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Sustainable Yield in Groundwater Management: Bridging Science and Mainstream Vernacular

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Sustainable Yield in Theory and Practice: Bridging Scientific and Mainstream Vernacular

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Abstract

Groundwater is a vital resource in California, and the concept of "sustainable yield" is an attempt to determine a metric that can ensure the long-term resilience of groundwater systems. However, its meaning is ambiguous and quantification is challenging. To provide insight into developing a working definition that encompasses the inherent uncertainty and complexity of the term, this paper examines how sustainable yield in groundwater is interpreted by (1) scientists, (2) the courts in groundwater adjudications, (3) state agencies, and (4) local water practitioners. Through qualitative interviews, this paper identifies problems that local water agencies in the state encounter in engaging with sustainable yield as they incorporate the term in groundwater management practices. The authors recommend that any definitions make explicit the human dimensions of, and assumptions embedded in, the use of these terms in groundwater management practices, and they point to the value of participation in this process.

Introduction

Groundwater is a critical and endangered resource in many parts of the world (Wada et al. 2010). Over the last several decades, the concept of "sustainable yield" emerged as a way to incorporate both scientific and societal issues in determining appropriate withdrawals to minimize declining levels and ensure the long-term resilience of groundwater systems (Sophocleous 1997; Sophocleous 2000; Alley and Leake 2004; Maimone 2004; Kalf and Woolley 2005; Gleeson et al. 2012). However, the term is ambiguous and may be interpreted to support different socioeconomic and political interests. To address the challenge of developing a working definition that can encompass the inherent uncertainty and complexity of the term and that bridges scientific and mainstream vernacular, this paper examines how sustainable yield in groundwater is conceptualized, defined and implemented by (1) scientists, (2) the courts in groundwater adjudications, (3) state agencies, and (4) local water practitioners.

We particularly focus on water agencies in California, where despite groundwater supplying about 30 to 40% of the state's overall dedicated water supplies, many aquifers are in overdraft with declining levels (LAO 2010; California Water Plan Update 2013, Groundwater Enhancements and Recommendations). Interviews with agency staff illuminate the problems they encounter in engaging with "sustainability" and "sustainable yield" in practice, and the specific concerns they seek to address through the use of these terms. To acknowledge the human-influenced aspects of groundwater management we propose that any definition make explicit the assumptions embedded in the use of these terms in groundwater management practices, and we support the call by other scientists for transparency and participation in this process (Gleeson et al. 2012).

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Origins of "Sustainability" in Natural Resource Management

The concept of "sustained yield" originated within the field of forestry in 18th and 19th century Europe

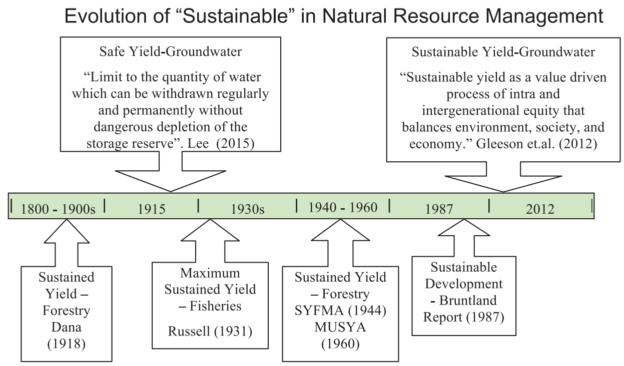

Figure 1. Evolution of sustainable in natural resource management.

where it defined setting timber harvest equal to timber growth (Figure 1) (Behan 1997). In the late 1920s, sustained yield was redefined from sustaining timber yields to sustaining forest industries (Clary 1986). The subsequent 1944 Sustained Yield Forest Management Act (SYFMA) (58 Stat. 132) and the later 1960 Multiple-Use, Sustained-Yield Act (74 Stat. 215) (MUSYA) were both passed to "promote the stability of forest industries . . . through continuous supplies of timber," and focused primarily on resource productivity and market conditions (Robbins 1989). In the fisheries industry, the concept of sustainable yield was utilized in the United States in the early 1930s as a way to predict the consequences of harvesting activities on fish populations. "Maximum sustainable yield" (MSY) in this context quantified the largest catch that could be taken from a species' stock over an indefinite period without causing depletion of the resource (Russell 1931; Barber 1988). In both fisheries and forestry there were debates, which continue today, over criteria and measurement indicators.

In groundwater management, the concept of "safe yield" was introduced in the early 1900s. Scientists focused on aquifers as physical systems and utilized hydrological and groundwater flow principles to determine withdrawals (Alley and Leake 2004; Kalf and Woolley 2005; Gleeson et al. 2012), emphasizing the dynamic response of the aquifer to pumping as a key factor in determining the safe yield of a groundwater basin (Bredehoeft 1997; Zhou 2009). But even early definitions acknowledged the ambiguous economic and social dimensions of "safe yield" (See Meinzer 1923), and by the 1950s the USGS proposed to discontinue use of the term (Thomas 1955).

