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PLOS Water

RESEARCH ARTICLE

Assessing climate and water information systems affordances for the agricultural sector in western United States

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Abstract

There has been a dearth of studies on the use patterns and uptake of climate and water information systems (CWIS) to aid agricultural sector adaptations to climate change and uncertain water availability. In this study we identify patterns of use of CWIS and precision agricultural technologies and the utility--or affordances--these tools provide to users. We conducted a web-based survey (May – Sept. 2022) delivered by email via convenience sampling. Respondents were 46% growers, 33% ecosystem or water managers, and 21% other occupations and were primarily from California (66% respondents), New Mexico (15%) and Utah (19%). We analyze geographic and stakeholder-specific patterns of CWIS use, including types of decisions faced daily and information sources used by these user types. Next, using a 2-parameter Rasch analysis, we analyze the technical and climate adaptation affordances of the webtools. Our results reveal that information systems related to weather and irrigation information are preferred by growers. Water and ecosystem managers are more likely to use long-range climate information systems. Finally, growers show more reliance on socially oriented information sources such as reliance on consultants, Extension sources, and on-farm observations for decision-making suggesting pathways for integrating climate and water information systems within the universe of integrated farmer management information systems. CWIS developers and investors will need to consider the affordances users access when building and training, and adaptation to climate change among growers and resource managers may be hampered by the limited information afforded and low adoption of tools.

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1 Introduction

A lack of available water for agricultural production and ecosystem management is a major issue globally and expected to grow more severe with the compounded effects of anthropogenic climate change and increasing population and resource demands [1,2]. Irrigation is the largest use of water worldwide, accounting for over 90% of global consumption [3]; surface water availability and timing is expected to change declines in snowmelt contributions impact seasonal water availability [4]. The western United States is highly dependent on a combination of snowmelt-generated runoff for seasonal water supply, reservoirs for interannual storage, and groundwater aquifer storage and pumping [5–7]. While advances in technology have allowed for achievement of economic efficiency in labor and farm inputs, water remains a limiting factor in food production [8,9]. Recent developments of information systems and services are intended to support data-driven decision-making, but little research explores the benefits of these tools to diverse users.

Agricultural production is vulnerable to future and current climate change, and the persistence of food systems could benefit from precise timely information management systems to manage risks and ensure agricultural sustainability [10]. While components of the agricultural industry rely on place-based data, more advanced data and technologies that provide information on climatic and environmental conditions for optimal farm management are disparately adopted by operations [11]. Digital technology is disparately adopted, leading to data-driven decisions and enhancing farming practices for some growers [12], while others continue to rely on interpersonal information like other growers, crop consultants and University Extension do [13–15]. Early studies on the efficacy of weather and climate decision-support systems to aid in agricultural decisions highlighted that such systems are not well enough advanced and/or integrated to lead to widespread confidence and adoption by growers [16–19]. Furthermore, modern water conservation methods include a suite of approaches including technological advancements in irrigation (drip irrigation, sprinkler systems, subsurface irrigation) alongside agronomic practices like crop rotation, soil moisture management and mulching [20]. With regard to state-of-the-art smart monitoring and irrigation systems, combining soil-based, plant and weather-monitoring methods in a modelling interface with predictive control can reduce uncertainty and significantly improve water use efficiency [21–23]. Additionally, beliefs and perceived risk about climate change are highly predictive of behaviors and people who make decisions under conditions of uncertainty and imperfect knowledge also rely on trust in institutions which is a predictor in support for climate action [24].

Most water conservation efforts on farms have only extended to changing the volume of water withdrawn or applied while neglecting the volume and fate or return flows back to the original or alternate water source, creating a greater net consumptive use [3]. weather variability information helps to solve identification problems and fosters responses valid in the short run but poorly approximates needed adaptations to longer term climate change [25]. Evidence suggests that though agricultural practices such as crop choices may respond to local climate trends, practices such as cover cropping may be more of an adaptation to economic conditions than climatic

ones [26]. Adaptations to water scarcity have usually taken the form of improvement of water allocation, type of irrigation technology, environmental conditions and scheduling of water application, in addition to other agricultural practices such as soil management, fertilizer application, and disease and pest control [27,28].

Prior reviews of farmers' technology uptake reveals that a majority of the approaches rely on established social psychological theories followed by innovation-diffusion theories to understand whether farmer demographics, attitudes and perceptions, technological factors or institutional factors play a role [29–31] with mixed results. Such reviews find that there has been an overemphasis on the role of farmer demographics, environmental attitudes and climate risk perceptions, as well as institutional factors such as social networks and extension services, among others, in technology uptake but very few studies focusing on technological factors for precision and adaptation decision-making. While the Technology Acceptance Model identifies perceived usefulness and perceived ease of use as factors affecting technology adoption [29,32], profitability is a major concern when farmers make decisions regarding the uptake and use of precision agricultural technologies [33].

Among growers, the ease of use and benefit of use, as well as attitudes toward technologies, profitability and climate risk perceptions affect CWIS and digital tool engagement. Therefore, our study of the two key criteria, user experience ease of technology use (0–5, with 0 being the easiest) and, independently, the affordances technology can provide independent of user perception (0–2 with 0 being the least useful) will address a key need for developers and users of CWIS.

This study seeks to interrogate the affordances provided by climate and water information systems (CWIS) to agricultural stakeholders in three states in the American West, including California (CA), New Mexico (NM) and Utah (UT). Specifically, we study CWIS use and utility to advance understanding of technology uptake and climate change adaptation. These states face shared challenges due to anthropogenic climate change, including drought and heat stress, decreased and different timing of surface water availability, and dependence on groundwater pumping and decreased aquifer storage, and. Specifically, we ask the following questions:

(1) What are the patterns and distribution of CWIS in the western US?

(2) What are the affordances provided by CWIS and how does this affect uptake?

(3) What do agricultural sector water users' decision-making patterns reveal about pathways to increase technology uptake and adaptation to climate change?

1.2 Affordance theory

This paper explores usability and utility of CWIS through the lens of affordance theory—that is the benefits to the participant interacting with the interface and shared information of the resource. While there are several types of affordances (cognitive, physical, and sensory), we focus on the functional affordance provided by the design, access to information, and benefit to the user for each of the web tools. In this paper the authors assigned affordance value to each of the webtools used. Affordances are action possibilities afforded by a technology to users or what the users can potentially do using the technology [34–36]. The debates over affordance theory primarily arises from two fields – ecological psychology and information systems [37]; out of these, two central themes of usability and utility emerge as competing issues of importance in affordance theory. Additionally, reductive views of affordances tend to view them as dispositional properties and reducible to the objective properties of the organism and the environment, while non-reductive views treat affordances as relational properties emerging from the interaction of parts of a given organism-environment system [38]. Affordances have been classified in several ways including a classification by [38] that distinguishes between basic (related to movement) and complex affordances (related to intention). Furthermore, [39] clarify four complementary types of affordances based on Norman's conceptualizations including:

(a) *Cognitive affordance* – A design feature that helps the user in thinking and/or knowing about something.

(b) *Physical affordance* – A design feature that helps the user in physically doing something.

(c) *Sensory affordance* – A design feature that helps the user in sensing/seeing/feeling.

(d) *Functional affordance* – An affordance that helps or aids the user in accomplishing a goal [40].

Sensory and cognitive affordances as described by Hartson [39] are analogous to complex affordances put forth by Tillas et al. [38]. Additionally, Ditzler at al. [41] conceptualize affordance emergence as a layered model with structural affordances (objective material features, properties or capabilities of a tool) and functional affordances (what a tool enables when a user interacts with structural affordances). Within functional affordances, first-order affordance is instructive in the sense of clarifying or deepening system understanding, while second-order affordance is productive leading to new action [40,41]. We can see that the Ditzler et al. [41] structural affordance definition is analogous to Hartson's [39] physical affordance definition; first-order functional affordances are analogous to cognitive and sensory affordances and second-order functional affordances are the same. This conceptualization forms the basis of our study, where we focus on structural affordances offered by web tools and first-order functional climate adaptation affordances of these tools. For the purposes of this study, we expand the traditional understanding of functional affordances of CWIS to include not just user perceptions of technical complexity, but the climate adaptation affordances the technology provides, which is a function of climate risk perceptions of users.

1.2.1 Climate risk perceptions. Farmers in the US are adopting a range of strategies to adapt to climate change and deal with its impacts. These strategies range from conservation agriculture practices predominantly adopted in the Northeast to technological adaptations predominantly adopted in the Southeast [42]. Risk perception associated with climate change is multidimensional and influenced by a host of factors [43], though personal experiences with extreme weather events directly influence risk perceptions and are also significant predictors of climate change beliefs and support for adaptation [43–47]. High levels of perceived economic and environmental risks including a fear of regulation also affect decisions to adapt to climate change [48,49].

