# Rainfall to Groundwater Executive Summary

July 2021 – Updated & Refined

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# Overview

"Rainfall to Groundwater" is shorthand for an approach to water resources in California and beyond that emphasizes ecological restoration of catchments, a.k.a. watersheds., whose vital original functions have been degraded through historical, and even in concert with prehistoric, human land uses. This approach is offered as a cost-effective, ecologically sound alternative to mechanistic engineered solutions that have predominated since at least the 19th century.

Rainfall to Groundwater is a stand-alone project of V•Jigour LLC, solely owned and operated by Verna Jigour, PhD, based in Mariposa County, PO Box 462, Coulterville, CA 95311.

# Rainfall to Groundwater Mission

Serve all who depend on water by hastening understanding, planning and collaborative action to restore degraded watershed detention functions.

# Intent & Caveats

The original intent of Rainfall to Groundwater was to offer insight into opportunities to increase natural recharge without needing to divert surface waters – applicable to California's Groundwater Sustainability Agencies (GSAs), especially in northern and central California, who are responding to California's 2014 Sustainable Groundwater Management Act (SGMA). But then it surely applied to California's Water Resilience Portfolio.

But the GSAs and then the California Natural Resources Agency, in its Water Resilience Portfolio, have ignored my invitations to date to consider a **water storage alternative** to surface reservoirs. So, if nothing else, consider this evidence of *missed opportunities*.

The intent of this Executive Summary is to encapsulate the Rainfall to Groundwater approach in a quickly digestible format. While this approach is soundly supported by the extensive literature review I, Verna Jigour, completed as part of my interdisciplinary doctoral dissertation [Jigour 2008 (2011)], literature citations are kept to a minimum in this summary for the sake of brevity and to facilitate review by readers who may be put off by such scholarly writing.

Readers seeking more robust literature support are invited to peruse the various Rainfall to Groundwater pages, Blog posts and Citations on This Site , moreover to eventually read the two Rainfall to Groundwater books I have in progress.

Meanwhile, please do what you may to help bring this approach to the attention of the pertinent bureaucrats and politicos.

# Concepts & Context

A few fundamental concepts form the basis of Rainfall to Groundwater. Foremost among them is understanding the difference between:

## Retention vs. Detention Storage

When drought-weary observers of winter flood flows yearn for more storage capacity they are typically thinking of reservoirs **retained** by dams. But opportunities for **detention storage** are off most folks' radar.

That needs to change, especially since the opportunities to expand/ restore detention storage are vast, in California and doubtless elsewhere. Humans have been unwittingly degrading watershed detention functions since our mastery of fire and agriculture.

As defined, with illustrations, on the page Retention vs Detention Storage, as well as in the Rainfall to Groundwater Glossary:

**Retention**: water is held against the force of gravity, above or within the soil. Within the soil, retention occurs within capillary pore spaces (micropores), where the retained water is available for uptake by plants. Above-ground retention is accomplished by dams or similar barriers to free flow.

**Detention**: temporary storage of water. Below ground, soil water drainage by gravity is slowed, though not stopped, in macropores. In fact, macropores are among the primary conduits for "preferential flow" through the soil profile. Above ground, runoff is typically detained by snow, but may be slowed by other semi-permeable means — most typically by routing through soil, but other means are possible. Beavers are engineers par excellence of detention storage.

Restoration of detention storage to lands with degraded infiltration and percolation functions will be far less costly to both establish and maintain than engineered retention storage. "The soil profile as a natural reservoir" (Hursh and Fletcher 1942). And, BTW, in my historical research I've learned that was not the first time that concept was expressed.

## Watersheds vs. Catchments

The convention in the U.S. is to refer to "watersheds", whereas hydrologists in other countries preferentially use the term "catchment", which better reflects the detention storage functions of these landscape units, especially when they remain intact. I used "watershed" in the title of my doctoral dissertation, *Watershed Restoration for Baseflow Augmentation* [Jigour 2008 (2011)] because that term is more commonly understood (actually misunderstood) here.

But given my experience as I've attempted to get this concept into consideration by the powers that be in water resources, especially the California Department of Water Resources (DWR), I've come to realize that the word "watershed" itself may be part of the problem. The California water "cognoscenti" appear (based on their concept diagrams) to interpret the word literally, believing that watersheds only *shed*, rather than *capture* water.

That may be closer to the truth with respect to lands where detention or catchment functions have been degraded through human land uses, which applies to the vast majority of lands today. But history shows that the "watershed" term came into popular use well after U.S. attitudes about water resources became entrained to focus on surface waters and before formal U.S. study of groundwater began in the early 20th Century.

For more on that, see Surface Water Diversions vs Baseflow Augmentation, among several applicable Alternate Paradigms. The surface water bias also helps explain the bias toward Stream Networks vs Watersheds/ Catchments, which is also partly a Figure vs Ground dilemma.

I also suspect that most folks preferring the "watershed" concept have never actually been outside when it rains in places where native land cover remains essentially intact. On the most pristine vegetated lands there is actually little to no surface runoff, at least until the soil profile has become fully saturated – which takes a while, depending on precipitation rate..

## How Does Groundwater Get There Naturally?

The nexus between watersheds/ catchments and groundwater lies in precipitation hitting the ground. Provided intact vegetation and soil surface, most will infiltrate and percolate downward through the vadose a.k.a. unsaturated zone toward the respective groundwater table. This "infiltration theory" is among the historical fundamentals of groundwater theory, as discussed in blog post #10 How Does Groundwater Get There? Some Basics.

Another fundamental from the "birth" of hydrology is that runoff comprises but a small fraction of the precipitation falling on the land. The French "father" figures of groundwater hydrology had calculated and confirmed by the end of the 17th century that **precipitation on the River Seine catchment totaled six times the runoff**, reaffirming the infiltration theory of groundwater origin.

That blog post includes a diagram, Surface-Groundwater Interactions, with iterations showing the parts of the system affected by different perspectives. As observed in that blog post, doesn't it seem odd that, given those historical groundwater fundamentals, the solutions proposed by California water "experts" all focus on diverting surface waters to point infiltration sites (human-engineered, of course)?

## The Rational Formula

My masters program in Landscape Architecture conditioned me to a "big picture" perspective on landscapes, considering them on regional and watershed scales. But among the critical influences of that program on my perspectives expressed herein was training in applying the Rational Formula, a.k.a. Rational Equation/ Method, to planning and design for changes in stormwater runoff due to proposed landscape topography changes. This formula is used by engineers, as well as landscape architects, though hydrologic engineers usually confine its use to smaller watersheds/ catchments.

A summary of the Rational Formula appears in February 2019 blog post 9. Rational Way to Recharge & Cold Flows for Fish. So we'll just note here that changes in vegetation cover impact the percentage of precipitation routed directly to runoff rather than infiltration and percolation – as expressed in the Rational Formula. Woodlands and forests are recognized for detaining more stormwater than do "Meadows & Pasture Land".

## California "Grasslands"

There is a broad tendency to view California's "golden rolling hills" romantically as our "natural" heritage. Their summer simultaneous color contrasts with cloud-studded blue skies have engaged many painters' palettes. But that romanticism glosses over the incremental impacts humans have had on these lands over the centuries and millennia humans have been here.

While some stands of native perennial grasses remain in California, they persist predominantly in patches distributed among or within other vegetation types. By far the broadest expanses of grassland in the state are **dominated by *nonnative* annual grasses**.

Adapted to the Mediterranean-type (summer dry season) climate that prevails over most of the state, many of them hailing from the Mediterranean region of Europe and North Africa and lengthy coexistence with regional civilizations, these annual plants green up the hills during the rainy season, then die at its end, leaving us with the familiar golden brown expanses over vast areas of northern and central California foothills, occupying smaller but apparently increasing areas of the "southland".

Most of us without plant knowledge have become so used to those summer-brown hills that we take them for granted as the "natural" landscape. Even among those with California-specific plant knowledge the majority have long assumed that existing expansive nonnative annual grasslands were once clothed with native perennial grasses.