In lieu of "safe yield," hydrogeologists proposed the term "sustainable yield" to reflect the relationship between socio-political factors and groundwater withdrawal (Alley and Leake 2004; Kalf and Woolley 2005). The shift toward the utilization of "sustainable yield" in groundwater management reflected the emergence of the discourse of sustainability as a dominant paradigm for addressing environmental management practices. The Brundtland Report (1987) played a significant role in this process, and defined sustainable as " . . . development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). But the Brundtland definition of sustainability also encountered criticism owing to conceptual and philosophical ambiguities (Loucks 2000). As MacCleery (2001), forest expert with the USFS, claimed " . . . one must ask: sustainability, for whom and for what?" Any form of development alters the natural environment in some way. Determining sustainable yield for groundwater management will thus always express a subjective perspective that implies what effects of withdrawal are acceptable. Despite this ambiguity, the terms "safe yield" and "sustainable yield" continue to be referenced in groundwater management.

Sustainable Yield Terminology by Hydrogeologists

Hydrogeologists emphasize the contribution of aquifer dynamics and groundwater flow principles to the concept of safe or sustainable yield (Bredehoeft 1997; Kalf and Woolley 2005), and the majority of hydrologeologic studies primarily focus on the use of a mass balance equation to quantify appropriate groundwater withdrawals. Newer considerations embodied in the concept of sustainable yield include temporal patterns of withdrawal and economic, legal, and water quality issues. For example, Alley et al. (1999) defined groundwater sustainability as development and use in a manner that can maintain an aquifer for an infinite time without causing unacceptable environmental, economic, or social consequences. In 2004, the Australian National Groundwater Committee (NGC) defined sustainable groundwater yield as "the groundwater extraction regime, measured over a specified planning time frame, that allows acceptable levels of stress and protects dependent economic, social, and environmental values" (NGC 2004). While these definitions acknowledge that any human-induced groundwater regime will have certain consequences, it leaves variables such as "specified time frame" and "acceptable stress" open to interpretation.

Although water management agencies have attempted to assess and operationalize the term "sustainable," defining and quantifying sustainable yield is complicated and difficult. Many basins are in states of deprivation that are not currently "sustainable" in the first place. In addition, some basins that are at dynamic equilibrium over the long term (decades or centuries) may not operate at equilibrium for shorter time periods. Other basins may appear to be at equilibrium at present, but will not remain in equilibrium over longer time periods because of large-scale hydrologic changes. In all basins, calculating inflows and outflows is complex, imprecise, and can require expensive field monitoring and/or modeling studies. And as noted, sustainability discourse is often fuzzy with respect to delineating relevant time frames and user prioritizations.

To incorporate some of these concerns, hydrogeologists Kalf and Woolley (2005) propose a number of amendments, including: making sure that the definition of sustainable yield applies to the basin aquifer system and not to the performance of production facilities; not applying assumptions of outflow and inflow to all sites; acknowledging that changes in water quality and ecological constraints will affect the rate of abstraction; indicating situations where groundwater cannot ever be developed sustainably; and ascertaining sustainable yield within a hydrogeologic basin, rather than a municipal boundary. Maimone (2004) proposes another modification to the concept of sustainable yield, emphasizing an adaptive management approach that not only utilizes a water budget that includes surface and groundwater, but also incorporates an understanding of the hydrogeophysical characteristics of the basin, technological developments, and stakeholder needs.

Gleeson et al. (2012) proposed that groundwater sustainability is not an objective goal, but is "a value-driven process of intra- and intergenerational equity that balances the environment, society and economy." Because sustainability is not value-neutral, they recommend groundwater management practices that set explicit long-term (defined as 50 to 100 years) sustainability goals, and then use backcasting strategies to meet these goals through management that is integrated, inclusive, and local. They also emphasize an adaptive management approach.

Our paper extends these discussions to focus on how water institutions and practitioners conceive of and represent sustainable yield in groundwater management goals. We are particularly interested in how abstract definitions of sustainable yield are concomitant with actual on the ground use of these terms. As noted, our study focuses on California, where an average of 18,502,227,829 cubic meters (15 million acre-feet) of groundwater is used each year (California Department of Water Resources 2003). Many aquifers in the state have declining levels of groundwater with associated impacts (see Figure 2), generating significant interest by water agencies to reduce overdraft and establish what they understand to be sustainable yield.

The Courts

In some California groundwater basins with declining groundwater levels, disputes over extraction are brought to the courts. While the term "sustainable yield" is invariably implied in court decisions, most groundwater adjudications apply the term "safe yield" in determining water rights. A court-appointed Watermaster facilitates quantifying the "safe yield" of the basin, utilizing studies of basin hydrology and past groundwater production, and early court proceedings established rigid pumping rules to maintain this court mandated and Watermaster monitored "safe yield" (e.g., in the Raymond and West Coast Basins 1944 to 1970s).

California legal proceedings also operationalized the terms "natural safe yield," and "operating safe yield." In the San Gabriel and Chino Basins, the former was defined as "the quantity of natural water supply which can be extracted annually from the Basin under conditions of the long-term average annual supply," and the latter as the quantity of water that the Watermaster determines may be pumped from the Basin in a particular fiscal year (Main San Gabriel Water Master 2013, Main San Gabriel Basin Glossary).