In California's Central Valley, farmers who experienced water shortages adopted more efficient irrigation practices [50] though preferred status quo for land use [51]. Northern California farmers primarily showed understanding of changing weather patterns and random weather events and acknowledged paleoclimate science but expressed disbelief in anthropogenic climate change, revealing a nuanced understanding [52]. Historically underrepresented farmers in California were shown to be very concerned about climate change-related impacts to water, temperatures and natural disasters and are implementing adaptation practices for water management, soil health and renewable energy as well as seeking insurance and government assistance [53].

In Utah, farmers believe that climate variability has unfavorable effects on agricultural production and the most adopted adaptation strategies include farm and ranch management innovations such as changes in hay and cattle production to adapt to water stress [54]. Interestingly, the use of advanced technologies over the past decades such as automatic moisture sensors, efficient irrigation systems, fertilizers and farm mechanization have contributed to increased production and subsequent water stress [54].

In New Mexico, despite extended drought, overallocation of water and growing uncertainty of water availability, a growing number of farmers in the Lower Rio Grande Basin are rapidly transitioning to highly water-intensive pecan orchards in response to socioeconomic drivers [55]. This is in large part because the ability to acquire water rights to meet or exceed adjudicated irrigation amounts has disproportionately ensured livelihood resilience of large farmers [55]. Farmers in New Mexico appear to be more likely to participate in short-term water mechanisms such as spot water markets and water banks rather than permanent transfer mechanisms [56]. Among technological adaptations suggested for the Rio Grande region, advanced or scientific irrigation scheduling, involving data, measurements and estimations, is one of the most important practices that could advance sustainability and lead to significant water savings [57]. However, multiple adoption barriers remain including lack of access to weather data, uncertainty about future water availability,

cost effectiveness of technologies, reliability of weather data, lack of availability of irrigation scheduling tools and risk of reduced yield [57].

Risk perceptions have been shown to influence the kinds of climate services information people use to make decisions because the types and timescales of information used within various decision contexts vary depending on perceptions of climate change risk [58]. This points to the need to investigate climate risk perceptions as a determinant of CWIS uptake.

2 Methods

To examine the complicated questions of utility, usability, technology adoption and climate change adaptation, we applied mixed methods: (1) surveys of growers, natural resource managers and others use and familiarity with CWIS; (2) review of all CWIS and subjective weighting of "Type of affordances;" and (3) Rasch analysis. In our presentation, given sample size disparities between California, which is the bulk of the sample and a much smaller response rate from New Mexico and Utah, we pool the latter two states for a conjoint yet distinct comparative analysis.

2.1 Survey design and dissemination

The survey was developed through a collaborative and iterative process and was reviewed by an internal review board (IRB) (UCM2021–124). A consent waiver was obtained for the study, and a description of the study and participant rights was provided at the beginning of each web survey. The study included metrics on perceptions of climate change, familiarity and use of CWIS, barriers to their use, and perceptions and participation in water management practices.

We collected data through web surveys using Qualtrics from March to September 2022. Our convenience sampling design invited water leaders, members of water-related organizations, and major water users in California, New Mexico, and Utah to participate. Based on prior research [51], we found familiarity to support response to a survey and allows for experiences to be shared around risk, novel policy and land use situations, including around water management. The three states, in addition to being part of the Secure Water Future project, are similar in terms of cropping systems, water scarcity, water storage in groundwater and snowpack, agricultural contributions to local and regional economies, water insecure communities, and ecosystems dependent on in-stream flows and groundwater. Given the focus of the survey and the level of engagement with water resources, and due to the geographically disparate nature of water managers, we employed convenience sampling, and emailed the survey to individuals, known contacts, participants in prior events, and email lists through organizations. These contacts were asked to complete the survey themselves and distribute it to their readership or member lists. We assigned each convenience sample its own URL and added that information and removed all identifying information, separating emails and contacts from respondents' answers. The web instrument included multiple metrics, like 5-degree Likert scale with neutral middle alternatives including "check all that apply" and qualitative open-ended questions. Climate perceptions were analyzed using scales that have been used in different contexts from available literature [59,60] and prior research with growers web-tool use in the Pacific Northwest [61].

As the project attempted to collect data on tool use to design a tool for Wester US water management, the instrument emphasized data-driven decision-making opportunities and barriers to engagement for measurement, management and water markets. A subset of the data is published on Dryad database (https://doi.org/10.5061/dryad.6m905qgd9). Respondents working in the Western US replied to the survey N = 268. We could not calculate the response rate because of the distribution method of listservs and convenience sampling through related partners. In terms of data cleaning, we limited respondents to CA, NM, and UT; and respondents who did not engage in the responses. All duplicates were removed and any response that was not 30% complete was removed. We included all respondents who had engaged with the CWIS tools. For the purposes of this study, N = 165. We codified respondents who identified as (a) growers, or producers of agricultural products, (b) water managers and ecosystem managers, or people who manage natural resources, and (c) all other respondents. Our study is limited in having 165 respondents and representation from two of the partners states is disproportionately low.

2.2 Data analysis

We used Python, SPSS and Microsoft Excel to clean, review and analyze the data. We categorized by user type into growers, managers (including both ecosystem managers and water managers) and others. The level of agreement is also a categorizing factor with responses ranging from "Agree" to "Disagree" to "Neither Agree or Disagree" (entered as "Neutral") or no response entered. The sum of counts for climate change perceptions in any category does not include any inputs that feature no response. A Sanford heatmap in Python was used to recreate a heatmap of a response count of climate perceptions by user type and level of agreement with the climate perceptions.

The distribution of growers, water and ecosystem managers, and other users of CWIS by state or user type. These data are presented in Section 4. Additionally, we also present the decisions faced daily disaggregated by user type and the non-exhaustive list of information sources indicating their use preference diversity. The survey data reveals the percentage of users by state and type who have (a) used a particular interface, (b) heard of or (c) neither. For the purposes of our study, we reduce responses from multiple choice to binary, CWIS usage is entered as "Used" (or 1) and "Not Used" (or 0) for all other type of response and non-response. "Use" in this instance refers just to actual use of the CWIS by users to make a decision without accounting for the number of times they may have used it, what they used it for and how they integrated it into decision-making as this is covered separately in Table 2. Although this rudimentary measure may seem simplistic, it gave us a distinct line between familiar and unfamiliar or experienced and unexperienced. Further research will explore level of engagement and utility.

2.3 Rasch analysis

Next, we undertake an analysis of the affordances of the various CWIS based on a discussion of affordance theory in technology use in Section 2. Data was extracted from the survey on the distribution of users and whether they used a particular CWIS in a binary 1/0 format. Each CWIS could only be rated as "used" once by each respondent. Responses for the Irrigation Scheduler were aggregated from all three state responses were paired with federal CWIS in the Rasch analysis. We used the IRT package in R [62] to run the Rasch analysis for all federal CWIS and separately for California and New Mexico-Utah combined. The Item Characteristic Curves (ICC) as well as the Item Information Curves (IIC) for the three categories are reported. ICCs display the probability of increasing or use as a function of the users access to information based on the ease of engagement with the tools' interface and information types available, while IICs are a derivative of ICCs and show the rate of change in the probability based on a person's ability, thereby denoting the information provided by the CWIS based on the slope of the users' ability.

2.4 Affordance Theory Application

The Rasch Analysis captures user perceptions of technology affordances as per [63] characterization. We further characterize in this section, the action possibilities afforded by the information systems independent of the actors as per Gibson's use of the term [64]. We developed an affordance scale for each CWIS based on analysis of the IS and provided a subjective score (see Supplementary Information S1 and S2 Texts). The score was developed by affordance analysis of various CWIS, we researched the technical and climate adaptation information affordances for each CWIS by visiting the websites. We listed these affordances for each CWIS and gave different weightings for technical affordances based on a subjective assessment of the ease of use and information provided by the CWIS interface. Similarly, we also assigned different weightings for climate adaptation information that addresses weather variability and local climate (including soil moisture), land use change and trends (including vegetation and faunal surveys, irrigated acreage, crop patterns, and topography), water availability (including water supply and depletions or extractions, water quality, groundwater levels and quality), disasters (including extreme events and risk) and social aspects (use of extension or citizen science). The full table of affordances assigned to the CWIS is shown in Supplementary Information S1 and S2 Texts. The aggregate affordances against the difficulty levels of CWIS which were obtained via a Rasch analysis (Fig 8).

3 Results

This section is organized into two subsections, with the first subsection showing the patterns of CWIS used by state and/or user type, where applicable as well as a qualitative discussion of the decisions faced by users and information sources used. The second subsection shows the distribution of climate change perceptions by user type and level of agreement. Finally, the results of the Rasch analysis and the relationship between technology characteristics and use difficulty and benefit are shown.

