DESIGNING DROUGHT INDICATORS

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Methods from the industry of product design can improve the usability of drought indicators by reformulating how indicators are made to meet stakeholder needs.

Droughts inflict devastating socioeconomic and ecologic impacts (Howitt et al. 2009; National Oceanic and Atmospheric Administration 2016). During drought, farmers and water managers are forced to make difficult decisions that affect the livelihood of communities dependent on water resources. Numerous agencies at the federal, state, and local levels can play a role in how water moves from mountain snowpack through streams, reservoirs, or canals to riparian environments, farms, and cities. The overlapping jurisdiction of various levels of water governance charged with managing this precious resource creates interconnected needs for stakeholders across the hydrologic system. Under a changing climate, model projections indicate that drought frequency, extent, and duration will only worsen, putting a great strain on the management of water resources (Sheffield et al. 2012; Strzepek et al. 2010). To combat this pressing problem and mitigate the adverse effects of drought, water managers and farmers rely on timely information to warn of pending prolonged dry conditions and monitor how drought impacts cascade across the various components of the water cycle (Janetos and Kenney 2015; Otkin et al. 2015; Wood et al. 2016). In response to the demand for information, numerous drought indices and indicators have been developed as tools to categorize, understand, and track droughts and their ramifications (AghaKouchak et al. 2015; Svoboda et al. 2002; Svoboda and Fuchs 2017; Zargar et al. 2011).

However, scientists have inundated stakeholders with an overwhelming number of drought data products, generally produced with little design expertise, meaning the drought indicators are not always aligned with actual user needs (Schubert et al. 2007; Svoboda and Fuchs 2017) (Fig. 1). In fact, a recent review found over 100 methods have been developed to monitor and analyze drought (Zargar et al. 2011). These indicators track multiple forms of drought including meteorological, soil moisture, vegetation, snow, total water storage, groundwater, agriculture, ecological, socioeconomic, and recently classified flash droughts (Fisher and

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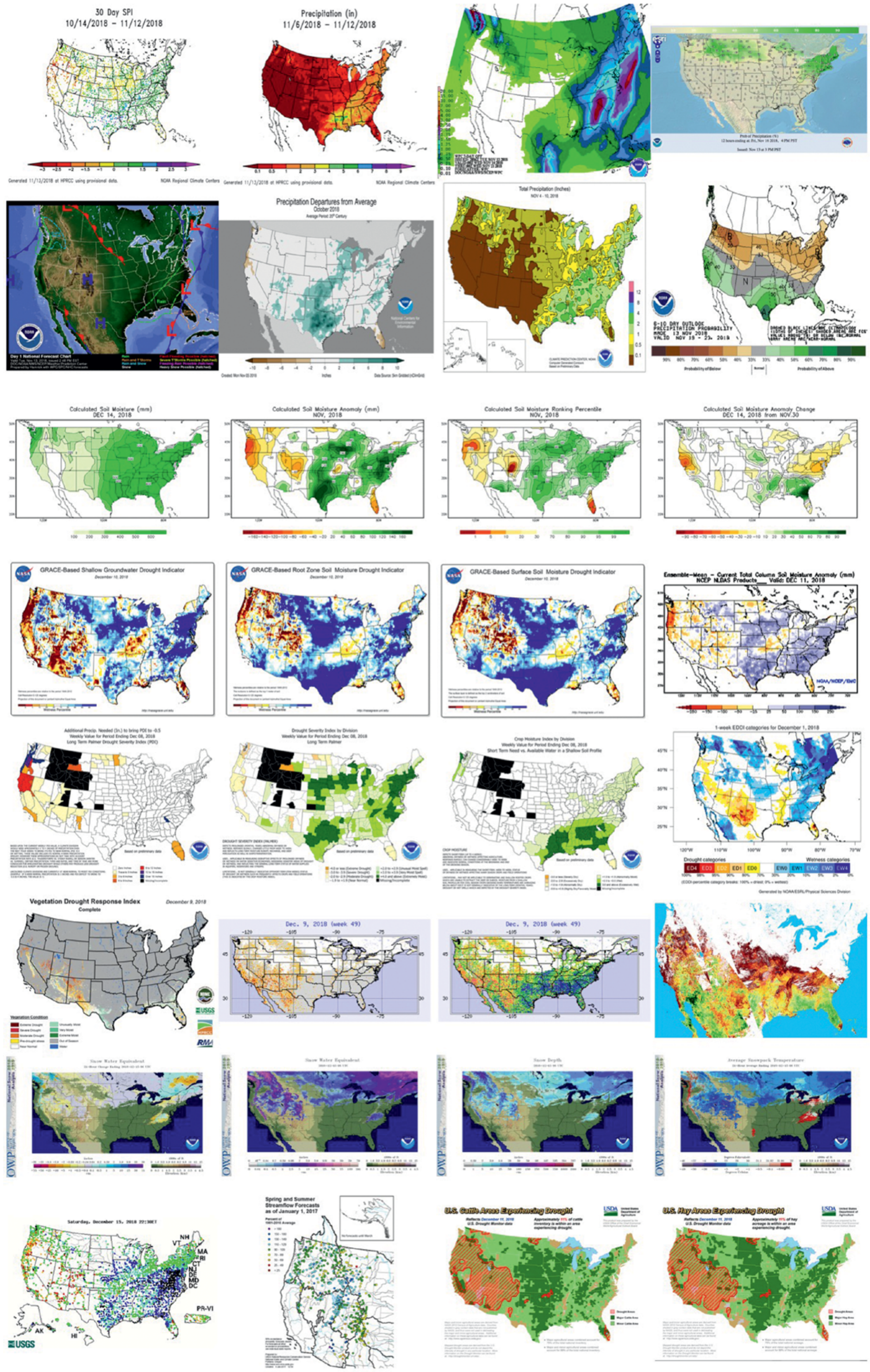