In the most recent 2004 Seaside Basin court adjudication, the objective was "to ultimately reduce the drawdown of the aquifer to the level of the 'natural safe yield,'" defined as "the quantity of groundwater existing in the Seaside Basin that occurs solely as a result of natural replenishment." "Operating safe yield" was defined as "the maximum amount of [g]roundwater resulting from natural replenishment that this Decision, based upon historical usage, allows to be produced from each subarea for a finite period of years" without material injury to the Seaside Basin, the subareas, or a producer (California American Water v. City of Seaside, et al. 2006). In operationalizing the term "safe yield," the Seaside Basin adjudication moved the definition closer to the concept of sustainable yield by acknowledging hydrologic and social issues, including that safe yield is not a "static" amount, and needs periodic re-evaluation. Yet there continues to be a lack of technical agreement on basin yield in many of California's basin adjudications (Bachman 2010).

California Department of Water Resources (DWR)

The State of California does not have a permit system for groundwater production. However, California's Department of Water Resources (DWR) is concerned with overall water planning and provides sustainability principles for water resources management, describing a renewable natural resource as sustainable only "if the rate of use does not exceed the rate of natural renewal." In this context, DWR defines "safe yield" as "the maximum quantity of water that can be continuously withdrawn from a groundwater basin without adverse effect." The agency defines overdrafted basins as those where the amount of water extracted exceeds the amount recharging the basin (DWR 2013b, Groundwater Terms) resulting in groundwater levels that decline over a period of years and never fully recover, even in wet years. Overdraft can result in significant adverse social, environmental, and economic impacts including increased extraction costs, land subsidence, saltwater intrusion, water quality degradation, and permanent loss of aquifer storage (DWR 2003, Bulletin 118 Update Report). Additionally, DWR encourages agencies developing new water sources to consider the needs of people and ecosystems up-stream and down-stream and throughout the hydrologic cycle (Shilling et al. 2012).

DWR also provides general principles for sustainability planning, describing a sustainable system as one that meets today's needs without compromising the ability

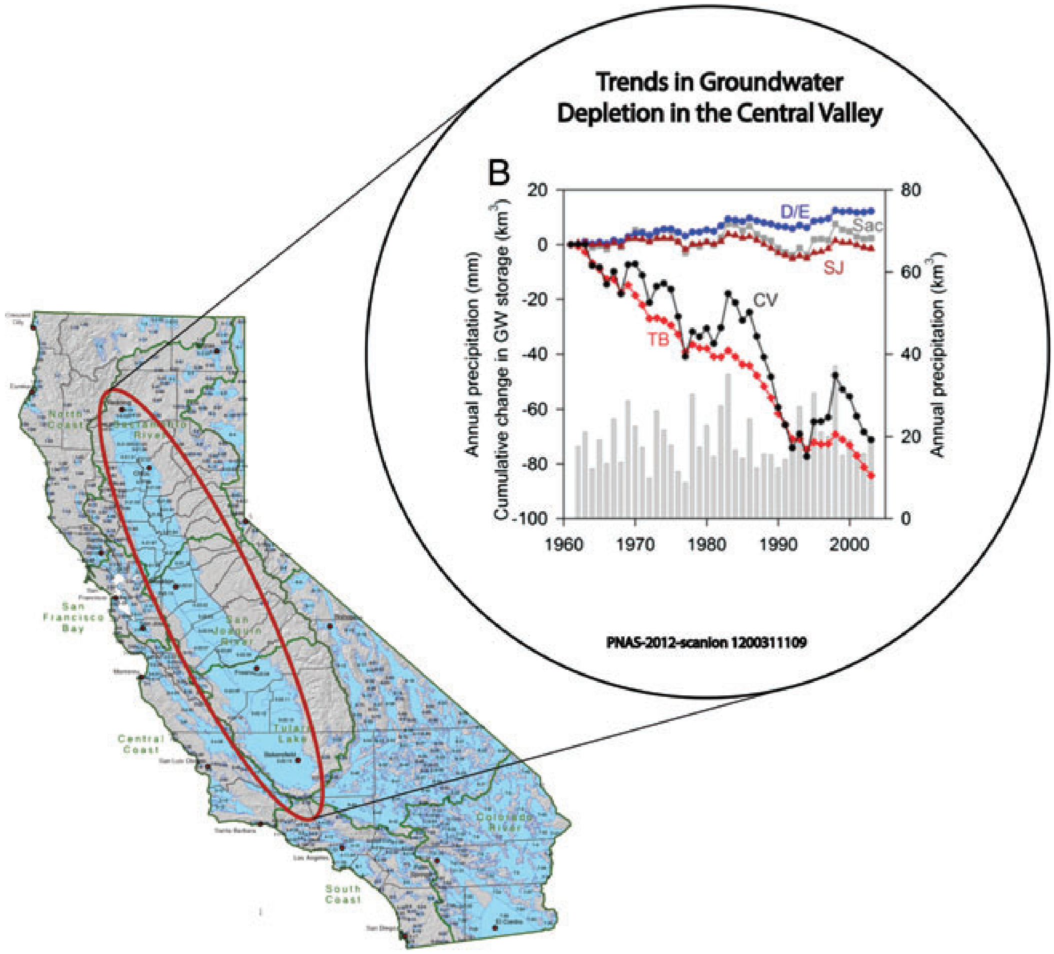

Figure 2. Declining groundwater levels in California's Central Valley.