3.1 CWIS use patterns

The following Table 1 shows the distribution of respondents by user type and by state. Most of the responses were from growers in California, with the next major set of respondents being water managers in California. Respondents from ecosystem and water managers in New Mexico and Utah were comparable to those respondents in California, but fewer growers responded in these states. Other respondents also featured in California and to a lesser extent in other states.

CWIS adoption varies by state and user type (Figs 1 and 2). The graphs for Utah are not shown due to lack of respondents. Californians' use of CWIS ranges from 7%-61%. Growers are more likely to use National Weather Service (66%, n = 43) and California Irrigation Management Information System (21%, n = 14). They use California State departments' CWIS including California Soil Resources Lab information, California Department of Water Resources Tool and California Natural Flows Database. However, we find that one third of California growers have heard of CWIS though they do not indicate using them.

By comparison, half of California natural resource managers (n = 25) use CWIS such as California Department of Water Resources, California Data Exchange Center, California Natural Flows Database and the California Open Data Platform. The managers also use federal CWIS including Open ET and Climate Engine. Half of California natural resources managers (50%, n = 13) report having heard of CWIS but not using them. A greater percentage of "Other" users report having heard of CWIS but few report having used them and these tend to show more usage of information systems including California Soil Resources Lab and SNOTEL.

New Mexico respondents (n = 25) show low adoption of CWIS, with few using NM Climate Hub and NM Climate Center. Among NM managers, 50% of respondent report using most CWIS, particularly the Irrigation Scheduler, Climate information systems and NM Water Data. Other respondents report using NM surface water quality maps, New Mexico Water Rights Reporting System and the NM Integrated Water Management Handbook. About 60% of growers report only hearing of the NM Water Rights Reporting System, 60–80% (n = 9) of managers report hearing of most CWIS but not using them and 50% of other users report hearing of the Irrigation Scheduler but not using it.

User adoption of CWIS as opposed to non-adoption may be influenced by decisions faced daily by user type as well as the diversity of information sources they commonly use (Table 2). Growers prioritize water availability metrics, choice of crop and crop-related decisions, irrigation timing and scheduling, livestock-related decisions such as forage and stock ponds, groundwater quality and quantity, soil, and tree health among other issues. Common information sources they tap into include significant use of consultants to interpret complex data for use, visual observation and in-field assessments,

Table 1. Distribution of survey respondents by location and type.

User Type	State			Total
	California	New Mexico	Utah	
Growers	61	7	8	76
Managers	25	13	16	54
Other	23	5	7	35
Total	109	25	31	165

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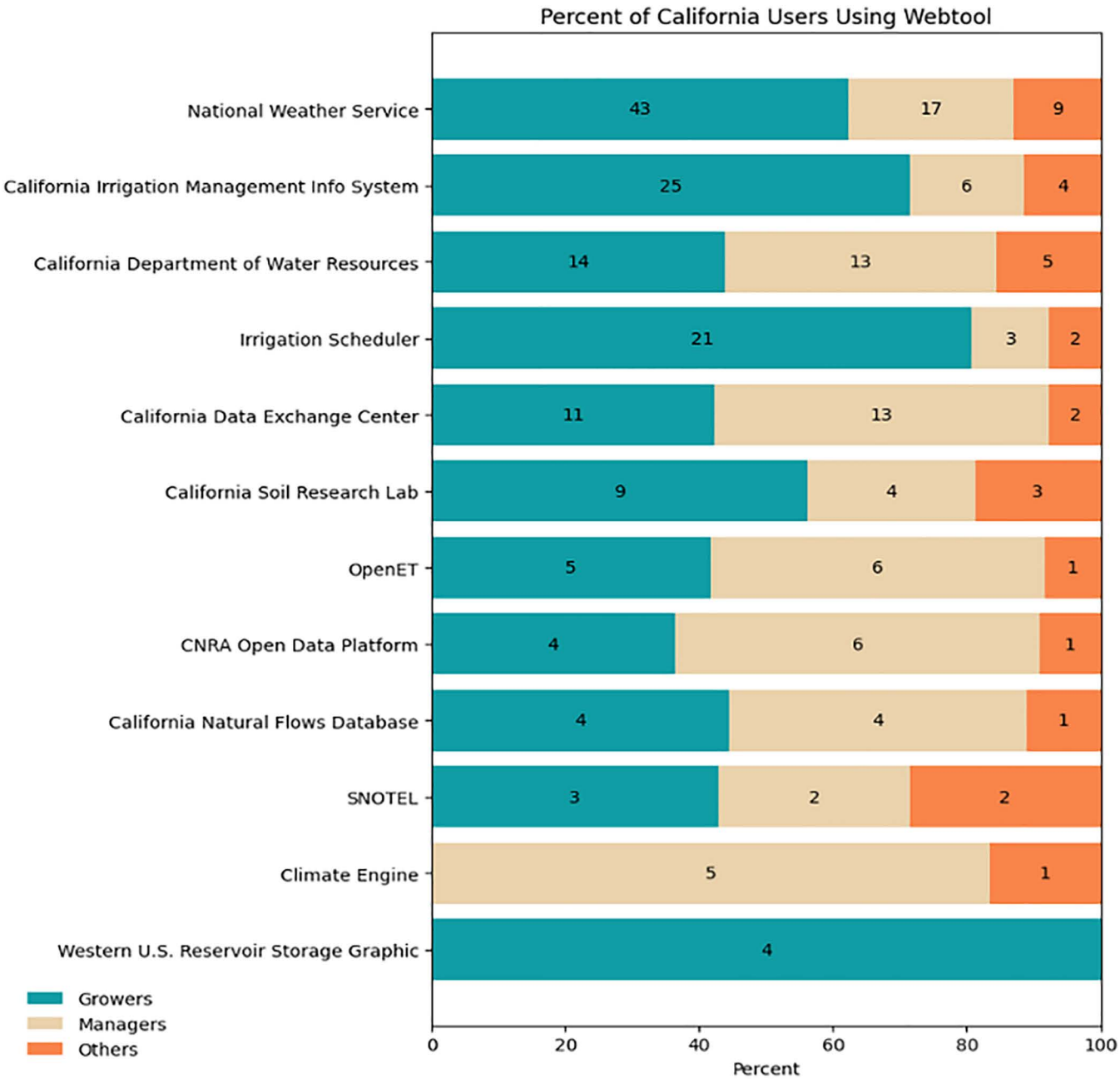

Fig 1. CWIS use distribution for users in California and respondent type.

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federal and state agricultural institutions such as US Department of Agriculture (USDA), National Weather Service and Farm Bureau, news, community water meetings, university research and cooperative extension.

Ecosystem managers faced decisions on irrigation efficiency, crop water requirements, drought mapping and hydrologic models, water availability and withdrawals, all with an eye to habitat restoration, endangered species protection and ecosystem health. The predominant information sources they used included sophisticated planning and modeling tools including the US Geological Survey (USGS) water data, National Weather Service, SNOTEL and other complex CWIS. Water

