.

Deep groundwater recharge is estimated to produce an average of 20 percent of annual river flows into Lake Oroville and is predominately associated with forests above 5000 ft. in elevation and north facing forested slopes above 3500 ft. elevations (UFR 2016).

<u>"Water wise" fire and fuels management strategies for high elevation forests</u> in the snow zone:

- Along roadways: Depending on site conditions, fuels reduction along ridgeline roadways includes mechanical and hand thinning treatments maintained by periodic managed burning, pruning, and chipping programs in road and railroad rights-of-way.

- Reintroduction of landscape-scale managed fire: Burning downslope from ridgelines located on federal lands can protect down-gradient communities and habitats from dry lightning wildfire storms. Wildfire contained within fire management "cells' that are bounded by ridgelines treatments in areas with high lightening intensities, slows wildfire spotting from ridge to ridge. Some treatments on ridge tops that are also characterized by retreating snowlines and highly fractured geology could be designed to retain open stands of mature trees and natural openings like meadows and aspen and riparian forests that enhance forest moisture by accumulating snowpack and extending groundwater infiltration.

6.2: The shallow to moderate recharge portion of the UFR hydrograph.

Shallow to moderate recharge is estimated to produce approximately 73 percent of annual river flows into Lake Oroville and is associated with mid-elevation "rain-on snow" forest elevations (Source: The Forest and Water Balances Study.)

<u>"Water wise" fire and fuels management in mid-elevation forests </u>in the "rain-on-snow" zones would incorporate enhancing transitory storage of rain and snow precipitation in alluvial valleys, alluvial fans, aspen groves, riparian forests, and black oak stands, and permeable and porous forest uplands for forest management actions in productive water areas.

- Selective conifer overstory removal to regenerate black oak and aspen, stands, riparian forests and meadows and alluvial valley edges and fans to recover their historical range, in some locations, may also recharge aquifers. Meadows, aspen and oak groves function as natural "patch openings" where snow drifts can accumulate and are retained by surrounding forest tree shading, tree canopy openings, and root interception and conveyance to underlying soils and aquifers during the winter months.

- Integrating TEK into fire reintroduction and other vegetation management techniques for critical habitat conservation and connectivity**.** Cultural priorities include " feathering out" from core habitat and culture areas to the surrounding forest to 1) increase landscape productivity by increasing ecosystem diversity and resilience through low and moderate intensity fire, and 2) increase landscape and climate change resilience through low and moderate intensity fire that increases fire succession mosaics.

Postscripts from Hessburg et al. 2015:

Use topography to guide restoration of successional and habitat patchworks. Landscape prescriptions can use topography to tailor species composition, vegetation density, canopy layering, and other structural conditions to edaphic and environmental conditions (Lydersen and North 2012; Merschel et al. 2014). Partitioning the landscape into basic topographic settings, such as valley-bottoms, ridgetops, and south and north-facing slopes, can be an aid in distributing forest treatments. (PIN 7) The effect of this template is expressed most strongly in montane forests where ridges and valleys, benches, toe-slope environments, and north- and south-facing aspect patches shaped characteristic patterns and size distributions of historical successional patches (Lydersen and North 2012a; Fig. 4). For example, north-facing aspects and valley-bottoms historically supported many of the densest and most complex (multi-species, multi-aged and multi-layered) mixed conifer forest conditions (Camp et al. 1997, Olson and Agee 2005; Fig. 5). When fires occurred, these settings typically experienced more severe fire effects than south-facing aspects and ridges. In contrast, south facing aspects and ridges displayed relatively low tree density, open canopy conditions, and burned more often and less severely

> (Agee 1993; Habeck1994; North et al. 2009). Tree-killing bark beetles played a natural role in attacking fire-scarred, weakened, and low vigor ponderosa and Jeffrey pine, Douglas-fir, white fir and grand fir trees, and because of frequent fires, were generally endemic to the landscape. Likewise, defoliating insects frequented denser mixed-conifer patches, especially on north aspects and in valley bottoms (Hessburg et al. 1994) Successional patches include non-forested ''openings'', the largest of which may still be evident today, though their margins have been encroached upon (Arno and Gruell 1986; Coop and Givnish 2007). Smaller openings have disappeared (Skinner 1995), and their historical distribution can be determined from reconstructions of fine-scale forest structure…. In the absence of local, historically derived information, landscape prescriptions should focus on increasing the frequency of variably-sized openings and successional patches (Dickinson 2014). Patch size distributions will fluctuate as they adjust to climate, and to the proportion of the area affected by wildfire and managed fires and vegetation treatments (Keane et al. 2002). However, as patch size distributions of successional patches become more in sync with current climate and natural disturbance regimes, we expect that these adjustments will become less dramatic and abrupt, and offer less uncertainty to future habitat conditions. Spatially mapped climatic water balance metrics (e.g., actual evapotranspiration and deficit) can be used to further refine and quantify topographic conditions into useful ranges for site potential and species composition determinations, and to guide climate adaptation (e.g., see Stephenson 1998; Dobrowski et al. 2011; Churchill et al. 2013." Transitional zones with adjacent patches) might be more typical of the ''soft edges'' observed under more natural disturbance conditions (Stamps et al. 1987)."