Fig. 1. The trade space of drought indicators encompasses hundreds of variations of similar types of information. Here we present 32 indicators available through the National Integrated Drought Information System (different dates are displayed across thumbnails).

Andreadis 2014; AghaKouchak et al. 2015; Crausbay et al. 2017; Harpold et al. 2017; Otkin et al. 2018; Thomas et al. 2014, 2017). Despite stakeholders having many readily available drought indicators, they are unsure which, if any, drought indicator is suitable to support their operations (McNie 2007; Steinemann 2014; Steinemann et al. 2015). The Handbook of Drought Indicators was written to provide clarity to drought data users, but does not recommend under which circumstances to use which indicators (Svoboda and Fuchs 2017). In addition to the number of drought indicators, the lack of user experience design contributes to a gap between "usable" drought information that communicates its severity and "useful" drought information to support actionable management to mitigate potential negative impacts (Prokopy et al. 2017). Only the U.S. Drought Monitor (USDM) has sought to simplify and improve the user experience through categorizing drought intensity by the impacts on different sectors, but this "one size fits all" approach may not fit any one stakeholder well.

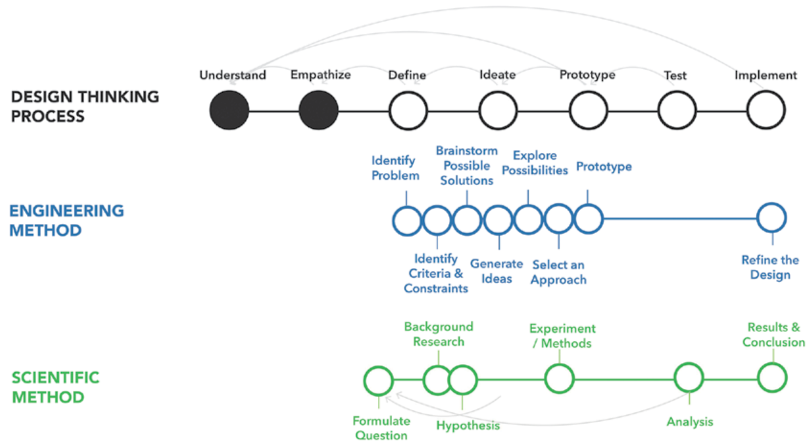

FIG. 2. The design thinking process distinguishes itself from the engineering process and the scientific method by understanding and empathizing the human dimension of the problem. Still, there are direct links to science and engineering methodologies, both of which are already intimately linked, facilitating integration of design thinking for enhanced outcomes.

In spite of good motivation behind indicator development, because limited energy and resources have been dedicated toward empathizing with stakeholders and the system they interact within, the current processes used to create drought indicators have been unable to address user needs. Design has potential to elevate the effectiveness and usage of scientific datasets by identifying and fulfilling user needs. Beyond the emotional connection with stakeholders, good design for drought indicators requires a holistic understanding of the hydrologic system including data requirements for each stakeholder (Schubert et al. 2007).