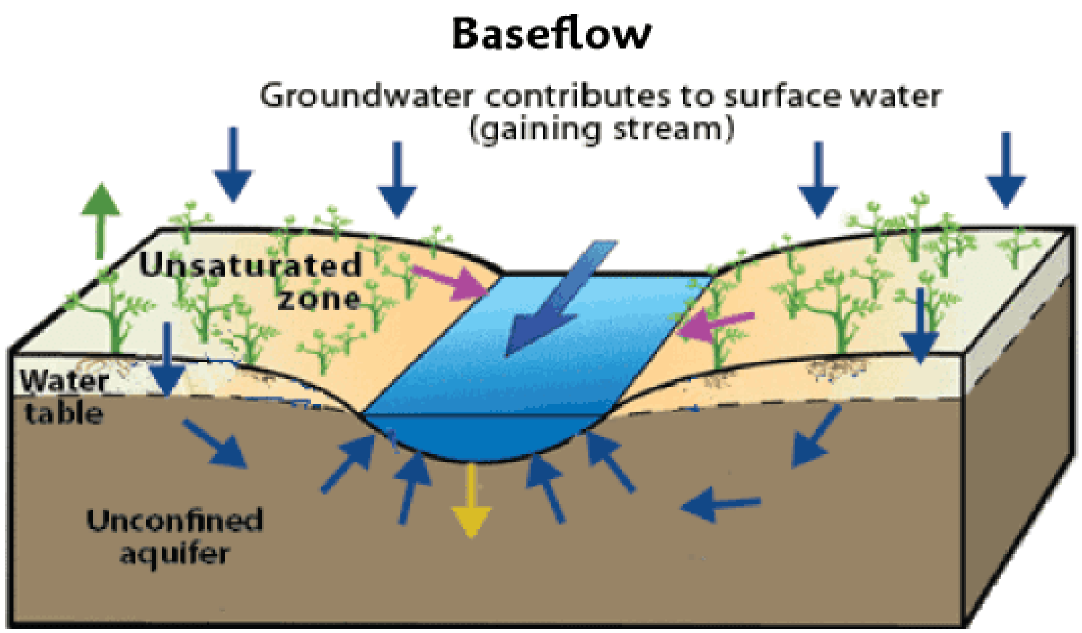
Seemingly only a handful of California plant cognoscenti have come to recognize those lands have likely experienced radical transformations from their natural states before human influences. More on these nonnative annual grasslands follows in subsequent sections.

First, consider some other contextual underpinnings – baseflow and bank storage.

## Baseflow As Groundwater Indicator

Baseflow: "the flow of perennial streams . . . , consisting of interflow and groundwater flow intercepted by the stream" (Ponce 1989b); "the fraction of streamflow that originates in ground water" (Ponce 2007). **Interflow** is depicted graphically in Figure 8, page 26.

**Figure 1. Baseflow • Source: USGS**




Baseflow supports steelhead, salmon and other fish species through the dry season, the original reason I was drawn to the concept. Since the enactment and beginning of implementation of SGMA, it has taken on greater legal significance.

Baseflow is the perennial source for many groundwater dependent ecosystems (GDEs), impacts to which must be considered in implementing SGMA. The influx of groundwater to surface flows provides cold water needed by salmonids and other aquatic species. For more on GDEs and SGMA, please refer to The Nature Conservancy's (TNC) Groundwater Dependent Ecosystems under the Sustainable Groundwater Management Act: Guidance for Preparing Groundwater Sustainability Plans (Rohde and colleagues 2018) and the many other resources and tools offered on TNC's Groundwater Resource Hub.

## Baseflow Augmentation – Rainfall to Groundwater Synopsis

The phrase, "baseflow augmentation" offers a convenient synopsis of the Rainfall to Groundwater approach to enhancing natural recharge and subsurface detention storage, contrasting with more common concepts (see Surface Water Diversions vs Baseflow Augmentation). A large portion of precipitation infiltrating/ percolating directly into the soil where it lands will eventually emerge as baseflow, barring interception by groundwater pumps before then.

If we restore catchment functions to vast areas of our watersheds where those functions have been degraded through human land uses we can catch more of what precipitation falls our way.

## Catchment Functions Include Streambank Storage (!)

Among the catchment functions being largely overlooked to date is that of streambank storage, despite that its water resources and ecological significance was documented three decades ago. In fact, the term, "bank storage" was mentioned in Oscar Meinzer's (1942) Introduction to the text, *Hydrology*.

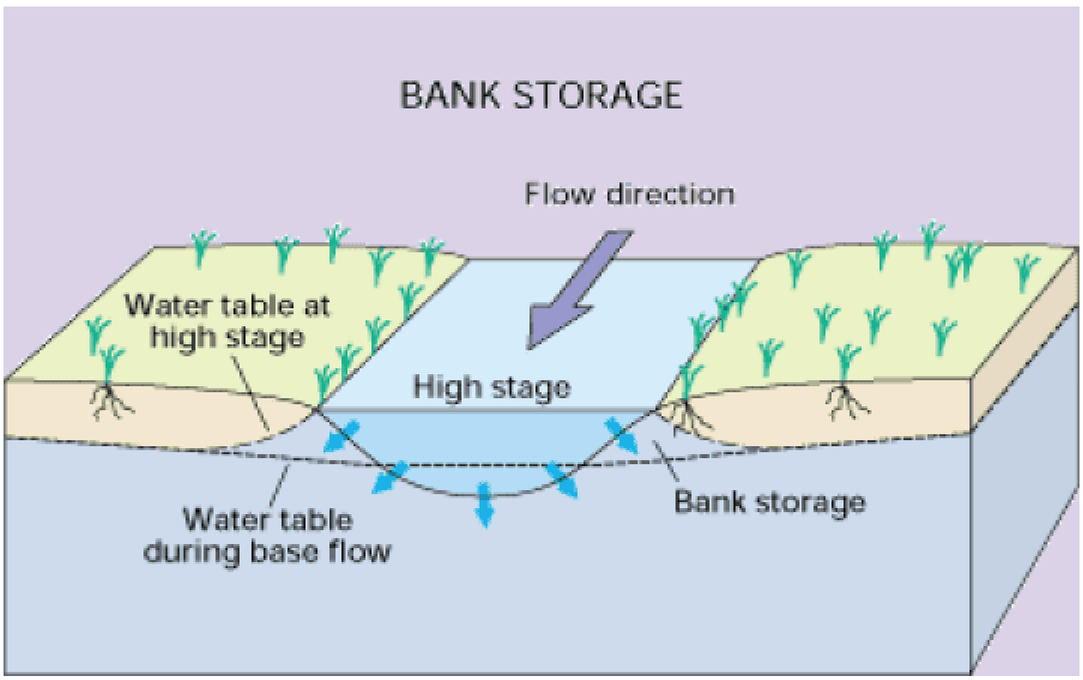



**Figure 2. Bank Storage • Source: USGS**

"Effects of bank storage and well pumping on baseflow, Carmel River, Monterey County, California"(Kondolf and colleagues 1987) documented the ability of bank storage to sustain flows on this regulated river "during May and June, months of critical importance to the downstream migration of steelhead trout smolts (Kelley et al. 1982) and probably to the success of willow seedlings" (Kondolf and colleagues 1987). Another example is "Improving southwestern riparian areas through watershed management" (DeBano and Schmidt 1989). At that time Leonard DeBano was Principal Soil Scientist at the Rocky Mountain Forest and Range Experiment Station.

But the report(s) most broadly applicable to California water resources and foundational to my doctoral work was "Baseflow augmentation by streambank storage" (Ponce 1989a), along with related publications (Ponce and Lindquist 1990a&b) which are freely available online and span extensive literature review. The clients for that initial effort were especially concerned with the Feather River watershed, among the state's largest contributors to water supply. These insights ultimately helped inspire at least some meadow restoration efforts in the Sierras. My dissertation took off from Ponce's (1989) speculation that uplands/ rangelands could also contribute to baseflow augmentation.

Yet, despite the longevity of this awareness in the literature, the concept of streambank storage has eluded most folks in the water resources community. While understanding of floodplains as infiltration opportunities has seemed to be expanding, the detention storage functions of robust riparian zones remain seldom applied to water resources projects, the sole exception being mountain meadow restoration, applied solely to the Sierra Nevada to date. It has yet to be applied to groundwater resources.

I first became aware of this disconnect when I offered a poster based on my doctoral work at the CALFED 5th Biennial Science Conference in 2008. My poster, which was mostly ignored by that audience, included nascent versions of the annual rangeland restoration concept illustrations that now appear on the Rainfall to Groundwater page, What's in it for ranchers?

Since the concept of baseflow augmentation by streambank storage had been documented nearly twenty years prior, I had figured that my concept of uplands restoration was the only new aspect and that streambank storage needed no further promotion. But upon scrutinizing the presentation and poster categories assembled for that conference, I discovered that riparian zones were considered only with respect to their functions as habitat or in water quality amelioration – ***nothing about water quantity*** whatsoever. Hence the holistic restoration concept graphics on the Rainfall to Groundwater Front Page and in Figure 4, page 14.

Fast-forward a decade and that error of omission still applies. A case in point is DWR's draft and final **Water Available For Replenishment (WAFR)** report, wherein there is **no consideration at all of how streambank storage contributes to groundwater sustainability**.