Project Examples: UF-1: Marion Meadow, UF-2: Rock Creek Meadow Restoration, and UF-11: Mountain Meadows Creek biomass.

From Gene Gentry's, presentation by the Board of Forestry to the California Water Commission in 2014:

> "I don't envy the task that this Commission has because if there's a more controversial issue than water, I couldn't imagine what it is. It really dominates our discussions because depending on what statistic you look at, 80 to 85 percent of the water of the state of California originates out of the forested landscape… The Sierra Nevada and the Cascades dominate the high priority landscapes, and that makes sense because a good portion of the water comes from those particular areas and feeds into the Sacramento…The Board initiated regulations several years ago to help with Aspen meadow restoration which is important for groundwater preservation," "What we did is we looked at regulations that would make it easier for landowners to remove conifers and bring these meadows back."

"Water wise" fire and fuels management in mid-elevation forests in the Wildland-Urban Interface (WUI) and Community Water Recharge Areas (CRA):

Management in these forest zones focuses on community wildfire protection and safety, and on protecting domestic and agricultural water sources from catastrophic wildfire. WUI and CRA management is integrated with the surrounding upland forests when WUI and CRA zones are "feathered out" to the more effective "watershed" or "fireshed" scale. Integrating groundwater recharge and water quality protection with public safety and ecosystem values across ownerships is the desired outcome of the WUI and CRA strategies because neither fire behaviors nor water dynamics recognize ownership boundaries.

Project Example: UF-6: Round Valley/Keddie Handthin.

Postscripts from Hessburg et al. 2015:

> "Today, successional patchworks of many forest landscapes no longer reflect a tightly linked relationship with their natural disturbance regime calling for restoration of many watersheds and lands (Keane et al.; Wiens et al. 2012; Moritz et al. 2013). Instead, new fire, insect and pathogen disturbance regimes are driven by past management, a warming climate, and contagious patterns of fuels and hosts (Noss et al.), fostering increased numbers of larger and more severe disturbances than occurred historically (McKenzie et al. 2004; Hessburg et al. 2005, 2013; Miller and Davis 2009). Predicted changes in the climate could exacerbate these trends (Millar et al. 2007; Allen et al. 2010; Stephens et al. 2013)."

"Water wise" fire and fuels management in mid-elevation forests with "all-scale" biomass utilization, including community and tribal biomass projects. The following projects were designed to integrate ecological enhancements and economic recovery for nearby DACs by locating fuels reduction treatments in catchments surrounding popular meadows and streams and where biomass utilization facilities make such projects more affordable for forest landowners.

Project Examples: UF-8: Goodrich Creek biomass and UF-10: Greenville Creek biomass.

At a presentation by Dr. Bales and Dr. Conklin to the California Water Commission in 2014, Commissioner Delfino asked about meadows. Dr. Conklin replied,

> "When you look at a catchment, meadows are incredibly important… for biodiversity, but if you look at the area of the catchment, and the area of the meadow, and if you start thinking about that water storage, there's a lot more water in the whole catchment than there is in the meadow. The reason meadows exist is that they are groundwater discharge points, often starting at the beginning of a stream running through them, but that's where the groundwater comes out due to bedrock controls, so what we're trying to do is put those meadows in terms of the whole catchment process. They are incredibly important for the biodiversity of the whole system; they are low-sloped so they capture a lot of sediments and are really important for the water quality, but I don't think you can understand the groundwater flow in the system unless you think about the whole catchment."

6.3: For enhancing and conserving deep, shallow, and moderate recharge portions of the UFR groundwater hydrograph, implement "water wise" landscape-scale forest and fuels management that includes multiple forest fuels management strategies such as those described above, and that incorporate TEK to strategically and safely reintroduce the historic fire regimes that were sustained by tribal management and by the upland forest and water ecological processes that shaped the UFR before the European fire suppression and forest utilization period, and until the Gold Rush era of water developments.