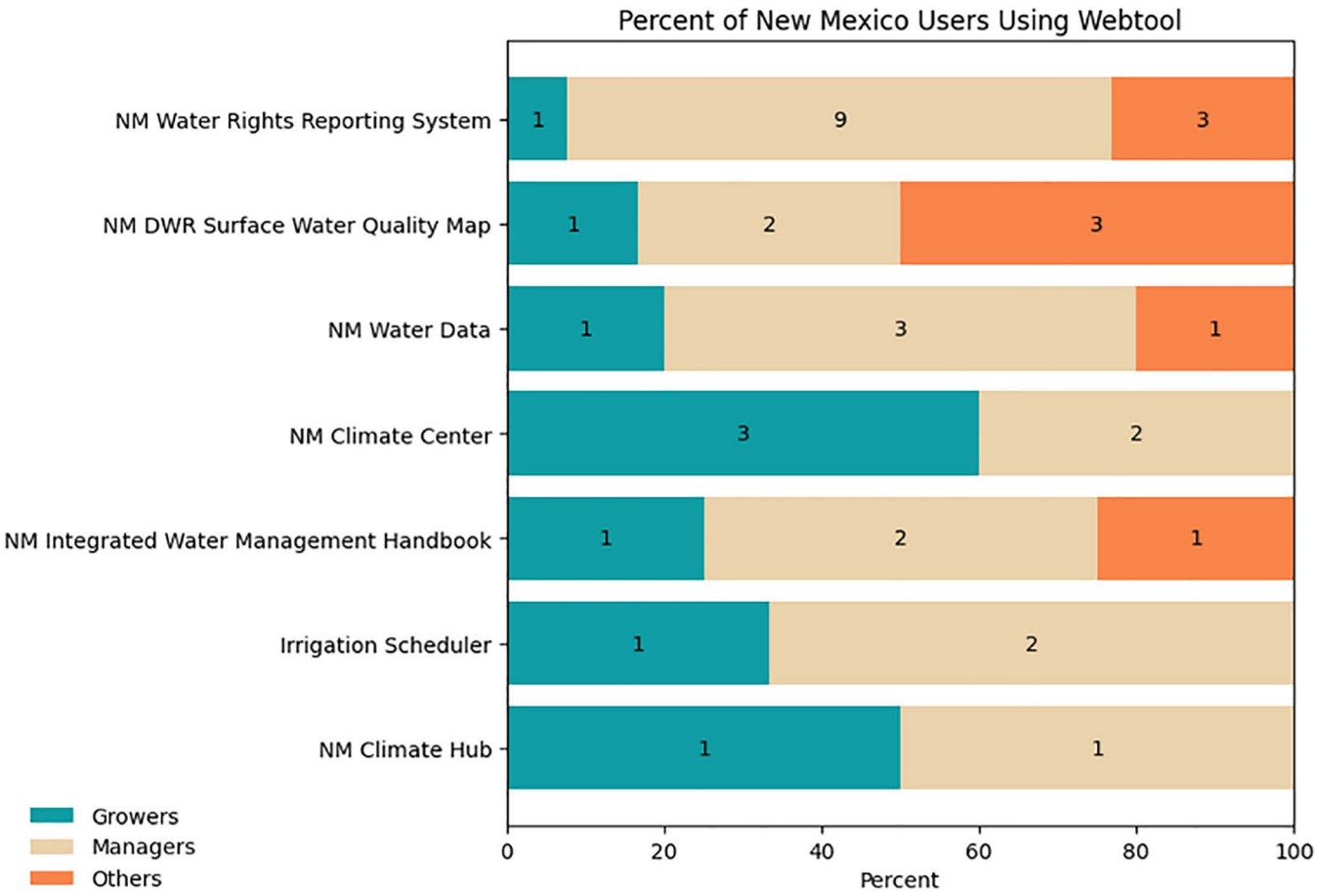

Fig 2. CWIS use distribution for users in New Mexico and respondent type.

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managers faced daily decisions relating to planning for water and water-related contingencies, storage and recharge, residential water use monitoring, water rights applications, water pricing, purchase and transfer, water infrastructure maintenance and future planning. The main information sources they used include federal and state water modeling systems, drought and soil moisture data, monthly pumping and delivery reports, water rights, water law and regulations and sophisticated climate information systems.

Other users faced decisions pertaining to irrigation timing and water budgeting, delivery issues, local weather and soil moisture monitoring, compliance and rationing, among others. The predominant information sources they use are eclectic and include municipal water bills, information from conservation district and canal companies, Farm bureau, extension services, weather reports and news, state and local agencies and NGO presentations and information and word-of-mouth channels, among others. They also tend to use webtools for crop-related decisions.

Turning to the use of technologies for on-farm decisions, we observe from Fig 3 that a high number of growers tend to use soil moisture sensors followed by weather stations and water quality tests. The next significant use of technologies by growers is in the use of plant monitoring and aerial and satellite imagery. The lowest use by growers is for technologies such as groundwater monitoring, geophysical technology, and yield maps. Among water managers, 15 reported a consistent use of all technologies across the board for all technologies. Next, we turn to climate risk perceptions of users and the affordances offered by CWIS to identify factors hindering more widespread uptake. It is imperative to note that many of the CWIS identified in the survey were not used. Even those who were familiar with the CWIS do not use them.

Table 2. Common decisions faced by user type and information sources used from survey responses (See S3 Text for full responses).

User Type	Decisions Faced Daily	Information Sources Used in Decision-Making
Grower	Effective agricultural and grazing water management involves optimizing distribution, maintenance, crop and irrigation decisions, resource allocation, tree and forage health, water quality, and groundwater-surface water balance.	Water management decisions rely on data from consultants, research, modeling, field observations, historical records, government and extension resources, industry publications, academic studies, and real-time weather, soil, and water data from agencies and organizations. Example data sources include USDA, NOAA, and CoCoRahs; tools include irrigation scheduler, NWS, DWR webtools from state databases
Ecosystem Manager	Ecosystem management integrates water availability, drought impacts mapping, hydrologic modeling, precipitation trends, flow regulation and withdrawals, ecosystem health, water quality, habitat restoration condition, and endangered species protection objectives.	Ecosystem managers rely on tools, local expertise, regulatory data, and climate and hydrological datasets to inform decisions. Data examples include NWS, SNOTEL, and USGS; tools Open ET, Climate Engine
Water Manager	Water managers make decisions based on demand management; drought and flood contingency planning; water rights allocations and usage records; compliance with regulations, pricing structures, water transfers, conservation initiatives; and infrastructure capabilities, forecasts for snowpack and reservoir capacity.	Water managers integrate agency data, hydrologic models, geospatial tools, and regulatory resources to monitor and plan water use. Data sources include NRCS, SNOTEL, and USGS; tools include Google Earth and GIS.
Other	General water management decisions involving irrigation scheduling, water budgeting, water delivery logistics, pump operations, soil moisture conditions, and groundwater use.	General users rely on diverse information sources for decision-making, including utility and conservation districts, extension services, state and federal agencies, research institutions, public media, social networks, newsletters, professional listservs, weather reports, reservoir status updates, and word-of-mouth insights.

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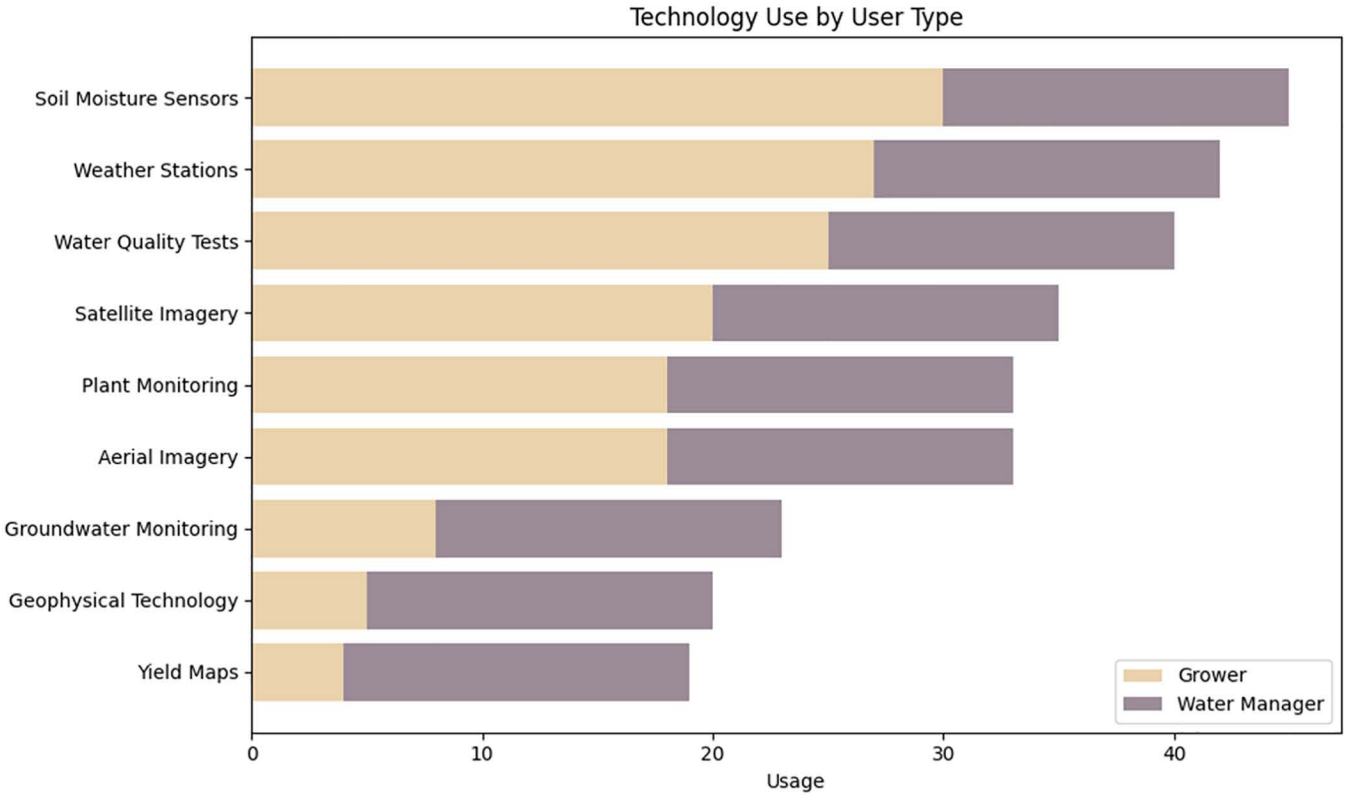

Fig 3. Technology use distribution for growers and water managers.

https://doi.org/10.1371/journal.pwat.0000458.g003

Only 18 respondents cited factors preventing use, and these included lack of awareness, training, specificity to location or current uses, internet access, and technology skills within the individual or their team. Some prefer to use their own methods such as “I only go by the conditions of the crop itself” or use a “Excel spreadsheet I developed” to monitor applications for water and nutrients.