This is especially irksome in the case of overdrafted groundwater basins threatened by seawater intrusion, such as the Pájaro and Salinas Rivers. In 1995 public agencies responded to the severe flooding that year on the Pájaro coastal plain by decimating the riparian vegetation, as though it was the cause of the flooding (NOT). Refer to "Stuck in the Mud: the Pajaro River in Peril" (Robin 2006) for video documentation of the aftermath.

In contrast, robust riparian zones on the coastal plain can serve as bulwarks against seawater intrusion – at least in upper groundwater strata –as well as serving detention storage and baseflow augmentation functions upstream. Perhaps the removal of riparian vegetation was meant to placate local farmers, but surely they experience even greater, more lasting impacts from increasing salinity below their fields, than from one acute instance of flooding.

But what about inland rivers? The San Joaquin River particularly comes to mind. With only peripheral knowledge of the restoration plan for that river, I can only speculate that bank storage has not been among the considerations. Given that the focus of the CALFED Science Conferences was the San Francisco Bay-Delta and the San Joaquin drains to the Delta, it seems a good guess this has been overlooked in restoration planning. Yet, again, the cold water offered by baseflow and bank storage, along San Joaquin tributaries, as well as the mainstem, is among the features that could support recovery of salmonid populations there.

## California's Nonnative Annual Rangelands and Catchment Functions

And then there are the watershed/ catchment uplands draining to the San Joaquin. At least the relationship of Sierra Nevada forest health conditions to water supply has increasingly come to the consciousness of many. Still, certain folks of the engineering mindset apparently think approaches like Sierra Nevada meadow restoration are not worth investment by water agencies because the downstream (engineered) dams overshadow the timing of drainage, as noted in my 3rd blog post, How Watersheds Relate to Groundwater.

Noted in that post is how early 20th Century mainstream attitudes about the importance of catchment functions was lost as engineering perspectives came to dominate the worldview – better living through engineering, eh? We could say (much) more about forests and catchment functions, as well as the trajectory of this apparent paradigm shift, but since this is an executive summary, we'll save those topics for another time and place.

What attention has been paid to watersheds/ catchments has been focused on forested headwaters – lands whereon original catchment functions have remained mostly intact. The potential of lower elevation rangelands has been ignored in that context, simultaneously ignoring their anthropogenic nature.

The watershed/ catchment restoration opportunities overlooked to date by apparently everyone (except me and my doctoral committee) are California's nonnative annual rangelands. For the most part they lie downstream of the major reservoirs, although there are exceptions, especially around the San Francisco Bay Area – the point of my 2nd blog post, Expand existing reservoir capacity non-structurally.

And most oak woodlands, often referred to as “hardwood rangelands”, have understories now dominated by nonnative annual grasses, which have similarly changed their catchment functions, so the same principles/ call for restoration apply to oak woodland understories in reservoir watersheds/ catchments.

Because drainage from these annual rangelands is generally not held back by dams, restoring their detention functions offers particular benefits to sustainability of their respective groundwater basins.  It also offers hope for maintaining the cold baseflows required by native salmonids as they traverse the lower reaches of rivers and streams.

These annual rangelands certainly already contribute subsurface flows to the alluvial aquifers of greatest concern.  Restoring their catchment functions offers greater cost-effective, immediate, potential than do all engineered approaches being considered. But because SGMA focuses attention solely on the basins, **subsurface inputs to groundwater basin Water Budgets are likely to be overlooked by GSAs** not considering the watersheds/ catchments feeding their basins.

While other nominal descriptors of these annual rangelands have entered into and gone out of usage by botanists since they were lumped together into the “nonnative annual grassland” category, the earlier, “lumped” category remains the most telling with respect to their impacts on watershed/ catchment functions.  In many cases significant botanical diversity may remain on these lands but their dominance by exotic annual grass species, imported intentionally or inadvertently, particularly from the Mediterranean region, is a hint at how their land cover changed with the influx of Europeans to California since the 18th Century.

Especially impactful on catchment functions was the progressive loss of woody and other perennial vegetation.  If you have any inkling of how forests serve catchment functions, it shouldn’t be too much of a stretch to imagine why this is the case. To get a sense of the extent of opportunities for annual rangelands restoration, please see the “high albedo” (light-colored areas) in the Figure 3 satellite image., next page.


**Figure 3. Rangeland Opportunities for Rainfall to Groundwater**

## Historical (and Pre-Historical) Impacts to Catchment Functions

My 4th blog post, Think Outside the Basin includes a few literature-supported details on pre-historical, as well as historical impacts of human land uses on watershed functions. For this executive summary it is appropriate to just note a synopsis.

Over the 20th Century, Euro-centric attitudes about California's aboriginal human populations evolved significantly, from disdain to appreciation and even reverence. In all, they were humans, just like us. These first peoples apparently expressed greater gratitude for and satisfaction with the natural blessings our region offered them than the majority of the population does today, but they needed to support themselves, just like us. While there is evidence of only incipient "agricultural" activities (in the European sense) within California, increasing evidence and appreciation has emerged of aboriginal land management strategies that were overlooked by European colonizers due to their cultural biases.

Of the aboriginal land management strategies we've become aware of, the one that doubtless had the greatest impact on catchment functions was burning. Many reasons have been cited for aboriginal burning, including maintenance of plant species preferred for economic needs and driving of game for hunting. But the evidence indicates that, despite their relatively low population numbers, widespread intentional burning actually altered the composition of the landscapes Europeans beheld when they first arrived here. While the newcomers viewed these lands as pristine "wilderness" – again, because their cultural biases precluded perception of aboriginal land management skills – these lands became altered from their natural states prior to human occupation.

While the European colonizers documented but typically failed to understand aboriginal patterns of burning, they continued the practice of burning "undesirable" vegetation to enhance their own economies, especially for livestock grazing. The practice only expanded with the Gold Rush and the influx of Americans into the state. The need to feed and clothe the expanding population resulted in further land clearing – by burning and, in many areas, by grazing and overgrazing, especially by sheep.

Then, there was the wheat boom (and bust) wherein dryland farming converted vast areas of the state – until their productivity for wheat growing declined, typically within about two decades from inception on any given plot of land. Among historical human impacts, this one is probably the most overlooked to date. The notion that our annual rangelands were once impacted by the plow goes right past most folks who ever consider historical impacts to our landscapes. As if that wasn't enough, these dryland wheat fields were subject to catastrophic wildfire, brought to my attention by the grandson of a witness to such maelstroms in the Central Valley.

California state policy, even into the mid-20th Century, advocated removal of woody vegetation, including oaks, to enhance rangelands for grazing. See blog post #6, Ball and Chain & Other Links for more on that topic.

On top of that, charcoal production consumed significant oak woodlands until relatively recently. An exceptional must-read documentation of these patterns is Scott Mensing's (2006) "The history of oak woodlands in California, Part II: The Native American and historic period".

See the Alternate Paradigms page, California "Grasslands" vs. Altered State(s) for the big picture and more botanically specific detail.

Elucidating the true implications of the thinning and removal of oak woodlands on catchment functions is a (much) bigger task than is appropriate for this summary. Suffice it to say, that oak woodlands (i.e., in contrast with oak savannas) are the archetypical model of vegetation supporting catchment functions.

While their above-ground canopies are a significant part of the equation, their subsurface components, including roots and the soil ecosystems they support, have everything to do with supporting infiltration and percolation. The same is true for other woody and perennial plant species that are their natural associates and, in many cases, serve as "nurse-crops" for oak seedlings. In lieu of robust scientific documentation of these catchment functions – which I assure you I can provide – please refer to Figure 4. Holistic Restoration Concept, next page.

While California remains blessed with significant stands of oak woodlands, the catchment functions of their understories have been significantly compromised by the encroachment of exotic annual grasses, to the point that it even impacts oak regeneration. So the Rainfall to Groundwater approach applies not only to the most obviously visible nonnative annual rangelands but also to oak woodlands understories a.k.a hardwood rangelands.

The Rainfall to Groundwater aspiration for voluntary, incentivized rangelands restoration is to restore native woody and perennial plant species to all these rangelands for their watershed functions. The ideal restoration "target" or goal is oak woodlands, wherever physiographic conditions are appropriate. But in certain cases, other woody vegetation, including chaparral and scrub plant species, may be the most appropriate or perhaps interim target, again since such vegetation can serve as "nurse crops" facilitating regeneration and development of oak woodlands.