Project Examples: UF-12: UFR Cooperative Regional Thinning and TAC-5: Indian Jim River Resource Center.

Postscripts from Vose et al. eds. 2016:

> "Extensive research in mesic forest ecosystems has shown that a reduction in forest cover generally reduces stand transpiration and leads to an increase in streamflow (Bethlahmy 1974,

Bosch and Hewlett 1982, Hadley and others 2008, Stednick 1996, Zhang and others 2001); however, these forest-streamflow relationships are less well understood in semi-arid regions and are potentially very different than mesic regions (Wilcox and Thurow 2006). (P.236)…When available to tree roots, groundwater may help vegetation avoid drought-induced effects (Ehleringer and Dawson 1992). This strategy is well-known in groundwater-dependent ecosystems (Orellana and others 2012) such as wetlands and riparian forests (Busch and others 1992, Thorburn and others 1992), but has also been recognized in upland systems (Dickson and Tomlinson 1996, Miller and others 2010), which can be referred to as groundwater-influenced ecosystems. (P.240)…. Examples of long-term vegetation responses to drought include reduced leaf area index from abscission or mortality, altered root-to-shoot ratios (Joslin and others 2007), differential species responses in mixed species stands (Ford and others 2011a), and changing species composition (Anderegg and others 2013, Klos and others 2009). All of these factors drive or feed back to ET, ultimately influencing stand water balance and streamflow. (Tague and others 2013) (P.240)… Root architecture and depth distribution…also influence plant responses to water stress, if roots growing deep into the soil profile can access subsurface sources of water that are uncoupled from recent precipitation events. (P.52)…There is support for the hypothesis that water-stressed trees increase allocation to roots growing deeper in the soil profile (Breda and others 2006, Schenk and Jackson 2002). Deeper rooting allows trees to access subsurface water resources in both saturated and unsaturated zones; if they possess the appropriate traits, trees may also transfer water from moist regions of soil to dry regions of soil through the nocturnal process of hydraulic redistribution (HR), which generally correlates with the degree of water limitation in an ecosystem (Schenk and Jackson 2002). (P.53).... However, it is important to note that the amount of water transported through HR also depends on soil type and underlying geology (soil texture, depth to bedrock and water table, etc.). In shallow soils, for example, HR is likely to have limited effects on resilience to drought (P 54)."

Postscripts from Hessburg et al. 2015:

"Emerging from all seven principles is the idea that landscape prescriptions are foundational to restoration. Landscape prescriptions are a way for managers… to move beyond stand-centered forest management. A landscape prescription provides guidance for landscape composition, structure, and spatial arrangement in terms of the elements comprising the next lower level of the hierarchy. We identified four hierarchical levels:

1. Large-scale ecoregional prescriptions are important to reconnecting broad habitat networks and rescaling disturbance processes. Ecoregional prescriptions are strategic—they highlight priority areas for reconnecting habitats and conditions under which wildfires may/may not contribute to restoring desirable local landscape patterns (North 2012). Ecoregional prescriptions should identify areas where post-disturbance silviculture or burning may be appropriate/inappropriate, and where wildfires can contribute to restoration (Allen et al.2002; Reinhardt et al. 2008; Peterson et al. 2015). Ecoregional prescriptions should provide clear guidance for reestablishing large-scale ecoregional connectivity for wide-ranging and migratory aquatic and terrestrial species.

2. Local landscape prescriptions define objectives for successional patch types, size distributions, and spatial arrangements across the topographic template. Local landscape prescriptions are tactical—they identify specific project areas where treatments can begin to restore ecoregional patterns and processes for multiple resources.

3. Patch-level prescriptions describe target conditions within successional patches. Successional patches are ''landscapes within landscapes''. Even though patches themselves define the heterogeneity of local landscapes, they too are defined by within-patch heterogeneity. Reconstructions from pre-settlement era and contemporary forests with active wildfire regimes (Fry et al. 2014; Larson and Churchill 2012) Lydersen et al. 2013; show that patches in fire-prone dry and mesic mixed-conifer forests comprised fine-scale mosaics of individual trees, and tree clumps and openings (gaps) of various sizes. These spatial patterns influence patch-level resilience to disturbances, rates of succession and stand dynamics processes (Sa´nchez Meador et al. 2009; Stephens et al. 2008; Dodson et al. 2008; Fettig et al. 2007), and wildlife habitat characteristics (Kotliar and Wiens 1990; Dodd et al. 2006; Wiens and Milne 1989)… and in microsites with springs, seeps, or hyporheic exchange.