3.2 Technology uptake and climate affordance analysis

To understand the uses of technologies in users’ decision-making, we first examine the climate change risk perceptions by user type and level of agreement. Fig 4 shows that a high number of growers agree on specific aspects such as observation of weather variability, harm to ecosystems, water scarcity and longer-term drought forcing water management changes in the region. Respondents somewhat agree on the prevalence of climate change, its threats to water quantity, water management and agricultural risks. Growers also demonstrate significant neutrality as well in these same areas. The level of disagreement with the prevalence of climate change and its threats and impacts is very low among growers, managers, and other users. Managers demonstrate significant agreement across the board for the prevalence of climate change and its impacts. Other users also significantly agree on climate change occurrence, harm to ecosystems and water availability and management changes being forced in the region. Overall, the level of disagreement is very low

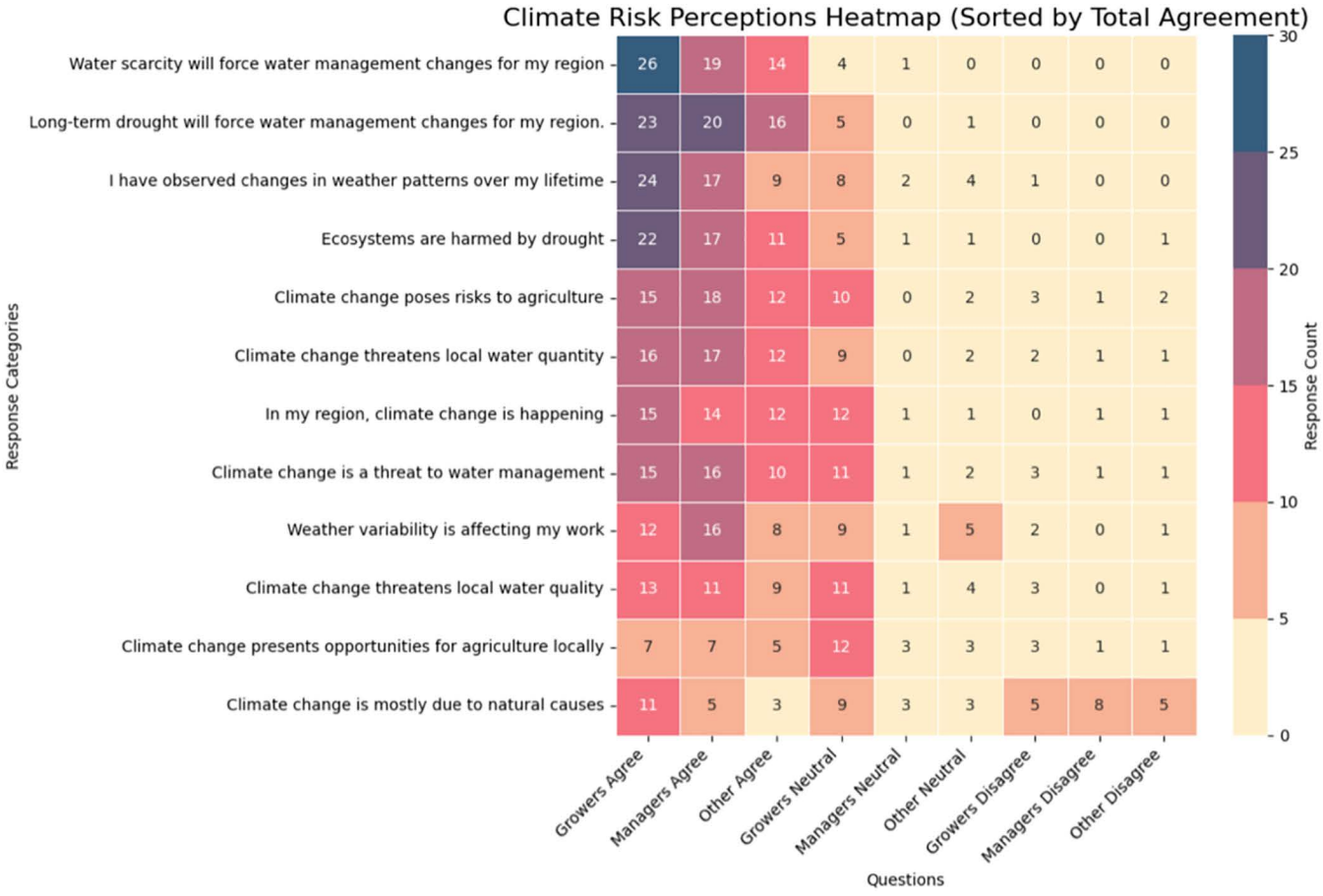

Fig 4. Climate risk perceptions of growers, managers and other users based on levels of agreement. We combined strongly and somewhat agree/disagree.

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across all user types, even if some significant number of them demonstrate neutrality to specific aspects of the prevalence of climate change and its impacts.

Table 3 shows the descriptive statistics for the Rasch analysis for all CWIS. The standard error within the range of ~ 0.2 - 0.5 for most CWIS except for the New Mexico Climate Hub (NM7). The Z scores fall within a range of ~ 6 – 9 except for the National Weather Service (FED1). Chi-Square values are statistically significant for all CWIS except for the US Western Reservoir Storage graphic (FED5) where the null hypothesis is not rejected. The most statistically significant results occur for federal CWIS including SNOTEL and Open ET, California CWIS including CA Data Exchange, New Mexico CWIS including the NM Department of Water Resources Surface Water Quality Map, NM Climate Center, and all Utah CWIS as well as the Irrigation Scheduler for all states. The overall pattern of standard errors matched to Z scores shows that the standard errors are insignificant only at large Z scores, indicating that the model overall is a poor fit for lower standard deviations. This is also borne out by larger chi-square values that are statistically significant. This could be due to the sample size being inadequate and not broadly representative. It might also be due to the fact that the definition of "use" as we have described and operationalized it is not a good descriptor of "user measure" and better variables such as frequency of use and degree of meaningful application might be better descriptors. These are factors to be considered in a future survey design or that developers could access from user data. Perception and memory of engagement will be different from actual use.

For federal CWIS users from all three states, we can see from Item Characteristic Curves (Fig 5) the National Weather Service has the highest probability of being correctly interpreted and used compared to the rest of the federal CWIS. SNOTEL and Irrigation Scheduler is correctly interpreted and used by about 20% of users with no ability and ease of interpretation increases steeply for users with ability. Open ET has a lower rate of interpretation by users with no ability (10%),

Table 3. Descriptive statistics on Rasch analysis for all CWIS.

Webtool	Shortened Code	Coefficients		Item Fit Statistics	
		Standard Error	Z	Chi-Square	Sig.
National Weather Service Data	NWS	0.188	-2.296	15.805	0.003
Climate Engine	Climate Engine	0.384	8.955	17.783	0.001
SNOTEL – Natural Resources Conservation Service (NRCS)	SNOTEL	0.207	6.246	29.581	<0.001
Open ET	Open ET	0.276	9.035	63.921	<0.001
Current Western U.S. Reservoir Storage Graphic	Western Reservoirs	0.524	8.002	6.301	0.178
Irrigation Scheduler (for all three states)	Irrigation Scheduler	0.216	7.052	27.846	<0.001
California Data Exchange Center	CA Data Exchange	0.242	8.347	20.114	<0.001
California Department of Water Resources Tool	CA DWR	0.223	7.379	14.725	0.005
California Irrigation Management Information System (CIMIS)	CA Irrigation Management	0.218	6.982	10.767	0.029
California Natural Resources Agency Open Data Platform	CA NRA	0.309	9.327	17.324	0.002
California Natural Flows Database	CA Natural Flows	0.328	9.338	12.242	0.016
California Soil Resources Lab	CA Soil Research Lab	0.274	9.088	16.634	0.002
New Mexico Water Data	NM Water Data	0.476	8.449	13.423	0.004
New Mexico Integrated Water Management Handbook	NM Integrated WM	0.526	8.094	5.383	0.146
New Mexico Department of Water Resources Surface Water Quality Map	NM DWR	0.439	8.709	15.513	0.001
New Mexico Water Rights Reporting System	NM Water Rights	0.316	9.280	5.083	0.166
New Mexico Climate Center	NM Climate Center	0.439	8.709	18.105	<0.001
New Mexico Climate Hub	NM Climate Hub	0.727	6.862	14.206	0.003
Department of Water Quality Report Tool	UT DWQ Report Tool	0.476	8.449	9.633	0.022
Utah's Open Water Data	UT Open Water Data	0.476	8.449	9.633	0.022
Utah Climate Center	UT Climate Center	0.339	9.255	3.425	0.331