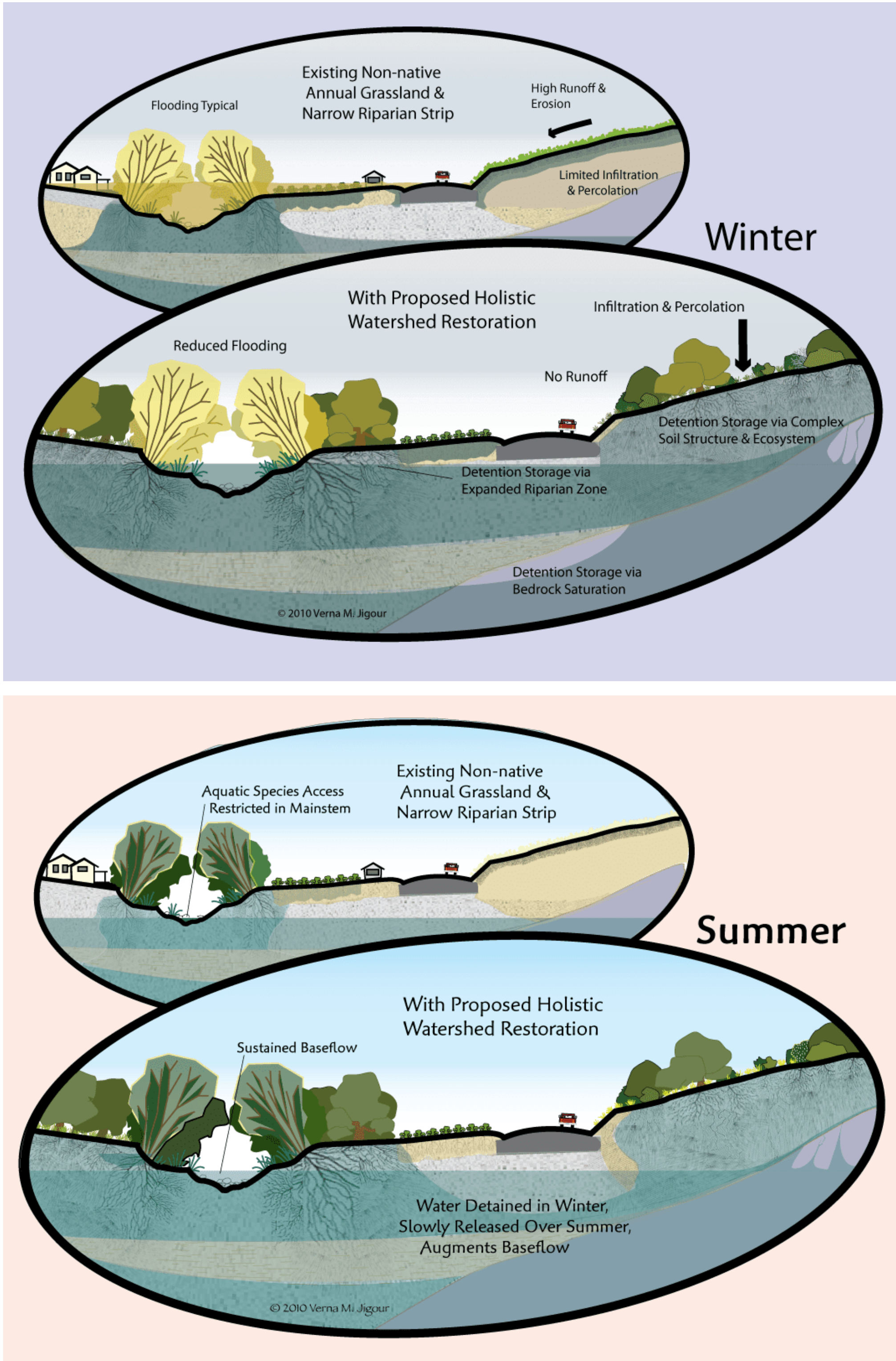
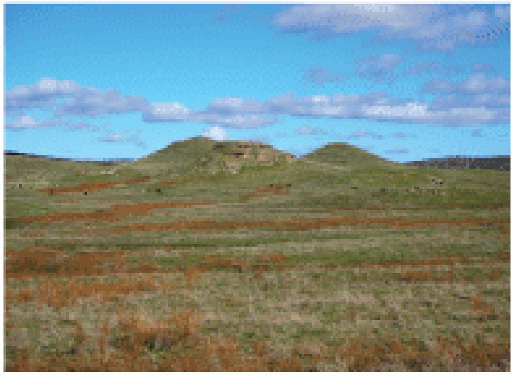
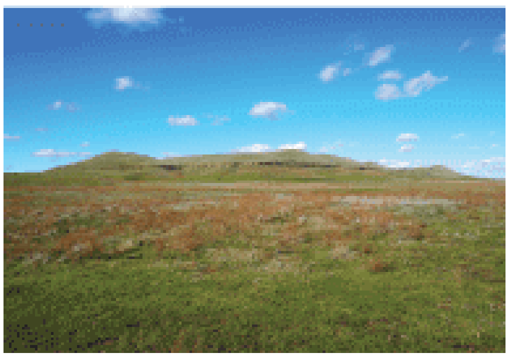



**Figure 4. Holistic Restoration Concept**



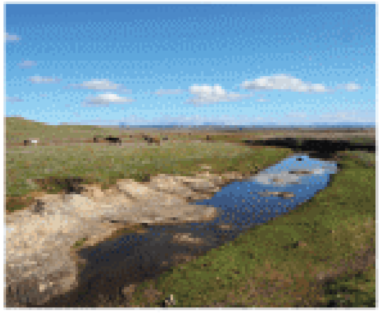
Stanislaus-Tuolumne Rivers Watershed
January 13, 2020



Stanislaus-Tuolumne Rivers Watershed
January 13, 2020

Merced River Watershed July 14, 2021, smoke from the River Fire tints air

**Figure 5. Historic Erosion Down to Bedrock on Annual Rangelands**



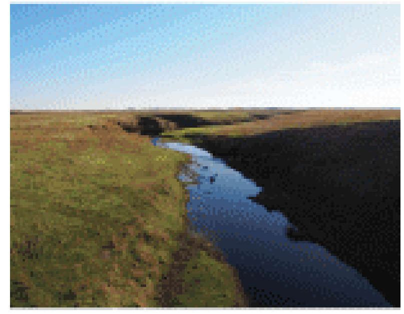
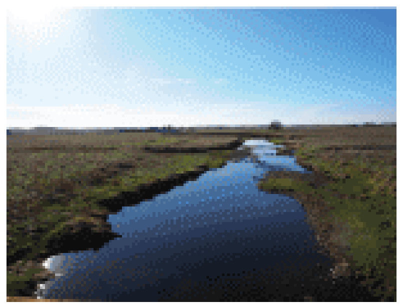


**Figure 6. Rangeland Degraded Riparian Zones**

Stanislaus-Tuolumne Rivers Watershed
January 13, 2020 & December 16, 2019



Merced River Watershed
July 14, 2021
Left: Browsed cottonwood on left, willow on right
Right: Downstream cottonwood and blue oaks

Tuolumne River Watershed
July 14, 2021
Browsed willows in foreground, blue oaks behind

## Catchment Functions Severely Degraded on Annual Rangelands

The preceding photos hopefully help visualize how surface catchment features have been lost – through shear loss of soil, as evident in Figure 5, and through loss of riparian vegetation that would support bank storage, among many other attributes, as in Figure 6. Examples like these are easy to find – just travel anywhere through the California annual rangelands.

What you can't see in those photos is the immeasurable historical loss of below-ground catchment functions, summarized in the subsequent section on the vadose zone.

## Steelhead and Salmon Habitat Restoration

Analyses of a geographic information system (GIS) database I developed around the turn of the millennium, of historical steelhead streams *and their watersheds* south of San Francisco Bay (extending to San Diego County) is what got me started on this path. So while the urgent concerns of implementing SGMA have come to the recent forefront – ***and the evidence suggests that humans as a whole will work to resolve our own water needs long before we do those of other species, even those we've depended on like salmonids*** – it is hoped that those aspects will not overshadow the crucial implications of Rainfall to Groundwater for restoration of salmonid habitats.

In fact, since potential impacts to groundwater dependent ecosystems (GDEs) must be considered in Groundwater Sustainability Plans, impacts to, or benefits for salmonid habitat are a natural component. Again, the Rainfall to Groundwater catchment restoration strategy offers an augmented influx of naturally cold groundwater supporting baseflows needed by salmonids at the cold temperatures they also need.

I was concerned with restoring baseflows that would support steelhead habitat connectivity (including thermal needs), given existing dams and diversions that impact those flows. Other concerned persons would bemoan the dams, but since they are existing "givens", why not see what may be done with the sub-watersheds/ catchments not obstructed by dams? The GIS I developed enabled me to correlate steelhead status on streams in the database with the land cover of those streams' watersheds/ catchments.

While I had observed the large extents of nonnative grasslands from ground level and from the air, it was only when I got the actual areal numbers from the database that I came to realize how truly vast the implications were for especially the Central West Ecoregion.