4. Treatment units… are the portions of a local landscape that will be treated to achieve the desired targets…. Critically, treatment units should not define landscape pattern as they currently do in many landscapes. Targets for heterogeneity within patches can be expressed in terms of the numbers and sizes of widely-spaced individual trees, tree clumps, and openings (Churchill et al. 2013), or using other metrics and tools (e.g. Jainet al. 2008; Reynolds et al. 2013). Patch-level silvicultural prescriptions provide targets for the structure, density, composition, and pattern of a patch, or patches, that are tailored to current vegetation conditions and the biophysical setting. "

Note: Workgroup Project examples are found in UFR IRWM Plan Appendix 9-3.

7: Forest Manangement through a WaterLens: Unfinished Business

Workgroup members have discussed future development of the following:

- Develop support tools for more strategy and project development including implementing UF-13 the region-wide LIDAR Project (with recommendations from the 2015 Sierra Nevada Adaptive Management Project (SNAMP) Appendix B: Spatial Team Final Report (Kelly and Guo 2015) and from experience with LIDAR aplications for fire and forest fuels management in the Klamath Basin and elsewhere in the Sierra-Cascade regions.) Develop maps and GIS layers that display forest vegetation ET and soils and geology permeability and porousity.
- Further develop the Forest and Water Balances Study to narrow conceptual and methodoligical uncertainties and to further develop integrated water balance monitoring and modelling protocols including updating the USGS PRMS Model for the NF Feather River and for incorporating vegetation water balance information into the Upper Middle Fork Model. Revisit and refine forest-water hypotheses as information becomes available at local and regional levels.
- Broaden the development of initial project examples and strategies (**Section 6)** for broader applications in deep, moderate, and shallow groundwater recharge forested areas with differeny precipitation characteristics in the region.
- Integrate the work of the Uplands and Forest Workgroup and the Feather River Stewardship Collaborative into the US Forest Service Land and Resource Management Plan updates for the Plumas National Forest, and for the portions of the Lanssen and Tahoe National Forests that are within the UFR region.

- Engage the other local governments in the UFR (Butte, Lassen, and Sierra counties) in further advocacy on state and federal planning documenta relating to forests and water for shaping legislative and investment initiatives for improving forest and watershed health in California and in other western states as appropriate.
- Work with DWR to integrate the Uplands and Forest Workgroup's recommendations into the next California Water Plan update.
- Work with other forest, water and tribal collaboratives in the state to secure durable investments into forest and watershed conservation and enhancements and for securing adequate capacity funding for the coordination of collaborative efforts including funding proposal development and for developing inter-regional forest-water balance studies and projects.
- Overcome barriers to benefits for disadvantaged communities in forests such as biases and errors in DAC assessment tools and data bases, and inadequate funding for projects that provide employment and other opportunities for economic recovery at community and UFR regional scales.

8: Appendices

Appendix A:

The Uplands and Forest Workgroup members:

Uplands and Forest Workgroup	
Plumas County	Lake Almanor Water Group
Plumas National Forest	Soper-Wheeler Company
Office of Emergency Services	Collins Pine Company
Natural Resources Conservation District	Feather River Land Trust
Central Valley Regional Water Quality Control Board	Sierra Institute
Plumas County Fire Safe Council	Environmental Water Caucus
Maidu Summit Consortium	City of Portola
WM Beaty	UC Cooperative Extension

Appendix B:

These projects were developed by the Uplands and Forest (UF) Workgroup and the Tribal Advisory Committee (TAC):

Project Number/Name	Project Sponsor
TAC-6: Traditional Ecological Knowledge	Maidu Summit Consortium
UF-1: Marian Meadow	Collins Pine Company and University of California, Cal Poly
UF-2: Rock Creek meadow restoration	Collins Pine Company and University of California, Cal Poly
UF-6: Round Valley/Keddie hand thin	US Forest Service
UF-7: US Forest Service road improvements	US Forest Service
UF-8: Goodrich Creek biomass	WM Beaty & Associates
UF-10: Greenville Creek biomass	WM Beaty & Associates
UF-11: Mountain Meadows Creek biomass	WM Beaty & Associates
UF-12: Upper Feather River cooperative regional thinning	Soper Company
UF-13: Upper Feather River cooperative LiDAR and GIS support program	County of Plumas

Please see the UFR IRWM website featherriver.org or UFR IRWM Plan (Appendix 9-3) for the full project proposals

Bibliography

Anderson, M.K. 2007. Indigenous uses, management, and restoration of oaks of the Far Western United States: Draft. USDA, Natural Resources Conservation Service, National Plant Data Center.