of future generations to meet their own needs. Nevertheless, agency documents acknowledge that "sustainable use of resources" may have different meanings depending on the perspective of the user. The DWR Water Plan Update includes a Water Sustainability Indicators Framework to inform the public about water system conditions and relationships to ecosystems, social systems, and economic systems. It incorporates five detailed domains: water supply reliability, water quality, ecosystem health, adaptive and sustainable management, and social benefits and equity (DWR 2013a, Water Plan Update 2013).

Local Water Agencies

Approach

Without a state permit system, local water agencies are the primary institutions governing groundwater management in California. To this end our paper focuses on these local institutions, using interviews to provide greater insight into the actual application of sustainable yield terminology on the ground. We selected 12 water agencies that rely either entirely, or in large measure, on groundwater for agriculture or municipal uses and that represent a range of geographic demographic and management characteristics. These agencies are all experiencing some decline in groundwater levels, and they share several variables of concern: seawater intrusion, subsidence, and pollution. Along with these characteristics, agencies we interviewed represent a range of attributes, including geographic location, size of the basin, and urban/rural usages. We include both adjudicated and non-adjudicated basins. Our goal is to represent prototypes of the diverse agencies that manage groundwater in the state.

Of the 15 interviewees, 4 were agency hydrogeologists, 1 was a district engineer, and 10 were agency managers. Several of the managers interviewed had backgrounds in hydrology and engineering as well as public policy. Of the agencies interviewed, 10 had recently or were in the process of moving away from using the term "sustainable yield" in their groundwater management policies. A review of these agencies' published groundwater management plans corroborated this recent shift in vernacular. While agency personnel expressed distaste for the term "sustainable yield," their public documents, many published within the last 5 years, relied heavily on the concept and term. For example, one agency's 2011 Progress Plan from their Groundwater Management Program states that their main objective is "to improve groundwater sustainability." A recent interview with this agency's policy manager revealed that in the previous week the board had decided to terminate using the term "sustainability" in their outreach materials.

Definitions of Sustainable Yield

When asked to define what they understand to be "sustainable yield," agency managers and hydrogeologists echoed the definitions provided in their public documents. These included:

> "what is being pumped out of the ground that can be sustained overthe long term, without causing negative impacts to the aquifer,"
> "a rate of withdrawal that has no negative impact on the groundwater basin,"
> "the long-term amount of groundwater, which can be extracted from theaquifer system without causing an adverse impact on the quantity and/or quality of the groundwater basin."

Three agency managers mentioned that they witnessed the concept of safe yield being replaced by that of sustainable yield. One expressed confusion with the rapid turnaround of term usage; "I don't know what they [those who are dissatisfied with "sustainable yield"] are saying . . . what's happened in my career is that safe yield has turned into sustainable yield." Agency managers and hydrogeologists also articulated significant concerns with both safe yield and sustainable yield terminology. One manager called the term sustainable yield, inherited from his predecessor, "the bane of my existence"; another described it as "contentious and constantly debated."

Shortcomings of "Sustainable Yield"

When asked to describe the shortcomings of "sustainable yield" as a means for managing groundwater, interviewees provided a variety of reasons including: the ambiguity of the term sustainable and its normative aspect, the timeframe being considered, the role of infrastructure, the use of a single metric to express a dynamic system, confusion over whose needs are being considered, and the omission of climate change impacts and catastrophic events. Their comments are illustrated below.

Ambiguity

With respect to the practical use of the term, one manager indicated "there's so much confusion with the term." Another reported that over the past few years his agency tried "to avoid the term at all costs, in part because the definition of what they mean hydrologically leaves a lot of subjectivity . . . depending on which people you have in the room, their opinions can be very different." He described the term as "opening Pandora's box" in that it allows for a wide variety of interpretations with respect to its main goals and significance.

Greenwashing

One problem with the word "sustainable" is that it carries a normative positive valence that can affect how sustainable yield is conceptualized. For example, six agency managers and one hydrogeologist noted that "sustainable" implies that if a basin maintains its current groundwater levels this is a "good" thing. For basins experiencing issues such as saltwater intrusion, sustaining current pumping levels would fail to remedy the situation but would instead exacerbate the problem. As one manager remarked, "It's not okay to keep a basin at a degraded level."

Relative Timeframe

The timeframe inferred by sustainable yield was another issue for watershed managers and engineers. Several managers said that sustainable yield had to be sustained "permanently," while others looked at it as "a 30 to 50 year horizon." One hydrogeologist described a proposed extraction project that was found to impact a nearby spring, but not for 300 years. He noted that this is a sustainable yield question, because "the argument is that you've exceeded the sustainable yield if you have an effect you don't want to see hundreds of years in the future . . . [Going by that definition] might prevent us from doing anything with groundwater, and that might not be a good thing." Another manager said that the term could apply to any time frame; "when I use the term I think it will harm the aquifer in two years, five years, or one thousand years." How this translates into policy is a question that almost all the interviewees raised as an important concern.