My doctoral dissertation abstract notes,

> Estimated additional storage possible on Salinas River subwatersheds not obstructed by dams surpasses the total storage capacity of the two largest reservoirs on that drainage. Potential detention storage in uplands of the upper Pájaro River watershed could significantly reduce downstream flooding
>
> This concept holds even greater potential for the watersheds feeding the troubled San Francisco Bay-Delta ecosystem.
>
> Jigour 2008 (2011)

It must be noted that groundwater occurs not as volume, but rather as **flow**, so the "ballpark" figures I estimated must be understood in that context. Still, especially given natural and perhaps increasing fluctuations in high/ low precipitation years, expanding detention storage on uplands works better than surface reservoirs, since there's no evaporation. Similarly to the "water banks" on alluvial aquifers – catchments can store water from wet years through the dry years.

In addition to the two greater watersheds mentioned in the abstract, I found significant potential in the greater Alameda Creek watershed and most other streams supporting steelhead in the southeastern San Francisco Bay Area. While I haven't the numerical data to arrive at any estimates for other California regions, Figure 3 in this Executive Summary, page 11, offers a visual estimate. Please also see What's in it for steelhead & salmon?

Now, as 2021 has wrought a serious drought, salmonids' thermal needs are back in the blogs and news, noted in my blog post 12. Newsom Administration – Progressive on Water Resources?, especially the management of Shasta Dam such that insufficient cold water has been allowed to meet salmon requirements. Please see blog post 11. Native Fishes Seek Cool Pools, where I envisioned a catchment restoration scenario on upper Sacramento River tributaries in Shasta County applicable to that region.

## Vadose Zone, Macropores, Soil Structure / Aggregation and Carbon

As the Figure 4 conceptual illustrations intend to convey, the catchment benefits of enhanced infiltration and percolation offered by woody and perennial plant species over nonnative annuals accrue especially from their root systems and the soil ecosystems they engender.

Recognize that these catchment functions we can influence through ecological restoration reside in the vadose zone – the unsaturated interface between surface and groundwater throughout the catchment/ watershed.

See Plants in an Ecohydrology Context and Surface-Groundwater Systems in a Holistic Water Cycle for more on the vadose zone, but remember, **this is the zone where biological/ ecological influences supersede hydrologists' models of surface and groundwater behavior.**

Macropores, the soil pore spaces large enough that the force of gravity outweighs other physical forces on the water they convey, develop from decay of former root channels. These typically occur between/among soil aggregates and their hydraulic functions are quite similar to the pore spaces within sponges. They detain infiltrated rainfall similarly to how a sponge holds water.

Soil ecosystems associated with perennial plant species also contribute to soil aggregation and macropore development in ways we are only beginning to understand.

As noted on the Rainfall to Groundwater page Carbon Farming & Watershed Restoration, with a selection of literature citations, near the end of the 20th century, USDA researchers found that fungal mycorrhizas associated with perennial plant roots produce particularly recalcitrant compounds referred to as glomalin-related soil protein, or glomalin for short. Glomalin has been found to act as a primary "glue" responsible for soil aggregation, so this is yet another important factor in macropore formation that enables the detention of percolating rainfall. Soil aggregation prolongs macropore stability.

While annual plant species may form mycorrhizas, the relationship is necessarily short-lived since the annual plants generally die at the end of each rainy season. And as the above-linked page notes, glomalin appears to be among the longer-lasting forms of soil carbon, doubtless contributing significantly to long-term carbon sequestration.

Furthermore, the ongoing natural leaf and branch fall from woody and other perennial plant species results in buildup of organic matter on the soil surface that serves as mulch, further facilitating infiltration.

When deep-rooted, especially woody, plant species are removed from a catchment area and replaced by shallow-rooted annual species, these macropores degrade over time, rendering the soils less permeable to rainfall infiltration and percolation. Loss of these functions through loss of perennial plant species becomes compounded by soil compaction arising from various human land uses, but aside from the impacts on forest soils through industrial logging operations, large-bodied grazing animals have probably caused the most widespread soil compaction impacts, especially in the context of altered vegetation.

## "Water Yield" Misconceptions

It is hoped that the foregoing brief summary of the below-ground catchment functions of woody and perennial plant species has opened the reader's mind to the significance of the subsurface environment, especially the vadose zone, to natural groundwater recharge.

Now we address what may be the most widespread misconception about plants among the water resources community – the concept of "water yield" as applied to vegetation and its removal. That term is in quotes because, while it does have a certain valld meaning in traditional hydrology in general, with respect to removing vegetative cover it is mostly a myth, but an incredibly persistent one. It is a catch phrase but moreover, a paradigm applied by folks who fail to view plants in a holistic context, considering only their water consumptive aspects, not what they offer infiltration and percolation. But then that does seem the prevailing paradigm.

The basic idea comes from knowledge that plants transpire water in order to carry out photosynthesis. As noted on Plants in an Ecohydrology Context, if they didn't do that, we wouldn't even be here. Transpiration is among the major factors supporting the world as we know it.

But those who fail to view plants holistically, have taken this little bit of plant knowledge and applied it – reductionistically – to support our seemingly self-serving economic interests, specifically logging. It's reductionist in that it fails to consider any other (holistic) benefits of plants, such as the contributions of their root systems and soil ecosystems to catchment functions.

The concept goes something like this – plants use water, so let's remove plants to get more of that water for our human needs. The history of "experiments" to test the "water yield" concept goes back more than a century now and the results of these experiments have been mostly nebulous.

When I was developing my dissertation literature review I incorrectly assumed that the concept had been sufficiently disproven through the sum total of these "experiments". But I knew the myth remained pervasive so I covered a good sampling of that scientific literature in a dissertation appendix, figuring that much would be expected of anyone addressing my topic. But since completing my dissertation, I've noticed the term still appearing not infrequently in scientific papers discussing native vegetation removal and I'd love to convince folks to at least consider a more holistic perspective on the subject.

The concept was initially applied, in the early 20th century, to forest logging operations, the facile notion being that pursuing this desired economic activity would reap corollary benefits for water resources. By mid-century the concept was being applied to rangelands, as a rationale for removal (typically by chaining) piñon and juniper stands in the southwestern U.S. to "improve" rangelands. An encapsulation of some of this history is offered on the Alternate Paradigms page, "Water Yield" vs Baseflow Augmentation.

While it's true that removal of forests is usually accompanied by initial increased yield of surface water (including flooding and increased soil erosion), time and again these "benefits" have been shown to be temporary, declining within just a few years of the "treatment". Nevertheless, these "experiments" were repeated ad nauseam throughout the 20th Century. Despite the nebulous results, it seemed little could daunt this scientific trend based on a reductionist paradigm.

While I refer to it above as mostly myth, "religion" may be the more apt term – to the extent that one forest manager titled his paper, "Water yields from forests: an agnostic view" (Ziemer 1986). Yes, this happens – **even in "Science"**.

With respect to the long-held notion of **shrub "encroachment"** onto rangelands, which began in the southwestern U.S., but has been repeatedly, erroneously applied to California's nonnative annual rangelands, it is hoped that "Woody plant encroachment paradox: rivers rebound as degraded grasslands convert to woodlands" (Wilcox and Huang 2010) may help put another spin on that notion, but chances are, you heard that here first and it is expected that the "water yield" myth, as well as that of ***native*** woody plant **"encroachment"** onto California's ***nonnative*** annual rangelands will only die a slow, lingering death.

As for "water yield", who wants more water if it all hits the floodplain at once? The vast majority of research on "water yield" focused on annual yields, not distinguishing whether additional water would be available later in the season when needed/ wanted for irrigation and/or municipal uses. **Timing is everything! Especially in California!**

This is foremost among the reasons "baseflow augmentation" is the preferred conceptual framework. Especially given California's Mediterranean-type climate regime, with rainy winters and hot dry summers, we want to **extend the flow of seasonal precipitation as far into the dry season as possible**. That means routing it to the groundwater right where it falls – **Rainfall to Groundwater**.

## Related/ Contrasting Approach – Pacific Forest Trust and AB 2480

Because my quest to bring the Rainfall to Groundwater approach to public consciousness has been a long, lonely and so far thankless toil, I was heartened to read two San Francisco Chronicle opinion pieces by Laurie Wayburn, co-founder and president of Pacific Forest

Trust: "Watershed conservation key to solving California's water problems" (Wayburn 2017) and "Invest in watershed improvements, not taller dams"(Wayburn 2018), the latter referring to the proposal to raise the height of Shasta Dam. Wayburn's opinion pieces demonstrate catchment consciousness similar to that of Rainfall to Groundwater. I was alerted to those pieces by the indispensable water news service Maven's Notebook – credit where credit is due.