Asner, G. P., et al. 2015. Progressive forest canopy water loss during the 2012-2015 California drought. Department of Global Ecology, Carnegie Institution for Science, Stanford, CA. Accessible: http://www.pnas.org/cgi/doi/10.1073/pnas.1523397113

Asner, G. P., et al. 2015. Progressive forest canopy water loss during the 2012-2015 California drought: supporting information. Department of Global Ecology, Carnegie Institution for Science, Stanford, CA. Accessible: http://www.pnas.org/content/113/2/E249.full.pdf

Austin, C. 2014. The importance of upper watershed management to California's water supply. Maven's Notebook, a blog accessible @ https://mavensnotebook.com/

Bales, R. C., et al. 2011. Forests and water in the Sierra Nevada: Sierra Nevada watershed ecosystem enhancement project. Sierra Nevada Research Institute, UC Merced; Center for Forestry, UC Berkeley; and Environmental Defense Fund, California.

Bales, R., et al. 2015. Appendix E: Water team final report. Sierra Nevada adaptive management project. SNAMP, CNR, Berkeley, CA. Accessible: http://snamp.cnr.berkeley.edu/documents/675/index.html

Berghuijs, W. R., R.A. Woods, and M. Hrachowitz. 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. Nature Climate Change, vol. 4. Accessible: www.nature.com/natureclimatechange

Bohm, B. 2008. Canopy interception in a coniferous forest in eastern Plumas County, California, memo. Accessible: http://www.countyofplumas.com/DocumentCenter/View/11648

Bohm, B. 2014. Ground water quality monitoring information in SV, a memo (unpublished data). Accessible: http://featherriver.org/_db/files/70_Bohm_2014_WQ_LocationDilemma.docx

Bohm, B. 2015. Groundwater recharge and forest canopy thinning, a memo (unpublished data).

Bohm, B. 2016. Forest and water balances, an exploratory study: Concepts of the Upper Feather Basin uplands hydrology. Publication data is unavailable at press time.

Britting, S., et al. 2012. National forests in the Sierra Nevada: A conservation strategy. Sierra Forest Legacy. Accessible: http://www.sierraforestlegacy.org

Calder, I., et al. Towards a new understanding of forests and water: An overview of the state of knowledge about forest and water interactions and salient issues in forest and water policy. Food and Agriculture Organization of the United Nations. Rome, Italy.

California Department of Forestry and Fire Protection. 2010. California's forests and rangelands. 2010 strategy report. Accessible: http://frap.fire.ca.gov/assessment2010.html

California Forestry Association. 2015. How severe fires impact our soil. California Forestry Association, Sacramento, CA. a blog @ http://calforests.org/category/blog/

California Oak Foundation. 2009. Oaks, CEQA carbon dioxide and climate change. Accessible: OaksCEQA_CarbDi_ClimChng_09.pdf

Constantz, J.E., et al. 2012. Expanded stream gauging includes groundwater data and trends. American Geophysical Union 93:48, p. 497. Accessible: http://sites.agu.org/sharingscience/files/2013/04/eost18922.pdf

Coppoletta, M., et al. 2013. Moonlight fire restoration strategy draft. 2013. Miscellaneous sections. USDA Forest Service. Accessible: Moonlight Fire restoration strategy draft (2).pdf

Daily, S., et al. 2008. Fire behavior and effects in fuel treatments, and protected habitat on the Moonlight Fire. Fire Behavior Assessment Team, (FBAT), USDA Forest Service, Pacific Southwest Research Station. Accessible: moonlight_final_082508.doc.

Dissmeyer, G.E., ed. 2000. Drinking water from forests and grasslands: A synthesis of the scientific literature. USDA Forest Service, Southern Research Station, Asheville, NC.

Earman, S. B. and M. Dettinger. 2008. Monitoring networks for long-term recharge change in the mountains of California and Nevada: A meeting report. Presented at California State University, Sacramento, July 30, 2007.Commission Public Interest Energy Research (PIER) Workshop Paper, CEC-500-2008-006.