Simplification

Agency spokespeople expressed concern that the term "sustainable yield" implies that a single number can be generated as a pumping goal that will meet the criteria of maintaining a sustainable groundwater supply. This over-simplifies the complex and dynamic hydrology of a basin, whose water supply varies over the course of seasons, years, and generations. One hydrogeologist spoke to this, "People get burned using [one number]. People get the wrong idea about what that number is and think they can extract that same amount of water every year." Another agency manager expressed a similar concern with associating a static number with sustainable yield: "It's hard to quantify, and there's a good chance those numbers will change."

Rather than stick with a quantified and constant sustainable yield, one manager suggested an alternative would be "a dynamic model that reflects changes in recharge, streamflow, pumping, water levels" so that "you can go forward and have various strategies for every year." This may be more difficult in an adjudicated basin, where water agencies have to work with a court decision that has come up with one number as the sustainable yield for the basin. The manager for one non-adjudicated basin elaborated on this, "In an adjudicated basin safe and sustainable yield are important terms because in a court they're not allowed to pump over that number . . . we don't want to be tied to certain numbers. At times we'll pump more or less of safe yield. That's why you don't see any of those words in our documents . . . we shy away from those terms to avoid getting them fixed."

Infrastructure

Another prevalent critique of the "sustainable yield" terminology in groundwater management was that the concept relies on a system's infrastructure, but that its common usage often obscures or renders invisible this reliance. One interviewee, an agency manager, noted, "To us, safe and sustainable is entirely contingent on facilities. So we avoid the use of those terms because what they say today is not what they mean tomorrow." Many of the agencies we interviewed expressed concern with saltwater intrusion, and their sustainable yield numbers were primarily motivated by a desire to avoid this problem. But, as one agency hydrogeologist pointed out, if you have one well for an entire distribution system that is located on the coast, the sustainable yield would be much lower to prevent salt water intrusion than a system that had multiple wells farther from the coast. Sustainable yield thus relies on anthropogenic modifications including infrastructure.

Ecological Concerns

As noted above, an additional area of debate revolves around whose needs are being met when it comes to sustainable resource management. This issue was illuminated by what appeared to be a striking omission of the nonhuman from conversations with water agency managers and hydrogeologists. When asked to discuss the concept of sustainable yield, not one interviewee spoke directly to the long-term resilience or compromise of indigenous plant or animal species (though later several suggested that ecological considerations had been implicit in their definitions and in their sustainable development plans). Instead, when asked to comment directly on how the utilization of "sustainable yield" helps or hinders ecological issues, seven interviewees acknowledged that attempting to quantify a pumping goal that will satisfy human needs while ensuring a reliable groundwater supply was tricky enough without factoring aquatic and riparian species into the equation. Because of this complexity, ecological concerns, though mentioned, are often left aside in developing sustainable groundwater yields. One hydrogeologist admitted that "[sustainable yield] gets fuzzy when you start looking at ecological impacts" and another described biological conditions as those "we don't measure." A third noted, "There's just too many complications with biological systems. How we measure sustainable yield is very physical water oriented."

Extreme Events

Another area of omission in the interviews pertained to the ability of sustainable yield to cope with severe or catastrophic events (Figure 3). While periodic droughts are projected to become more frequent and severe with climate change, resulting in reduced water availability and water shortages, agency personal never commented on how concepts of sustainable yield could or should account for climatic variation or extreme drought events. When asked if the agencies included the possible implications of climate change in their usage of the term "sustainable yield," only one respondent claimed that this was the case in his agency. Others admitted that while climate change is certainly an important issue, the complexity and uncertainty around the possible hydrological impacts of climate change were too difficult to incorporate into an already ambiguous term.

Alternatives to Sustainable Yield

In lieu of sustainable yield, several agencies had transitioned to relying on alternative terms that they hoped would avoid some of the semantic problems referred to above. One was overdraft, a term common in the hydrologic literature that refers to an undesirable condition caused by over-pumping that results in declining water levels over the long term. Although one manager described overdraft as the "undesirable results" that occur from withdrawing more than the sustainable yield, several managers said that the term overdraft was more "objective." As one manager claimed, if you define overdraft as "when outflows exceed inflows . . . .. it's easy to see whether you're in overdraft . . . Everyone can argue about what's sustainable and what's not, but no one can argue about inflows versus outflows, because it's a calculation." That said, overdraft defined in this way means that adverse effects may occur before pumping reaches the level at which you can see or measure those effects. Another agency that recently abandoned the term "sustainable yield" replaced it with "yield after recovery." This agency was concerned that the term "sustainable yield" implied that sustaining current water levels would be a good thing. In their case, to avoid saltwater intrusion they need to increase their baseline water levels; keeping them "sustainable" would not be a desirable situation.