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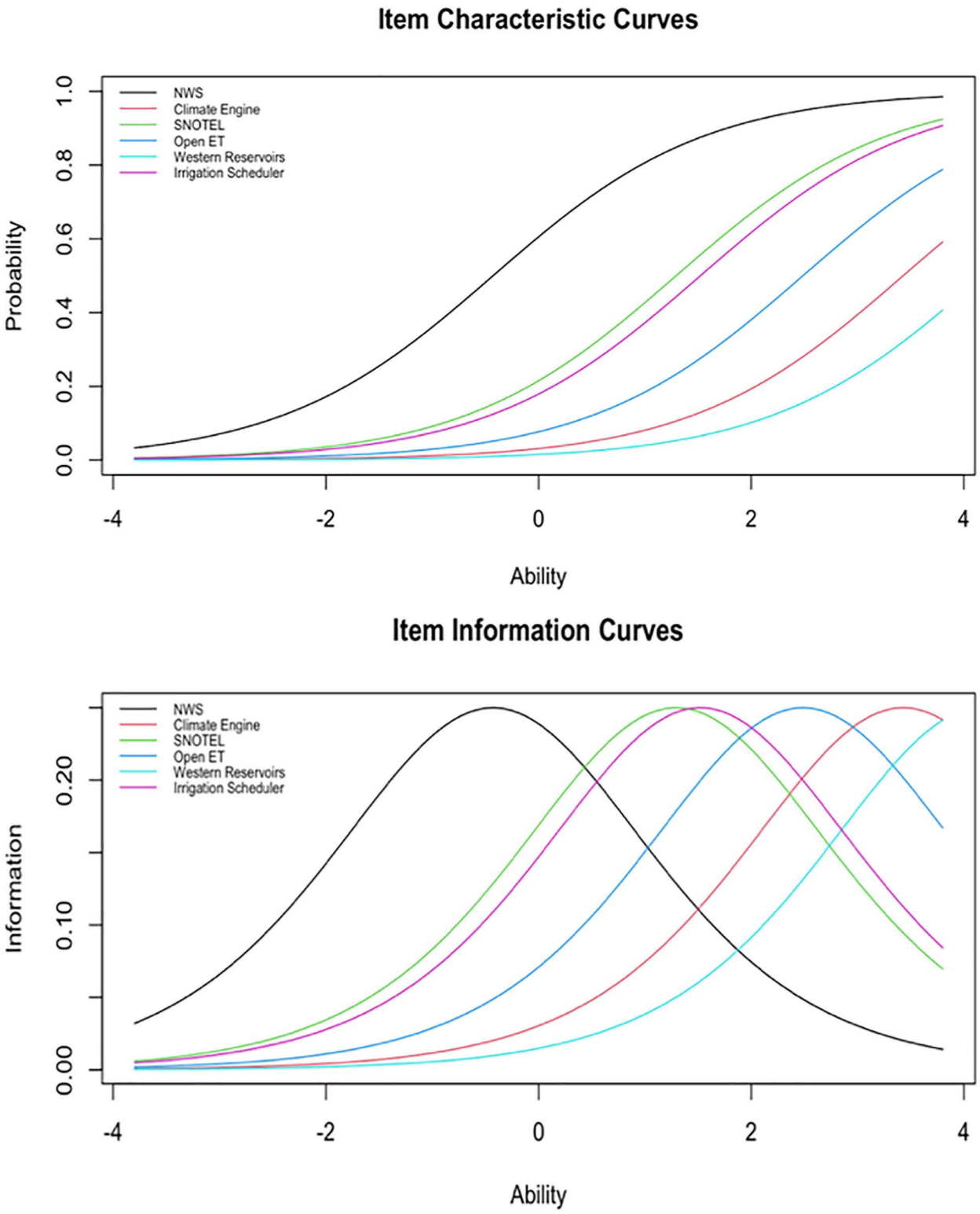

Fig 5. Rasch analysis for federal CWIS and irrigation scheduler for all 3 states (AIC = 815.38, BIC = 837.19).

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and it also increases less steeply than SNOTEL. The other CWIS illustrate that users would have a greater difficulty in interpretation of information. Item Information Curves (Fig 5) show that the National Weather Service provided the most information despite low or non-existent ability levels of users, whereas every other federal CWIS requires high user ability for information interpretation though SNOTEL does demonstrate some information provision for users with low ability. Climate Engine and Western Reservoir Storage Graphics have the lowest probability of interpretation even with users of higher ability and consequently only achieve more information provision at higher levels of user ability.

California CWIS shown in Fig 6 show more closely clustered results. The Item Characteristic Curves reveal that for the CA Department of Water Resources Tool and CA Irrigation Management, a probable 20% of users with no ability correctly interpret and understand these tools, while the probability of no ability user interpretation stands at ~ 10% for the CA Data Exchange and the CA Soil Research Lab. The slopes of California CWIS characteristic curves reveal that a significant amount of user ability is required for interpretation. Item Information Curves reveal that CA DWR and CA Irrigation Management demonstrate high information provision at lower user ability than CA Data Exchange and CA Soil Research Lab, which in turn demonstrate high information provision at lower user ability than California Natural Resources Agency Open Data Platform and California Natural Flows Database.

For CWIS from New Mexico and Utah, we see from the Item Characteristic Curves (Fig 7) that the NM Water Rights Reporting System shows a marginally higher to be correctly interpreted by users with no ability than the other NM CWIS. We also see that NM Water Rights shows a steep upward slope for users with greater ability. Among the other NM tools, NM Climate Center, NM Water Data and NM Integrated Water Management Handbook show an equal and less steep slope denoting lower probability of correct or useful interpretation for users of higher ability. The CWIS with the lowest interpretability even at higher user ability levels is the NM Climate Hub. Item Information Curves reveal that none of the CWIS provide high information for users with low ability, but NM Water Rights provides the most information for a greater range of user ability levels than observable for the other CWIS. All other CWIS require significantly greater amounts of user ability to be useful. Relative to NM CWIS, Utah CWIS do not show in the current graphs which may be a function of the low participation rate from Utah residents skews comparative assessment.

Assessing CWIS for the affordances that they offer as against their difficulty of use (Fig 8), we observe that the highest aggregate affordance (computed as the sum of weighted technical and climate adaptation affordances) is offered by Utah's Open Water Data platform, followed by Open ET and then SNOTEL, New Mexico Water Data, New Mexico Integrated Water Management Handbook, SNOTEL and Open ET. These platforms offer computational or explicit visualization characteristics such as technical affordances that increase usable information that can lead to longer-term climate adaptation planning affordances. However, CWIS such as Climate Engine, California Data Exchange, California Natural Resources Agency Open Data Platform, California Natural Flows Database, New Mexico Climate Center, New Mexico Climate Hub and Utah Climate Center, though they offer long term climate adaptation planning affordances, offer less in terms of easy-to-understand technical affordances such as visualization or computational outputs that aid in decision-making and only offer data and report formats that put more of the information processing burdens on end users. Therefore, they scored lower. The lowest scores are shown by CWIS that do not explicitly offer sophisticated technical affordances or long-term climate planning affordances such as National Weather Service, CA Irrigation Management Information, and the Irrigation Scheduler.