Essaid, H. I., and B. R. Hill. 2014. Watershed-scale modeling of streamflow change in incised montane Meadows. Water Resources. Research, 50, pp 2657–2678. doi:10.1002/2013WR014420

Foster, L., et al. 2015. Energy budget changes impact arid mountain hydrology more than rain-snow transitions H33M-04. Presented at the AGU fall meeting, 2015, San Francisco, CA. https://agu.confex.com/agu/fm15/meetingapp.cgi/Paper/84064

Forest Climate Action Team. 2016. California forest carbon plan concept paper: Managing our forest landscapes in a changing climate. FCAT. Accessible: http://www.fire.ca.gov/fcat/downloads/Forest_Carbon_Plan-ConceptPaper_Draft_PublicOutreach.pdf

Freeman, G. 2009. The hydrology of climate change on Battle Creek and the North Fork Feather River. LVNP Headquarters, Mineral, CA. Pacific Gas & Electric Company, Water Management, San Francisco. Accessible: http://www.battle-creek.net/docs/climate_change/BattleCreekHydrology_7_21_09Comp2.pdf

Freeman, G. 2015. Planning beyond California's three-year drought. A 2015 hydroelectric planning perspective. At the 83rd Annual Meeting of Western Snow Conference, Grass Valley, California. Pacific Gas & Electric Company, Water Management, San Francisco.

Goines, B. and M. Nechodom, team leaders. 2009. National forest carbon inventory scenarios for the Pacific Southwest Region (California): Region 5 Climate Change Interdisciplinary Team. US Forest Service, Pacific Southwest Region.

Goulden, M.L. and R.C. Bales. 2014. Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion. PNAS 111:39 pp 140710-14075. Accessible: http://www.pnas.org/content/111/39/14071

Hessburg, P.F., et al. 2015. Restoring fire-prone inland Pacific landscapes: seven core principles. Landscape Ecology 30:1805. Accessible: doi:10.1007/s10980-015-0218-0

Hubbart, J.A., T. E. Link, and J.A. Gravelle. 2015. Forest canopy reduction and snowpack dynamics in a Northern Idaho watershed of the continental-maritime region, United States. Forest Science 3:5 Society of American Foresters, Bethesda, MD.

Jones, B. E., M. Krupa, and K.W. Tate. 2013. Aquatic ecosystem response to timber harvesting for the purpose of restoring aspen. PLOS 1.San Francisco, CA. Accessible: http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0084561

Kelly, M. and Q. Guo. 2015. Appendix B: Spatial team final report. Sierra Nevada Adaptive Management Project. SNAMP, CNR, Berkeley, CA. Accessible: http://snamp.cnr.berkeley.edu/documents/672/index.html

Knapp, E.E. 2013. Long-term overstory and understory change following logging and fire exclusion in a Sierra Nevada mixed-conifer forest. Forest Ecology and Management. 310 pp 903-914.

Koczot, K.M., et al. 2005. Precipitation-runoff processes in the Feather River Basin, northeastern California, with prospects for streamflow predictability, water years 1971–97. US Geological Survey Scientific Investigations Report 2004–5202. USGS, Denver, CO.

Ligon, F., et al. 1999. Report of the scientific review panel on California forest practice rules and salmonid habitat. Prepared for The Resources Agency of California and the National Marine Fisheries Service, Sacramento, CA. Accessible: http://resources.ca.gov/docs/forestry/Richard%20Gienger%20Comment%203%20Attachment%202.pdf

Loheide, S.P. and S.M. Gorelick. 2006. Quantifying stream-aquifer interactions through the analysis of remotely sensed thermographic profiles and in situ temperature histories. Environ. Sci. Technol.. 40:10 pp 3336-3341. Accessible: http://pubs.acs.org/doi/abs/10.1021/es0522074

Lydersen, J. and M. North. 2012. Topographic variation in structure of mixed-conifer forests under an active-fire regime. Ecosystems. Vol. 15: pp 1134–1146.

Merriam, K., H. Safford, and S. Sawyer. 2013. A summary of current trends and probable future trends in climate and climate-driven processes in the Sierra Cascade Province, including the Lassen, Modoc, and Plumas National Forests.

Moody, T.J., J. Fites-Kaufman, and S. L. Stephens. 2006. Fire history and climate influences from forests in the Northern Sierra Nevada, USA. Fire Ecology 2:1.