Overall, the principal reason for transitioning from using the term "sustainable yield" was attributed to public relations. While agency managers and hydrogeologists claimed that within their agencies there was general consensus around what "sustainable yield" meant, they worried that its subjective nature and implied normative values confused the public and might lead to future conflicts or debates (Table 1). The terms "overdraft" and "yield after recovery" both direct attention to reasons for *not* pumping rather than calling attention to a simplistic quantification of what is safe, the former of which may be easier for a public not well-versed in hydrology to understand. This finding leads us to make an additional observation, which is that despite the consensus of relevant scholarship demonstrating the importance of inclusive and participatory planning processes for "sustainable" groundwater management (Gleeson et al. 2012), the interviewees did not describe "sustainable yield" or optimal groundwater management practices as requiring collaborative participation. Rather than incorporate public constituents into the development of groundwater management plans, they worried that the "public" would misunderstand hydrological concepts and terminology, and thus highlighted a model of policy as science-based and politically neutral (Jasanoff 2005). The above discussion is summarized in Table 2.

Figure 3. Interview sites.

Table 1
Agencies Interviewed

Location	North Coast	North Inland	Central Coast	Central Valley	SE Inland	South Inland	South Coast
Agenices Interviewed[1]	1	2	5	1	1	1	1
Adjudicated	No	No	No-4, Yes-1	No	No	Yes	No
Agency size	Large	Medium	Large-3 Medium-2	Medium	Small	Medium	Large
Primary water uses	Mixed	Urban-1 Rural-2	Urban-2 Agriculture-1 Mixed-2	Agriculture	Rural	Urban	Urban Agriculture

Note that several agencies included more than one interviewed individual, so total number of interviewees equaled 15.

Discussion

Our paper provides new insights into how definitions of safe and sustainable yield are implemented and practiced. While it is clear that "sustainability" discourse leaves room for interpretation and its ambiguity may be an obstacle for achieving and implementing specific management goals, there are lessons to be learned beyond simply acknowledging that "sustainability is subjective."

For one, effective groundwater management needs to be dynamic, flexible, and case specific to accommodate variations in timing and location. Interviewees emphasized again and again that one of the principal shortcomings of the "sustainable yield" terminology is the tendency to use it to apply a fixed or static number to an inherently dynamic system.

In addition, the more comprehensive the application of "sustainable yield" as a concept, the more difficult it becomes to quantify, model, or strategically apply it to a basin's water management plan. For example, if an agency decides that "sustainable yield" should operate within a 1000 year timeframe, or that "sustainable yield" indicates that management must account for the long-term resilience of all known endemic aquatic species, it becomes increasingly difficult to create a useful model

Table 2
Sustainable Yield—Definitions and Issues

Interviewees	Safe Yield	Sustainable Yield (SY)	Position on SY	Overdraft
Academic Hydrogeologists	"Limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve" (Lee 1915)	"Development and use in a manner that can maintain an aquifer for an infinite time without causing unacceptable environmental, economic, or social consequences" (Alley et al. 1999)	Challenge "to translate complex, and sometimes vague, socioeconomic and political questions into technical questions that can be quantified systematically" (Alley and Leake 2004)	Where "amount of water withdrawn by pumping exceeds the amount of water that recharges the basin over a period of time" (DWR 1980)
Water Agency Representatives (includes agency hydrogeologists and managers)	"Amount of water withdrawn annually without an undesirable result" "There's nothing really safe" "the amount of pumping you can do without overdraft" "Use safe yield and sustainable yield interchangeably. Most people don't"	".. what is being pumped out of the ground that can be sustained long term, without causing negative impacts to the aquifer" ".. a number you can count on every year [but some problems with that]" "Not wanting an undesirable condition" "A rate of withdrawal that has no negative impact on the groundwater basin" "a notion that you can continue forever – the basin stays in its condition with water levels not changing and storage not changing" "point of equilibrium that agencies were all comfortable with"	Dislike both terms Not used as a key term because of ambiguity and change Avoid use of term – "bane of existence" Replaced with "accumulated overdraft" "A lot of people like sustainable yield because it's a number – the problem is it's just not a very good number to manage to" "The concept of sustainable yield simplifies groundwater too much" "Groundwater management is dynamic year to year and sustainable yield is a fixed number"	"Amount of dewatered storage" "when outflows exceed inflows" "..typically used as a lay term, meaning we've got declining groundwater levels, diminishing groundwater and storage" "Any amount over sustainable yield is overdraft"

to account for these contingencies. As one agency representative reported, going those final steps can have the effect of paralyzing any kind of proactive management practices. Instead, this hydrogeologist suggested that "the only solution is to try things, see if there's an impact, and then don't do it again if it's harmful."

Alternatively, a more restricted definition of "sustainable yield" can lead to problems. Perhaps the most obvious concern is the exclusion of certain future and ecological needs from water management practices, and the obfuscation of the decision-making practices that prioritize these needs. In addition, while the term implies a specific metric, empirical modeling is inherently imprecise. One hydrogeologist spoke to the financial disincentives to developing complex models. "For a lot of money," he said, "I'll tell you [that] you have a little water. For a little money I'll tell you [that] you have a lot of water. We always count a big number to begin with. It's always the wrong number. And then we have to back off from this and tell them [water agencies] they have less."