Similarly, we can see that in terms of difficulty levels, the highest difficulty in use is applicable to CWIS from Utah and then New Mexico. Both these tools rely heavily on data, reports and computation and feature long range climate adaptation planning. So, although they offer significant aggregate affordances, they also require greater ability and knowledge on the part of the users. Federal CWIS have a much lower difficulty level except for the Western Reservoir Storage Graphic. Federal CWIS that offer long-range climate adaptation affordances such as Climate Engine, SNOTEL and Open ET also have less difficulty levels than comparable state CWIS from Utah and New Mexico, because of the visualization options they afford users that enables ease in interpretation and decision-making. California CWIS have the lowest difficult levels

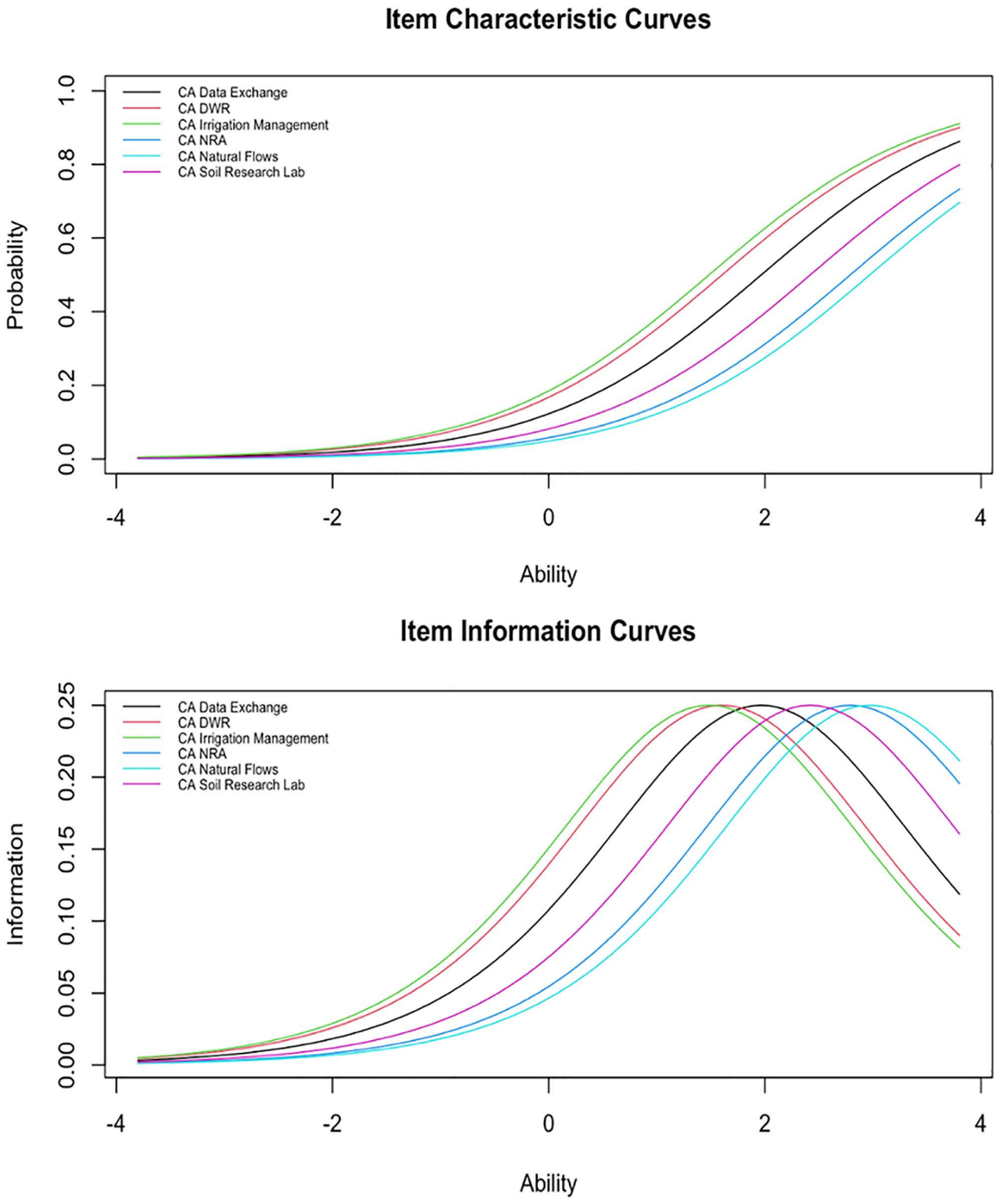

Fig 6. Rasch analysis for California state CWIS (AIC = 741.26, BIC = 760.08).

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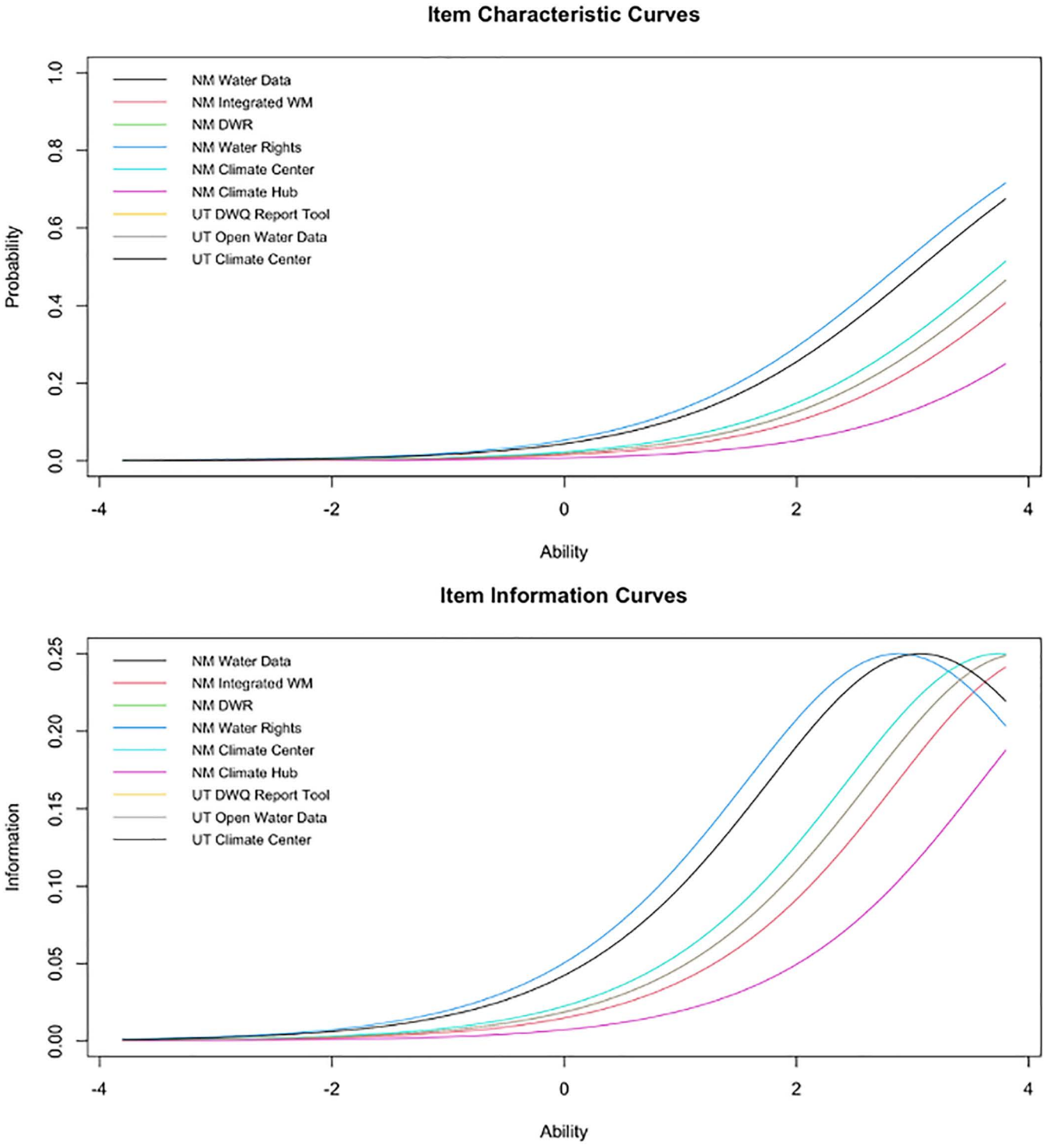

Fig 7. Rasch analysis for New Mexico and Utah state CWIS plus the irrigation scheduler (AIC = 454.35, BIC = 482.57).