Pacific Forest Trust's (2017?) report states, "In 2016, California enacted AB 2480, which defined source watersheds — the forests, meadows, and streams that supply water to its reservoirs — as an integral part of the state's water system infrastructure." I was happy to learn about that and to read the text of the bill, which, as Wayburn notes, does not define "source watersheds", but the Legislative Counsel's Digest indicates the term is defined elsewhere in existing state law.

I completely agree with equating watersheds/ catchments with the functions of engineered infrastructure. However, I find the term **"source watersheds"** – applied solely to reservoir sources of **"*water for use outside that watershed*"** (AB 2480) –unsettling. While those northern California watersheds absolutely comprise the source for the majority of the state's "consumed" surface water, it neglects the rest of the state's watersheds that serve as ***sources for local groundwater***, as well as many local reservoirs. Depending on the condition of catchment functions, these other watersheds detain (absorb and slow) winter runoff, forestalling flooding. Now that groundwater is receiving greater attention, it's time to apply this thinking to the rest of the state's catchments, recognizing that restoring natural detention functions may be much more cost-effective than engineered, mechanistic retention approaches.

Also somewhat disturbing are frequent references in that report to "water yield". But, those caveats aside, the watershed approach is appreciated.

## Surface-Groundwater Interrelationships

Among the benefits of SGMA is newfound public awareness of the interrelationships between surface and groundwater. But to date most of the new appreciation has been focused on the relationship of rivers and streams to groundwater.

If that awareness could extend to how precipitation gets into the ground initially – through the vadose, or unsaturated zone – that appreciation should extend to the Rainfall to Groundwater approach.

Surface-Groundwater Systems in a Holistic Water Cycle offers graphic images to help convey the complexity of the vadose zone, which remains mostly untouched by hydrologists. The few hydrologists who've made effective attempts to portray the vadose zone have used fractal or pre-fractal mathematics to describe the behavior of soil water under unsaturated conditions.

We shall see how Beven and Germann's (2013) approach, articulated in their "Appendix A: Preferential Flow as a Viscosity Dominated Stokes Flow and Kinematic Wave" fares (it's beyond my brain) but my guess is that flow through the vadose zone is highly site-specific, thus difficult to capture with universal equations.

Again, for a glimpse of the regional opportunities, see Figure 3, page 11, and recognize that ***sheer scale* of opportunities to restore detention functions** is part of the ***power*** of this approach.

## Water Available For Replenishment (WAFR)

DWR has shown that they are among those who fail to consider how natural recharge through the vadose zone can be enhanced. The draft and final versions of their Water Available for Replenishment (WAFR) report consider only surface water and how it may be routed to engineered recharge structures – what WAFR terms "active recharge".

A section of my 1st blog post, Water Storage & Water Available for Replenishment/Recharge: A Promising Marriage briefly encapsulates my frustration attempting to bring the Rainfall to Groundwater relationships to the attention of DWR, beginning prior to SGMA, with my (completely ignored) 2009 input to the California Water Plan then in progress and more recently with my comments on the draft WAFR in 2017. I take some small satisfaction in the fact that the WAFR report explicitly states its limitation to surface waters. (Yet, my input has been consistently ignored.)

Such limitations aside, DWR deserves major compliments on the report's distillation of an enormous amount of data and complex relationships into readily assimilable form. I especially appreciate the report's Hydrologic Region Results Summary Pages.

Each regional summary offers meaningful data compiled into readily accessible formats. From my perspective, inclusion of regional maps takes these summaries over the top since they "ground" the data to the physiographic regions. Also appreciated is the concept diagram (WAFR Figure 3 and its variations) illustrating the relationship of WAFR to daily streamflow, instream flow requirement and diversion capacity. So, again, considering the boundaries of their purview, DWR has done an excellent job of presenting the regional and conceptual data clearly. Great job on that, DWR!

But some critique is also warranted and a couple of WAFR's figures offer graphic opportunities for comment. (Note that I was unable to transfer all graphic layers of that WAFR figure into my software, so the pink color of uplands in Figure 7 differs from the original.)

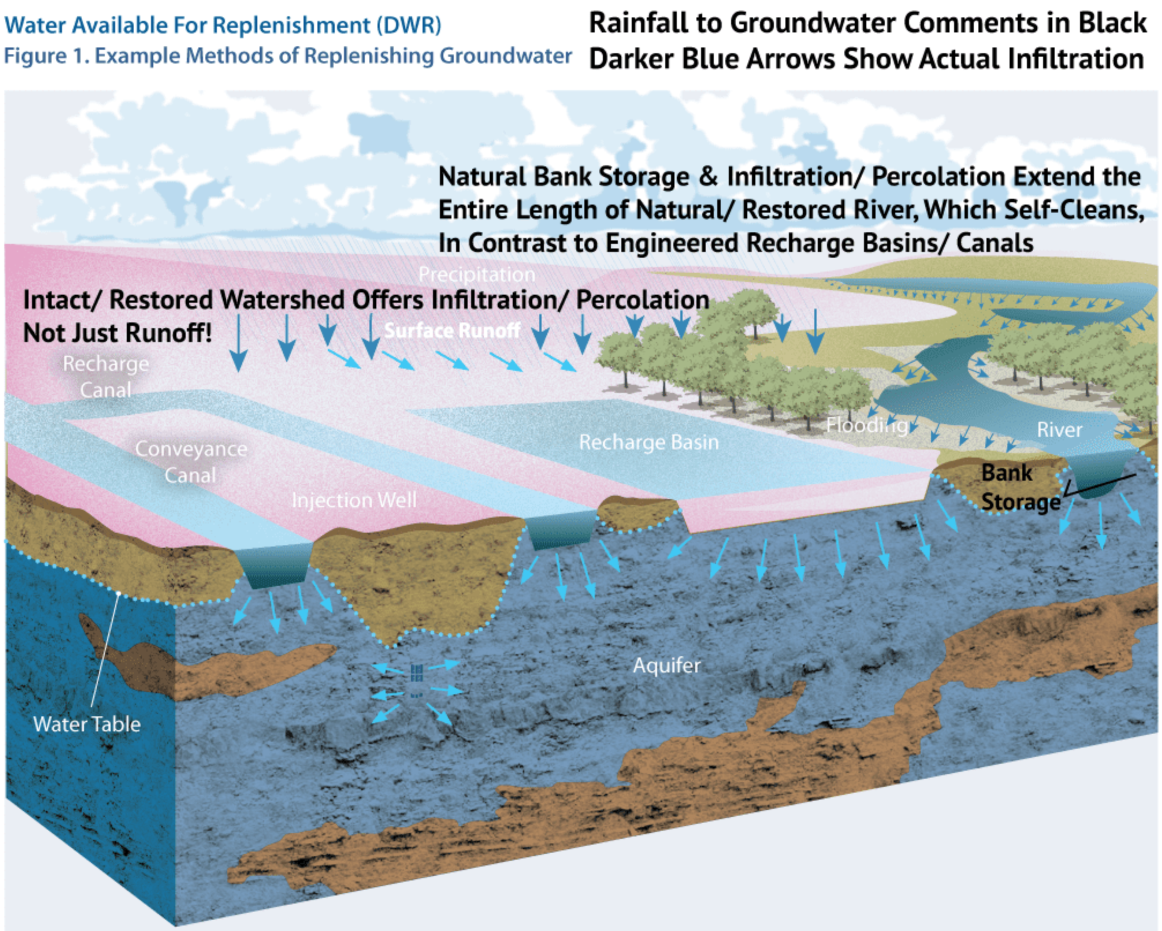



**Figure 7. WAFR Figure 1, along with Rainfall to Groundwater (R2G) comments**

The visual emphasis of WAFR Figure 1 is decidedly (deceptively) on the engineered "active recharge" structures. While infiltration from a river is shown on the right, the relatively smaller area and fewer arrows indicating infiltration/ percolation from the river visually suggest that the river offers smaller contributions.

Two problems with that: 1.) there is no indication of bank storage along the river, nor its contributions to recharge, and 2.) recharge from the river and its tributaries extends up the entire length and breadth of the catchment, so the total recharge volumes contributed by the natural river far exceed those of the relatively small, "point source" engineered recharge structures. This is an issue of scale, that is perceptually reversed in DWR's figure.

As shown in the R2G modified version, those infiltration arrows should extend along the entire length of the river. And to be fair and honest, the size of the engineered infiltration structures should be reduced relative to the size of the river.

Another major contrast between engineered and natural recharge is that fine sediments will precipitate in the engineered structures, clogging them and impeding their infiltration functions, thus requiring ongoing human maintenance and associated costs to keep the structures functional throughout their lives. Natural rivers and streams flush out those fine sediments during high flows into discrete, vegetation-colonizing zones, no human input needed.