North, M., et al. 2009. An ecosystem management strategy for Sierran mixed-conifer forests. General Technical Report. PSW-GTR-220, Albany, CA.USDA Forest Service, Pacific Southwest Research Station.

North, M., ed. 2012. A desired future condition for Sierra Nevada forests, Chapter 15. General Technical Report PSW-GTR-237. *In* Managing Sierra Nevada forests. USDA, Forest Service Pacific Southwest Research Station, p. 184. Albany, CA.

North, M., et al. 2015. Constraints on mechanized treatment significantly limit mechanical fuels reduction extent in the Sierra Nevada. Journal of Forestry 113(1) pp 40–48. Accessible: http://dx.doi.org/10.5849/jof.14-058

North, M., B. M. Collins, and S. Stephens. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. Journal of Forestry 110(7) pp 392-401. Bethesda, MD. Accessible: http://dx.doi.org/10.5849/jof.12-021
Peterson, D.W, E. K. Dodson and R. J. Harrod. 2015. Post-fire logging reduces surface woody fuels up to four decades following wildfire. Forest Ecology and Management, 338 pp 84-91. Accessible: http://www.sciencedirect.com/science/article/pii/S0378112714006823

Plumas County Fire Safe Council. 2005. Plumas County communities wildfire mitigation plan. US Department of the Interior, Bureau of Land Management, and the Sacramento Regional Foundation, California.

Podolak, K., et al. 2015. Estimating the water supply benefits from forest restoration in the Northern Sierra Nevada. An unpublished report. The Nature Conservancy and Ecosystem Economics. San Francisco, CA.

Royce, E. B and M. G. Barbour. 2001. Mediterranean climate effects. II. Conifer growth phenology across a Sierra Nevada ecotone. American Journal of Botany 88(5):919–932.

Safford, H. 2015. Climate change, forests and fire in the Sierra Nevada, California: implications for current and future resource management. USDA Forest Service, Pacific Southwest Region, Vallejo, CA.

Sahin, V. and M.H. Hall. 1996. The effects of afforestation and deforestation on water yields. Journal of Hydrology 178 pp 293-309.

Self, S. and S, Kerns. 2001. Pacific Fisher use of a managed forest landscape in Northern California. Wildlife research paper No. 6. Sierra Pacific Industries. Redding, CA.

Shaw, M.R., et al. 2009. The impact of climate change on California's ecosystem services. California Energy Commission, Sacramento, CA. Accessible: http://www.energy.ca.gov/2009publications/CEC-500-2009-025/CEC-500-2009-025-F.PDF

Sierra Nevada Conservancy. 2009. The climate action plan of the Sierra Nevada: A regional approach to address climate change. Vers.1.4. State of California, Auburn, CA

Sierra Nevada Conservancy. 2014. The state of the Sierra Nevada's forests. A report of the Sierra Nevada Conservancy. State of California., Auburn, CA. Accessible: http://www.sierranevada.ca.gov/our-work/docs/StateOfSierraForestsRptExSum.pdf/

Sierra Nevada Conservancy. 2014. The State of the Sierra Nevada's forests: Executive summary. State of California., Auburn, CA. PowerPoint presentation. Accessible: http://www.sierranevada.ca.gov/our-work/docs/StateOfSierraForestsRptExSum.pdf/

Silvas-Bellanca, K. 2011. Ecological burning in the Sierra Nevada: Actions to achieve restoration. Sierra Forest Legacy. Garden Valley, CA.

Spagna, A. M. 2015. A displaced California tribe reclaims sacred land. *In* Reclaimers, University of Washington Press, .Seattle, WA.

Stein, E. D., et al. 2012. Hydromodification assessment and management in California, Technical Report 667. California State Water Resources Control Board Stormwater Program.

Stephens, S.L., et al. 2014. California spotted owl, songbird, and small mammal responses to landscape fuel treatments. BioScience 64:10. pp 1–14. Accessible: http://bioscience.oxfordjournals.org/

Stephens, S. L., et al. 2015. Historical and current landscape-scale ponderosa pine and mixed conifer forest structure in the Southern Sierra Nevada. Ecosphere 6(5):79. Accessible: http://dx.doi.org/10.1890/ES14-00379.1

Stephens, S. L. and B.M. Collins. 2004. Fire regimes of mixed conifer forests in the North-Central Sierra Nevada at multiple spatial scales. Northwest Science 78:1.

Stephens, S.L. and J. J. Moghaddas. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. Forest Ecology and Management. Vol. 215 pp 21-36.