Design thinking is a human-centered methodology that originated from the field of product design where designers apply well-refined techniques to revisit how products are made, and deliver optimized products by distinguishing user *needs* from user *wants* (Fuge and Agogino 2015). Design thinking balances creative problem solving with customer needs, technological limitations, and the context of the situation. Design thinking successes have made it easier to file taxes online, book an apartment to stay in on your next vacation, and eased anxiety of children entering magnetic scanners at many hospitals (Lockwood and Papke 2017).[1] While the main applications of this approach are often couched within billion-dollar commercial industries,[2] the success stories are a result from human-centered design being adept at tackling ill-defined problems and figuring out why a gap between demand and service exists (Brown 2008; Brown 2009; Brown and Wyatt 2010). At its core, the product design approach to user-centered design thinking is similar to the engineering process and the scientific method, in which the main goal is to test hypotheses, answer questions, and solve problems (Fig. 2). The methods of design thinking draw from principles rooted in social sciences by approaching problems through a humanized lens and practices ideals of empathy, ideation, and experimentation (IDEO 2015).

Concepts from design thinking have recently been gaining traction in Earth and environmental science applications. For example, strategic storytelling has been integrated into mission formulation at NASA's Jet Propulsion Laboratory to connect the importance of space exploration and satellite missions to the human interest (Kawata 2015). Tools from user-centered design, such as surveys and multidirectional dialogue, lead to understanding the barriers to invasive species eradication and promoting soil health among landowners (Derner et al. 2018; Santo et al. 2015). Similarly, knowledge sharing between users, stakeholders, and

[1] http://newsroom.gehealthcare.com/from-terrifying-to-terrific-creative-journey-of-the-adventure-series/ and https://airbnb.design/the-way-we-build/

[2] https://blog.brainstation.io/how-5-ceos-used-design-thinking-to-transform-their-companies/

scientists helps to define potential decision spaces and useful scientific information (Dilling and Lemos 2011; McNie 2013, 2007). This type of engagement facilitates identifying end-user values and shifting the perception of scientific outreach from "controlling" to "supportive" (Sorice et al. 2018; Sorice and Donlan 2015). Likewise, iterative user feedback provides an avenue for end-user input on design elements to enhance data delivery such as weather forecasts or local groundwater quality (Argyle et al. 2017; Hoover et al. 2014). All of these examples showcase the value of incorporating stakeholders into the process of creating or delivering scientific datasets. Because humans are at the heart of drought response and its impacts, drought indicators should consider the human dimension (McNeeley et al. 2016). Indicators will continue to come up short of fulfilling the human need until the process of making drought indicators incorporates the environment in which stakeholders operate and the personal consequences that droughts impose (see sidebar).

Design thinking methodologies offer a path forward to understand the qualitative human need associated with drought, and, in turn, improve the design and user experience of drought indicators. Through systematic methods, designers put customers, such as drought data users, at the center of research, strategy, and the design process in order to determine why a disconnect between stakeholders and drought indicators exists, what drought data and data qualities are needed, and when and where they need them. Here, our multidisciplinary team of scientists and designers share how the methods of design thinking can be applied to improve how drought indicators are made. We detail how the tools and methodology of the design thinking process (Fig. 2) leads to new insights on drought indicator data requirements and opportunities to improve both the visual interface and user experience.

NASA JET PROPULSION LABORATORY'S DROUGHT DESIGN LABORATORY

Throughout its history, NASA has enlisted numerous artists and designers to illustrate mission ideas, paint future scenarios, and design logos, facilitating connections with the anticipatory public. Some of the earliest formal initiatives to connect NASA science and engineering directly with artists was the formation of NASA's Art Program in 1962 and the NASA Graphics Standard Manual in 1975, which featured the well-known NASA worm logo. During the 2000s, NASA mission design program managers began regularly interfacing mission teams with contracting visual design professionals on proposal covers and graphics. This prompted the many of the NASA labs to start investing in in-house designers of their own. However, as the success and integration of the visual design field grew, the definition of design to rocket scientists remained narrow. For years, the value of design at NASA was perceived to be visualization. Given the wide spectrum of design value from graphic design to transportation design, the opportunity to grow design capabilities beyond public outreach and into technical mission projects was prime.

In 2011, NASA's Jet Propulsion Laboratory (JPL) expanded into industrial design. JPL grew the practice of user-centered design in areas such as spacecraft design as well as cultivating innovation strategy and design thinking culture within mission systems formulation. The primary goal was to help JPL reframe and solve critical systemic problems using state-of-the-art creative practices from the industrial design field.