The point is that enhancing natural recharge across functionally degraded catchments (**source**) and their river/ stream systems offers far greater spatial opportunities for recharge than does focusing recharge efforts in the basins (**sinks**). Our money would be far more wisely spent restoring the natural functions of our catchments, rivers and streams – allowing more room for floodplains and restored riparian zones that offer bank storage detention, as well as infiltration/ percolation functions, and are *largely self-maintaining*.

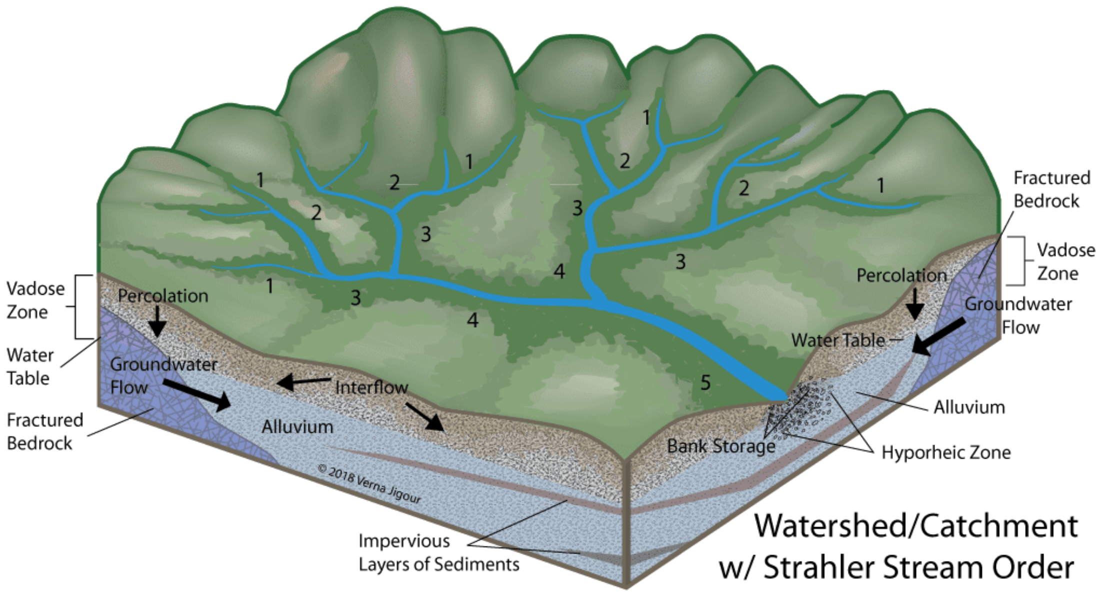
Another issue with WAFR Figure 1 is that it, like WAFR Figure 2, suggests only surface runoff from watersheds, ignoring catchment functions, which is a patently false depiction.

Yet such depictions unfortunately seem pretty standard online – again, that semantically problematic "-shed" in the word "watershed". Also there is the decided focus on river/ stream systems relative to the catchments, as discussed on the Alternate Paradigms page, Stream Networks vs Watersheds/ Catchments and encapsulated in Figure 8, next page.

Remember, precipitation DOES NOT fall solely on the surface streams (**sinks**) emphasized in Figure 6, upper. The **vast majority of precipitation falls on the far more expansive uplands** (**source**) – see the Infiltration arrows across the landscape in Figure 8, lower. And remember the historical underpinnings of groundwater hydrology, summarized in blog post #10 How Does Groundwater Get There? Some Basics.

Indoctrinated into and believing in the "power of story" to get a point across, I tried my hand at a pertinent story in blog post 8, Tale of Two Raindrops: A Pace Odyssey. It is admittedly longer than preferred but it does offer a "physiographically correct" sketch of the paths of two personified raindrops that choose different routes to the Pacific Ocean.

Figure 8. Stream Networks vs Watersheds/ Catchments, next page, lower diagram, offers a zoomed-out, geographically generalized depiction of elements along the route of raindrop Zimm's temporally extended route.



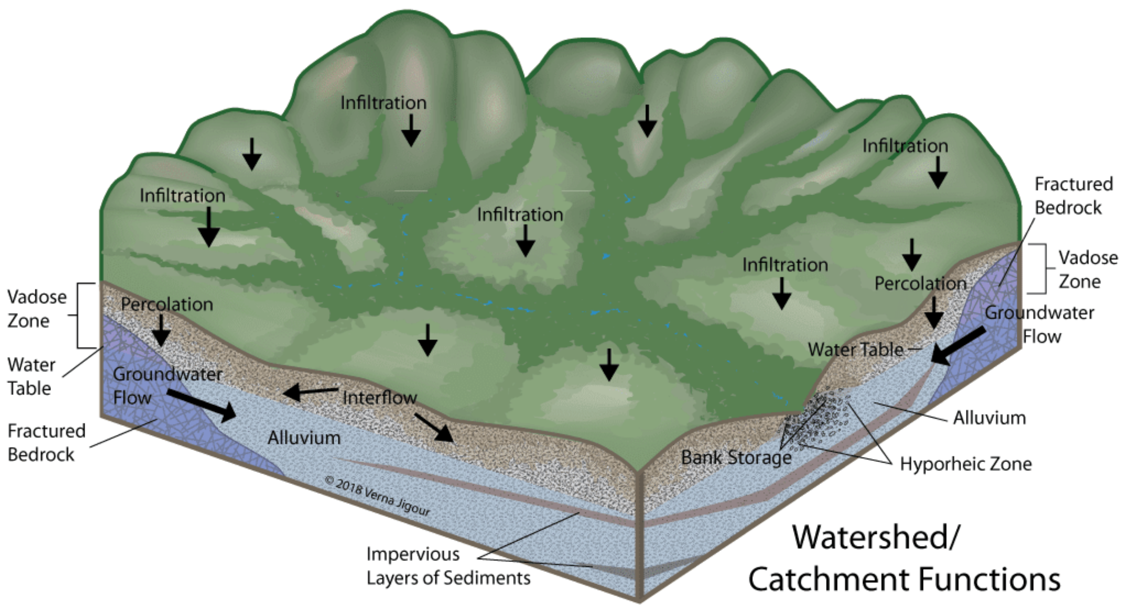




**Figure 8. Stream Networks vs Watersheds/ Catchments**

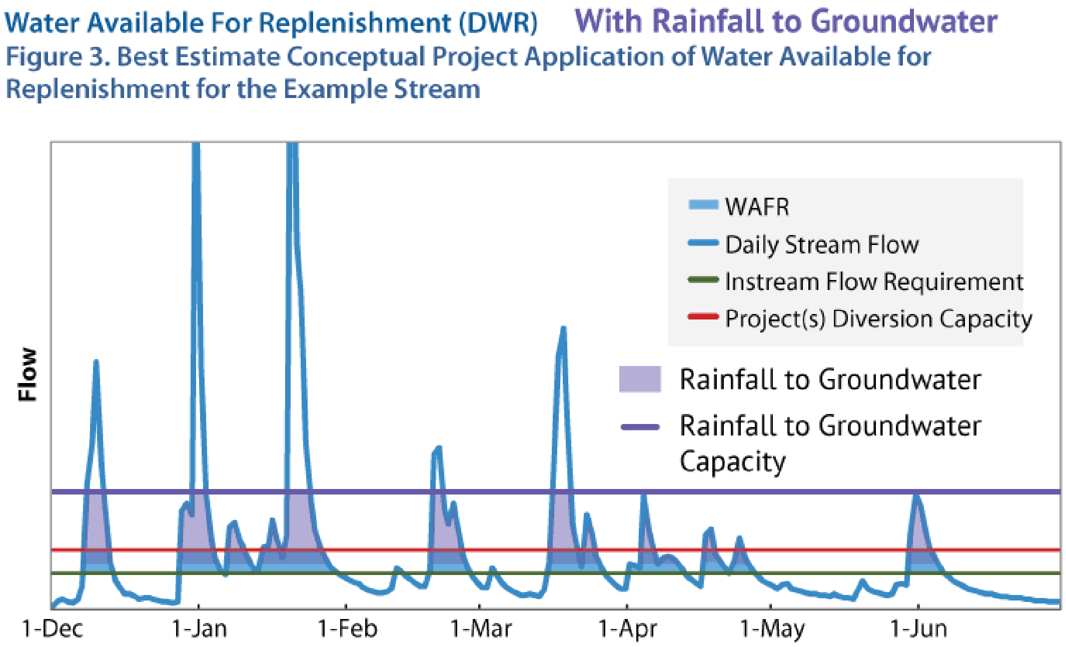



**Figure 9. WAFR Figure 3 With Rainfall to Groundwater Notes**

Figure 9, above, shows WAFR's (again) excellent Figure 3 with the addition of the Rainfall to Groundwater approach.