https://doi.org/10.1371/journal.pwat.0000458.g007

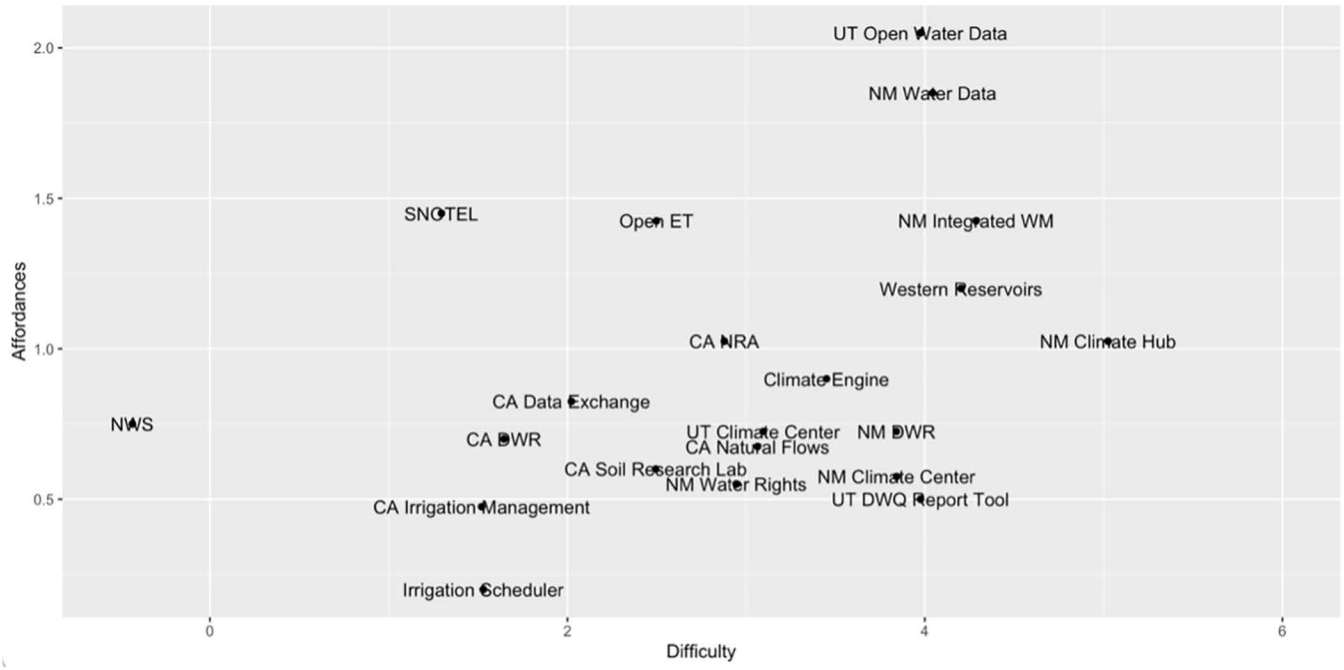

Fig 8. CWIS rated on aggregate affordances and difficulty levels.

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compared to all other information systems despite providing lower overall aggregate affordances. The affordance scores are expert-coded from tool features, while the Rasch analysis is based on binary usage data. Fig 8 is exploratory and hypothesis-generating, rather than a validated link between user perceptions and tool characteristics.

4 Discussion

The limitations of our interpretations reflect the limits of collaborative survey design and the limits of web survey responses. In attempting to be a unifying needs assessment of multiple CWIS users, we do not have the level of use or respondents' evaluation of each tool on difficulty or affordance. Instead, we had to mix methods. Also, self-evaluated use of tools is limited and instead, engaging actual user data from the CWIS apps would be better.

We do not assess users' adoption of affordances of CWIS users who use multiple CWIS or sources of information and have greater affordances than those who use fewer CWIS or information sources. Davis's conceptual model of technology acceptance suggested that users' motivations to use a technology can be explained by three factors: perceived ease of use, perceived usefulness, and attitude toward using [65]. Perceived usefulness is defined as the degree to which the users believe that using the particular system would enhance their job performance, whereas perceived ease of use refers to the degree to which users believe that using the particular system would be free of effort and that both beliefs are hypothesized to be directly influenced by system design characteristics [65,66]. Figs 4-8 show that this is indeed the case. We can see that certain CWIS such as the National Weather Service show both a high degree of perceived usefulness and perceived ease of use which translates into greater acceptance because the system design characteristics show the least degree of difficulty in using the information system. However, other state CWIS do not rate as highly because the difficulty of using them based on system design characteristics and the complexity of information they provide do not offer immediate perceived usefulness or perceived ease of use.

Furthermore, with freshwater availability becoming an increasingly scarce resource, collaborative management of watershed resources is increasingly involving diverse stakeholders [67], though participation has been significantly

limited due to technical and legal complexity [68,69]. One approach to deal with this complexity is to allow all stakeholders including managers, researchers, educators and the civil society to be able to contribute to the information system in any level they are inclined to do so [70]. Currently, there are limited ways in which information systems accomplish this. Participatory decision support systems incorporate analytic-deliberative decision processes where participants make use of GIS-based decision aids in an attempt characterize meaningful participation and is an example of stakeholder engagement in information systems [68,71]. Access to information is power in decision-making. In that vein, the spectrum of participation articulated by the International Association of Public Participation (IAP2) offers five levels including: inform, consult, involve, collaborate and empower, with each next level enabling a participant with increasing impact on the overall process [72]. However, a critique of the IAP2 spectrum is that they tend to mix process and outcomes and thus make it difficult to distinguish process impacts from outcome impacts [68,73]. For instance, while participatory GIS use produces findings high in construct validity, meaning that researchers can describe constructs in a way that participants agree with researchers' interpretations, construct validity is not enough to grow knowledge through research in a comprehensive and systematic way [74]. Other kinds of validity are also important including internal validity which refers to an accurate representation of relationships among constructs underlying findings within conceptual frameworks, external validity which refers to findings transferring from one real circumstance to another and statistical conclusion validity which refers to a sufficient number of observations to be statistically meaningful [68,75].

In this scenario, how could CWIS be improved or adoption be improved to enable better decision making? Despite rapid uptake of climate visualization tools (CVTs), many of them interactive and web-based, there are several factors that account for gaps in uptake and adoption. First, the main providers of CWIS tend to be universities, non-profits and government agencies with the most common target user group being specialists despite the focus on public-facing and application-oriented CVTs [76]. Second, the main focus of CVTs was in ***exploration*** of data and navigation of multiple datasets with little structure to user interaction with available information [77]. Exploration of water system performance under climate change is mostly being conducted by expert users [78]. This accounts for why the perceived usefulness of CWIS among growers ranks low among a majority of webtools. Third, the focus of CVTs was in meteorological datasets rather than an ***explanation*** of climate change processes and impacts as well as including such information as social and economic impacts. This distinction between exploratory and explanatory features of climate information systems might well be the factor constraining uptake and adoption [77]. We posit that the addition of explanatory information would enable greater use in decision-making with growers and the public.

However, because farmer decision-making tends toward incorporating short-term economic and weather variability-driven information [79], strategies to disseminate climate adaptation information might be more effectively enacted within a comprehensive agricultural information system (AIS) environment that includes precision agriculture. Precision agriculture is a management strategy that applies a wide range of technologies to collect, process and examine data to guide targeted actions that progress efficiency, productivity and sustainability of agricultural procedures [80]. It includes enabling technologies such as global positioning systems (GPS), geographical information systems (GIS), and numerous different sensors for assessing field variables and providing real-time information to growers [29]. Agricultural or farm management information systems is required to unite all parts of precision agriculture [81] and shift it from simple farm recordkeeping to sophisticated, complex systems to support production management [82]. Within this integrated system, there should be opportunities to integrate weather, climate, and water availability information from web-based and other sources. While farm management information systems and precision agriculture incorporate more economically relevant information into the system, the incorporation of climate and water information systems into an integrated farm management information system will account for the impacts of these variables in current and future agricultural productivity. This would expand the universe of stakeholder involvement in information interpretation, dissemination and engagement to include other agricultural stakeholders including growers, farm workers, government, research institutes, service providers, contractors, equipment producers, product developers and weather service providers among others [83].

5 Conclusion

Our results illustrate a trade-off between the complexity of information provided by webtools and the ability of different user groups to effectively engage with and interpret that information. We found that water managers and ecosystem managers are more equipped to engage with and interpret more sophisticated models, but growers show preferences for relying on multiple sources other than webtools including on consultants to interpret and provide them with usable information as well as cooperatives, extension services, on-farm observations and more socially oriented sources of information for various reasons including differences in education and profession training between managers and growers which is supported by available literature [84,85]. Our analysis of webtools affordances in this study shows that difficulty in engaging with and interpreting usable information from webtools may be part of the challenge facing growers of varying abilities. Furthermore, the webtools usage analysis shows that tools such as the National Weather Service and the Irrigation Scheduler, the CA Department of Water Resources Tool, and the CA Irrigation Management webtool clearly emphasize the preferences of growers who make are the most likely to adopt technologies to directly manage resources.

While these tools support short-term operational decisions, their limited focus on long-term climate adaptation presents a challenge for building resilience in agricultural systems. Water and ecosystem managers indicate a preference for greater usage of webtools for long range climate change planning than do growers. To bridge this gap, grower-preferred short-term planning tools should be integrated with socially oriented extension services and expert consultation, ensuring that farmers can interpret complex information and incorporate long-term adaptation strategies into their decision-making.

Prior research indicates tailoring information, including location, time interval, and relations among users, can benefit users and industry stakeholders [12,15]. Other researchers also mix tools with social media or anything online, not the information systems we discuss, so more research is needed on the full suite of influences on decision-making, knowledge-building, and relationships. Both developers of tools and investors in decision-making infrastructure like national and state agencies, research funding, and climate change adaptation supporters may benefit from a greater understanding of affordances and the challenge in accessing information from information systems.

Supporting information

S1 Text. Affordances of various webtools.
(DOCX)

S2 Text. Weight given to various technical and climate adaptation affordances.
(DOCX)

S3 Text. Common decisions faced by user type and web tool used.
(DOCX)

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