Conclusion

This paper analyzes the discourse of sustainable yield that California water agencies use with respect to groundwater management. We noted terminology and implementation limitations as described in state, scientific, and legal literature and as articulated by local agency representatives in California. While the paper focuses on the subjective nature of "sustainable yield" terminology, hydrology itself is a discipline that confronts imprecision in its attempts to map, predict and engineer the movement of water. This points to the difficulty of quantifying complex water systems, regardless of the terminology used to describe water management.

Previous scholarship stipulated that groundwater sustainability goals incorporate: the development of a conceptual water balance model, consideration of spatial and temporal dimensions, changes in technology, water demand and available supply, and also specify any underlying issues of uncertainty. Moreover, management practices that use "sustainable" to define a metric need to specify the *goals* that sustainability policy measures attempt to reach (Kalf and Woolley 2005; Gleeson et al. 2012).

Our research expands on these recommendations. Any definition of groundwater sustainability is not value-neutral, and as local water agencies focus their management practices on particular goals, we propose that the *specific assumptions and variables incorporated into both goals and objectives be explicit*. These can include very clearly spelling out for example: timeline utilized; spatial dimensions being considered; ecological, hydrogeologic, and economic considerations; and climate change and extreme event considerations.

Some of these variables are already being more widely acknowledged and incorporated into management goals and practices. For example, water management is increasingly using the scale of the watershed or the basin to inform management and water policy. In addition, hydrologic science is increasingly linked with sustainability concepts that incorporate multigenerational goals and acknowledge the connections between groundwater, surface water and ecosystems. Moreover, although "sustainable" is a problematic term, it is clear that metrics are needed to at the very least prevent groundwater levels declining over the long term that may result in situations, such as the permanent loss of aquifer storage, that are unlikely to ever be considered acceptable for future generations.

Finally, what previous scholarship has acknowledged is important in establishing a metric is the value of adaptive and inclusive planning processes in setting sustainability goals. Yet our findings demonstrate that, even with a participatory process, a major hindrance to implementing the term "sustainable yield" in groundwater management practices is that the variables and assumptions implicit in establishing a sustainable yield goal are not Armcanz generally transparent. And as (1997) notes, "Any definition of sustainable yield embraces a range of technical as well as social, environmental, and economic factors, therefore it is necessary for assumptions to be clear and incorporate considerable community input." Where hydrogeologists and agency managers make these explicit, there can be a clearer understanding by all parties regarding the meaning of sustainable yield. We note that in the interviews agency representatives were mostly concerned with stakeholders misunderstanding scientific concepts than with the importance of public input in characterizing sustainable yield.

If "sustainability" is defined as the "social acceptability of impacts" (Herczeg and Leaney 2002), then any groundwater management goal, regardless of terminology, essentially incorporates decisions about what is and is not an acceptable impact. It is therefore critical to make explicit the human dimensions of groundwater management goals, and prioritize what water management practices need most—a transparent decision-making process that incorporates a discussion of the variables listed above within participatory planning practices.

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References

Alley, W.M., and S.A. Leake. 2004. The journey from safe yield to sustainability. *Ground Water* 42, no. 1: 12–16.

Alley, W.M., T.E. Reilly, and O.L. Franke. 1999. Sustainability of ground-water resources. Circular 1186. Reston, Virginia: USGS. pubs.usgs.gov/circ/circ1186/ (accessed April 2013).

Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ). 1997. Allocation and Use of Groundwater – A National Framework for Improved Groundwater Management in Australia. Policy Position Paper for Advice to States and Territories, Sustainable Land Water Resource Management Committee. www.environment.gov.au/water/ . . . /pubs/framework-groundwater.pdf (accessed April 2013) .

Bachman, S. 2010. Groundwater Management Plan, Goleta Groundwater Basin, Final. w.goletawater.com/assets/documents/groundwatermanagement/Groundwater_Management_Plan_Final_05-11-10.pdf. (accessed August 2013).

Barber, W. 1988. Maximum sustainable yield lives on. *North American Journal of Fisheries Management* 8: 2.

Behan, R.W. 1997. Political popularity and conceptual nonsense: The strange case of sustained yield forestry. *Environmental Law Review* 8: 309.

Bredehoeft, J.D. 1997. Safe yield and the water budget myth. *Groundwater* 35, no. 6: 929.

Bruntland Report. 1987. World Commission on Environment and Development. Our Common Future, Report on the World Commission on Environment and Development. http://www.un-documents.net/wced-ocf.htm (accessed April 2013).

California American Water v. City of Seaside, et al., 2006. Case No. 66343. Monterey County Superior Court.

California Department of Water Resources (DWR). 2013a. Water Plan Update: Groundwater Enhancements and Recommendations. http://www.waterplan.water.ca.gov/docs/meeting_materials/plenary/2013.10.29-30/12-Workbook-GroundwaterEnhancements.pdf (accessed April 2013).

California Department of Water Resources (DWR). 2013b. Groundwater Terms. http://www.water.ca.gov/groundwater/groundwater_basics/gw_basic_terms.cfm (accessed April 2013).

California Department of Water Resources (DWR). 2003. DWR Bulletin 118 California Update Report. http://www.water.ca.gov/pubs/groundwater/bulletin_118/california%27s_groundwater__bulletin_118_-_update_2003_/bulletin118-chapter1.pdf (accessed April 2013).