Stephens, S.L., C.I. Millar, and B.M Collins. 2010. Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates. Environmental Research Letters. 5:024003. Accessible: http://iopscience.iop.org/article/10.1088/1748-9326/5/2/024003/meta;jsessionid=897012A68A4A241943748564D05A9597.c1.iopscience.cld.iop.org#citations

Stine, P. 2014. Landscape management demonstration areas: Concept presentation, PowerPoint. USDA Forest Service, Pacific Southwest Research Station

Sun, G., P.V. Caldwell, and S.G. McNulty. 2015. Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States. Hydrological Processes. Wiley Online Library. Accessible: wileyonlinelibrary.com DOI: 10.1002/hyp.10469.

Tory, S. 2016. Study finds surprising source of Colorado River water supply. Article, High Country News, June 20, 2106. Accessible: https://www.hcn.org/articles/more-than-half-of-the-rivers-in-the-upper-colorado-basin-originate-as-groundwater

UFR. 2016. The forest and water balances study. Upper Feather River (UFR) Integrated Resources Water Management Plan 2016, Uplands and Forest Workgroup and the Tribal Advisory Committee, unpublished data. For additional information about the Plan: http://featherriver.org/

University of California. 2015. California agriculture: Forestry: Managing for the future. Agriculture and Natural Resources. 69:1. Richmond, CA. Accessible: http://calag.ucanr.edu/archive/?issue=69_1

University of Utah. 2015. When trees die, water slows. Accessible: https://www.sciencedaily.com/releases/2015/12/151216082911.htm

USDA Forest Service. 2009. Water quality protection on national forests in the Pacific Southwest Region: Best management practices evaluation program, 2003-2007. USDA Pacific Southwest Region. Accessible: http://www.swrcb.ca.gov/water_issues/programs/nps/docs/wqmp_forests/bmpep20032007.pdf

USDA Forest Service. 2012. Forests to faucets. Accessible: http://www.fs.fed.us/ecosystemservices/FS_Efforts/forests2faucets.shtml

USDA Forest Service. 2013. Moonlight Fire restoration strategy. Plumas National Forest. Vers. 1.0. Accessible: Moonlight Fire restoration strategy draft (1).pdf

USDA Forest Service. 2013. Moonlight fire restoration strategy draft. Miscellaneous sections and appendices. USDA Forest Service. Accessible: Moonlight Fire restoration strategy draft (3).pdf

US Forest Service. 2009. Plumas Lassen administrative study (PLAS): 2009 annual report. Pacific Southwest Research Station, Sierra Nevada Research Center, Davis, CA. Accessible: http://www.fs.fed.us/psw/topics/ecosystem_processes/sierra/forest_health/plas/plas_annual_report_2009.pdf

USGS. 2015. USGS training resources for ground-water hydrology. Resources listed include reports, videotapes, and self-study manuals. Accessible: http://water.usgs.gov/ogw/pubs/resources_external.pdf

Vaillant, N.M., et al. 2009. Effect of fuel treatments on fuels and potential fire behavior in California, USA, national forests. Fire Ecology 5:2 pp 14-29.

Vose, J.M., eds. et al. 2016. Effects of drought on forests and rangelands in the United States: A comprehensive science synthesis. Forest Service Gen. Tech. Report WO-93b. USDA. Accessible: http://www.srs.fs.usda.gov/pubs/gtr/gtr_wo93b.pdf

Williams, J.E., et al. 2015. State of the trout. Trout Unlimited. Arlington, VA.

Wilson, R. 2016. Comments by Plumas County on the draft forest carbon plan concept paper. Submitted to the Forest Carbon Action Team (FCAT), fcat.calfire@fire.ca.gov, April 8, 2018? Plumas County Planning & Building Services Plumas County, CA. Accessible: http://www.fire.ca.gov/fcat/downloads/Comments_ForestCarbonPlanConceptStudy_PlumasCounty.pdf

Wilson, R. 2016. Comments on Draft EA and the proposed short-lived climate pollutant strategy. Submitted to Air Resources Board members and staff, May 25, 2016. Plumas County Planning & Building Services Plumas County, CA. Accessible:

Young, D. 2015. Carbon implications of fuels reduction and ecological restoration treatments in Sierra Nevada forests. Unpublished data, UC Davis, Davis CA.

Workman, J.G. and H.M. Poulos. 2013. Unlocking forest streams: Restoring the liquid assets lost to fire exclusion. Ecosystems & Biodiversity, The Forestry Source .