The reason the Rainfall to Groundwater Capacity bar is proportionately much higher than the others is another issue of scale. The spatial opportunities to restore historically degraded detention functions are vastly more expansive than are those for the engineered "Projects" and their diversion capacities. See Figure 3. Rangeland Opportunities for Rainfall to Groundwater, page 11, to visually grasp the areal extent of opportunities .

The reason the Rainfall to Groundwater volume extends below WAFR's Figure 9 red bar for "Project(s) Diversion Capacity" is that the recharge functions of at least some, if not most, of those engineered structures could be accomplished (at much lower cost) through the Rainfall to Groundwater approach.

## Water Budget – WAFR Appendix D Methods of Replenishment

While WAFR itself sticks to its surface waters focus, WAFR Appendix D Methods of Replenishment, pages 4-5, includes some language and a groundwater budget model supportive of Rainfall to Groundwater as follows,

> Replenishment can be accomplished when surface water moves through the topsoil and subsurface, or through injection of water directly into the aquifer through wells. ***Natural replenishment occurs from precipitation falling on the land surface***, from infiltration of water stored in lakes and streams, and from groundwater underflow into the basin. Natural replenishment occurs largely without intentional actions by man. (DWR 2017 WAFR Appendix D, page 4, emphases added)

However, while natural replenishment currently occurs without intentional actions by "man", humans can enhance natural replenishment, as previously noted in this Executive Summary.

Figure D-MR1. Basic Groundwater Budget, WAFR Appendix D, page 5, includes, under Inflow, "from adjacent aquifers". None of WAFR's illustrations highlight this relationship and since it seems likely to be overlooked, it must be stressed here that inflow from adjacent aquifers includes that from bedrock aquifers underlying upstream uplands and their vadose (unsaturated) zones.

For maximum understanding and effectiveness of the SGMA-required Groundwater Sustainability Plan (GSP) Water Budget, inflows from adjacent, upslope aquifers should be included in each water budget.

The Rainfall to Groundwater pages, Plants in an Ecohydrology Context and Surface-Groundwater Systems in a Holistic Water Cycle, include an illustration by USGS showing "Ground-water Inflow" from bedrock to alluvial aquifer (near page bottom on the second link) – just to assure y'all that I'm not making this up. (I did add the circle around that label for emphasis.)

But when my search for an existing diagram illustrating the whole picture of catchment functions came up nil, I decided I must develop my own, hence the diagrams comprising Figure 8. Stream Networks vs Watersheds/ Catchments., page 26.

The two versions of that diagram serve to point out that the prevailing concept of a "watershed" is that of stream networks (upper diagram). Most folks simply can't, or don't, see the watershed/ catchment (lower diagram) for the streams. It should be obvious to all that precipitation is not confined to the area right above streams. But is disturbingly common that when most folks think of watersheds they are thinking of stream networks, not catchments.

This illustrates the Figure vs Ground bias, one of seven pertinent Alternate Paradigms (including Stream Networks vs Watersheds/ Catchments) addressed on the Rainfall to Groundwater website. More than those seven are germane, but those suffice to begin.

If GSAs apply the Figure D-MR1. Basic Groundwater Budget and realize that we **can** enhance natural replenishment, they will be on their way to understanding how to apply the Rainfall to Groundwater approach.

Humans can enhance the infiltration and percolation of precipitation falling on the land surface where those functions have been degraded through historical land management. From there, that water flows through the vadose zone either 1.) to eventually emerge as surface water downstream or 2.) to enter bedrock aquifers which feed downstream alluvial aquifers.

As far as the "sustainable" aspect of SGMA goes, a recent paper, freely available online, How much water could be pumped from an aquifer and still remain sustainable? (Ponce and Da Silva 2018) suggests that "vertical recharge", such as Rainfall to Groundwater proposes, is the only truly sustainable approach.

## Biospheric Feedbacks with Local and Regional Climate

Restoration of native woody/ perennial vegetation types to existing nonnative annual grasslands has the potential to increase precipitation in those regions. This relationship may be verified by considering how earth surface energy and moisture budgets at local and regional scales portray their associated climates.

Higher albedo a.k.a. light reflectance, easily seen in Figure 3 . Rangeland Opportunities for Rainfall to Groundwater, page 11, is among the budgeted factors, along with turbulent sensible and latent heat fluxes. Changes in those earth surface factors affect climate changes at local scales.

My introduction to this topic appeared as, "Influence of landscape structure on local and regional climate" (Pielke and Avissar 1990) in the journal *Landscape Ecology*, and is freely available online. The same graphics and an extensive updated literature review are accompanied by text aimed at a somewhat broader audience in the second edition of

*Human Impacts on Weather and Climate* (Cotton and Pielke Sr. 2007). The material is also covered in *Reviews of Geophysics* (Pielke 2001) as well, also freely available online.

Simply put, restoration of darker canopied, "greener" i.e., moisture- detaining native vegetation can potentially bring increased precipitation to lands with historically degraded catchment functions. Lowering catchment albedo can make it more attractive to discerning raindrops like Zimm, of Tale of Two Raindrops.

California is especially primed for such a positive effect of land cover restoration due to its proximity to the Pacific coast, source of all our precipitation.

"Mesoscale" climate modeling advises us of the opportunities. Only strategic monitoring of restored catchments and their hydroclimatology will establish the hard data.

## Benefits vs Costs – Ecohydrological Economics

Among the clear benefits of the Rainfall to Groundwater approach is that it is wholly ecologically sound. Implementation of this approach means restoration of native vegetation and habitat types over vast areas – along with enhanced natural recharge and detention storage.

See Ecohydrological Economics for links to nine pertinent pages. Rainfall to Groundwater proposes that water users incentivize ranchers and other landowners to restore and manage their lands for their ecohydrological services. See What's in this for water users?

While baseflows needed by steelhead were the initial concern, reflected in, What's in it for steelhead & salmon?, it was long clear to me that this ecohydrological approach would also benefit vernal pool species like California tiger salamander, as noted on the page, What does Rainfall to Groundwater offer for vernal pools?

The proposal to replace the existing nonnative annual grasslands ranchers have grown used to might seem a threat to the existence of ranchers, but the pages, What's in it for ranchers?, Criollo Cattle? and Livestock Appellations for California? suggest ways that ranchers and other rangeland managers might thrive under Rainfall to Groundwater scenarios that emphasize the diversity of unique qualities inherent to each California catchment – terroir. Conservation easements supported by water users seem a likely path.

And then there are the direct benefits for GSAs. WAFR shows that for some regions there is precious little surface water available for replenishment. So no matter which of the report's "active recharge" methods may be selected there is only so much that may be achieved that way and that course requires various permits and expensive environmental documentation.

In contrast, as noted on the page, Who owns the rainfall? A legal frontier?, at least at present there are no legal limitations to the amount of rainfall that may be infiltrated. So basically, GSAs can restore infiltration and detention functions across the entire extent of ecohydrologically degraded lands that exist in their respective watersheds/ catchments. And the opportunities are vast.

Geographically linking overdrafted groundwater basins with the catchments feeding them offers the soundest approach to visualizing opportunities to enhance natural recharge. Speculative enhanced recharge can be linked to future groundwater withdrawals – with strategic monitoring keyed to disburse augmented groundwater as monitoring benchmarks are met.

Permitting for watershed/ catchment restoration with native vegetation types – uplands, along with expanded riparian zones and floodplains – will be far simpler and far less costly, compared with proposed engineered recharge structures. Restored catchments will become increasingly self-sustaining, while their detention storage capacity increases over time. What's not to love about that?

Even providing incentives to rangeland owners and managers for voluntary restoration and long-term management – payment for ecohydrological services – should prove less costly and far more effective than high maintenance engineered surface water conveyance, in the near-term and long into the future.

## Forthcoming Books

While timing and other issues remain uncertain, I have two books in progress, *Rainfall to Groundwater: History of the Science* and *Rainfall to Groundwater: California and Beyond*.

## Envisioned Group Learning Strategy

Because Rainfall to Groundwater represents "frontier science" albeit in a "Back to the Future" sort of way, implementation will necessarily present novel challenges. For that reason and because I know that many folks who need this information may prefer an alternative to books, I have envisioned a series of online group video / interactive courses, outlined in the Learn, Apply overview. TBD

## Abbreviations Used in This Report

DWR California Department of Water Resources

GIS Geographic Information System

GDEs Groundwater Dependent Ecosystems

GSAs California's Groundwater Sustainability Agencies

GSP Groundwater Sustainability Plan

SGMA California's Sustainable Groundwater Management Act

WAFR DWR's Water Available For Replenishment report

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