California Water Plan Update. 2013. California Water Sustainability Indicators Framework. http://indicators.ucdavis.edu/ (accessed April 2013).

City of Pasadena v. City of Alhambra. 1949. 33 Cal.2d 908.

City of Los Angeles v. City of San Fernando. 1975. 14 Cal.3d 199.

Clary, D.A. 1986. *Timber and the Forest Service*. Lawrence, Kansas: University of Kansas Press.

Dana, S.T. 1918. Forestry and community development. *USDA Bull*. 638. Washington, DC: USDA Forest.

Geological Society. 2002. Sustainable groundwater development. *Special Publications* 193: 1–14.

Gleeson, T., W.M. Alley, D.M. Allen, M.A. Sophocleous, Y. Zhou, M. Taniguchi, and J. VanderSteen. 2012. Towards sustainable groundwater use: Setting long-term goals, backcasting, and managing adaptively. *Groundwater* 50, no. 1: 19–26.

Herczeg, A.L., and F.W. Leaney. 2002. Groundwater Flow Systems and Recharge in the McLaren Vale Prescribed Wells Area. Report to Onkaparinga Catchment Water Management Board. CSIRO Technical Report No. 10/02. CSIRO Land and Water, Canberra, Australia.

Jasanoff, S. 2005. Judgment under siege: The three-body problem of expert legitimacy. In *Democratization or Expertise? Exploring Novel Forms of Decision-Making*. *Sociology of Science*, Vol. 24, ed. S. Maason and P. Weingart, 209–224.

Kalf, F.R.P., and D.R. Woolley. 2005. Applicability and methodology of determining sustainable yield in groundwater systems. *Hydrogeology Journal* 13, no. 1: 295–312.

Legislative Analysts Office (LAO). 2010. Liquid Assets: Improving Management of the State's Groundwater Resources. http://www.lao.ca.gov/reports/2010/rsrc/groundwater/groundwater_032410.aspx (accessed April 2013).

Lee, C.H. 1915. The determination of safe yield of underground reservoirs of the closed basin type. *Transactions of the American Society of Civil Engineers* 78: 148–151.

Loucks, D.P. 2000. Sustainable water resources management. *Water International* 25, no. 1: 3–10.

MacCleery, D. 2001. Sustainability and Your Forest: Understanding Sustainable Forests and Forest Certification. http://forestry.about.com/od/environmentalissues/a/sustain_forests.htm (accessed April 2013).

Main San Gabriel Water Master. 2013. Main San Gabriel Basin Glossary. http://www.watermaster.org/glossary.html (accessed April 2013).

Maimone, Mark. 2004. Defining and managing sustainable yield. *Groundwater* 42, no. 6: 808–814.

Meinzer, O.E. 1923. Outline of ground-water hydrology. Geological Survey Water-Supply Paper 494. Washington, DC: U.S. Government Printing Office.

Multiple-Use, Sustained-Yield Act of 1960 (MUSYA) (74 Stat. 215).

NGC (National Groundwater Committee). 2004. Knowledge gaps for groundwater reform. In *Proceedings from Workshop 12–13*. November 2003, Canberra, Australia.

Robbins, W.G. 1989. Lumber production and community stability: A view from the Pacific Northwest. In *Community Stability in Forest-Based Economies*, ed. D.C. LeMaster and J.H. Beuter. Portland, Oregon: Timber Press.

Russell, E.S. 1931. Some theoretical considerations on the "overfishing" problem. *Journal de Conseil International pour l'Explaration de la mer* 6: 1–20.

Scanlon, B.R., C. Faunt, L. Longuevergne, R. Reedy, W. Alley, V. McGuire, and P. McMahon. 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proc Natl Acad Sci USA* 109, no. 4: 9320–9325.

Shilling, F., A. Khan, and R. Juricich. 2012. The California Water Sustainability Indicators Framework. http://www.waterplan.water.ca.gov/docs/ . . . /ae/sustainability-framework.pdf (accessed April 2013).

Sophocleous, M.A. 2000. From safe yield to sustainability. *Journal of Hydrology* 235, no. 1–2: 27–43.

Sophocleous, M.A. 1997. Managing water resources systems: Why safe yield is not sustainable. *Ground Water* 35, no. 4: 561.

Sustained Yield Forest Management Act (SYFMA) (58 Stat. 132).

Synder, J.H. 1955. Groundwater in California – The experience of Antelope Valley. *Agricultural Experimental Station*, University of California, Berkeley.

Thomas, H.E. 1955. Water rights in areas of groundwater-water mining. U.S. Geological Survey, Circulation 347.

Wada, Y., L.P.H. van Beek, C.M. van Kempen, J. Reckman, S. Vasak, and M.F.P. Bierkens. 2010. Global depletion of groundwater resources. *Geophysical Research Letters* 37: L20402. DOI:10.1029/2010gl044571

Zhou, Y. 2009. A critical review of groundwater budget myth, safe yield and sustainability. *Journal of Hydrology* 370, no. 1–4: 207–213.