In response to the growing need of designers at the forefront of innovation strategy, JPL (led by coauthor Jessie Kawata) formed the Industrial Design Laboratory (ID LABORATORY) in 2015, the institution's first in-house industrial design team. This team of product designers and systems design strategists supported designs for a Europa lander and Mars 2020 Rover hardware, for example. The ID LABORATORY later partnered with Earth scientists to develop user interface and visualization strategies for hydrological data, eventually expanding to drought indicator development described here.

DESIGN THINKING TO IMPROVE DROUGHT INDICATORS.

Understand and empathize. Understanding how drought affects the interplaying stakeholders in a water management system is key to transforming drought indicators into simple, relevant, and timely data products that are better equipped to meet stakeholder needs. By observing, interviewing, and empathizing with stakeholders through a product design approach to research, our project's team of designers explored the contextual environment in which drought data are needed across the hydrologic system.

The field of product design is wide ranging, deploying expertise into many different types of industries. Through strategic design research methodologies, product designers are able to achieve enough contextual understanding of an issue in a moderately short amount of time to inform their design decisions. Due to the lack of background experience one might have within a problem area, product designers may engage in a number of preliminary design research activities prior to ethnography or other primary research techniques. Preliminary research consists of investigating existing information and collecting data sources or evidence in order to support the strategic planning of primary research. Here, designers research the

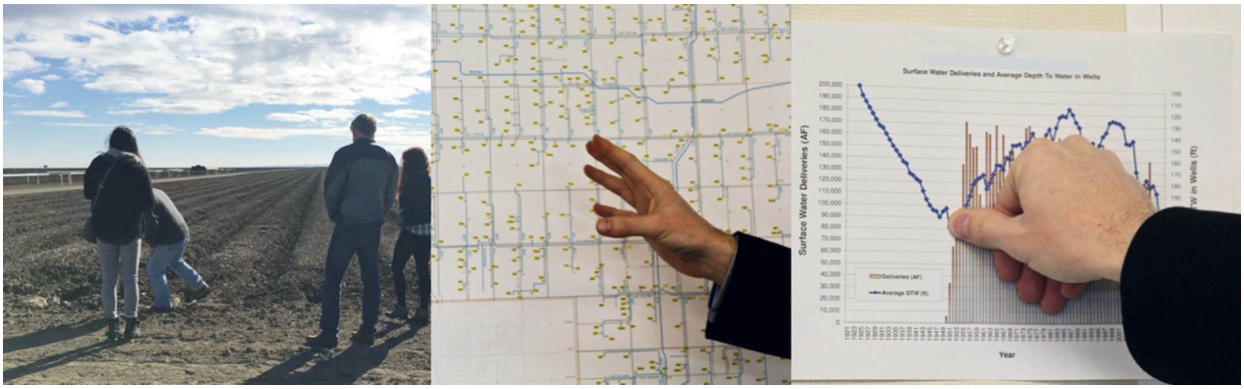

Fig. 3. Ethnographic on-site shadowing and interactions reveal far more detail into how decisions are made than remote interactions (e.g., phone, email). (left) Farmers share how impacts from drought are seen on the farm. (center),(right) Water managers explain how state and federal water management impact local water deliveries in an irrigation district.

complex systems of hydrological, agricultural, socioeconomic, and meteorological drought and contextually mapped these findings in visually compelling ways that provoke the revelation of patterns and gaps. For example, flowcharts and decision-making trees of different water management systems are created. Numerous geographic maps are used as boundary objects to plot existing quantitative and qualitative data together meanwhile discovering overlaps and therefore new user experience opportunities. The key benefit to analyzing in an analog capacity such as printed matter is that it helps to provoke important and inclusive collaboration or conversation between users and researchers.

Design ethnography is one method to gain the necessary cross section of unique perspectives and cultural context of stakeholders within a hydrologic system. This systemic method of observation inspired from research methods in the Social Sciences, focuses on gathering multiple points of view from the user's perspective. Research into the hydrologic cycle and water management facilitates the identification of key stakeholders and potential drought data users from farmers to federal water managers. Our work as applied to water management and drought has itself involved dozens of end users spanning multiple states. Participants for our project include farmers and farm advisors (~20%); local managers, for example, irrigation districts, water boards, and river authorities (~30%); and state and federal managers (~50%). Designers completed interactive phone and in-person interviews to gain an understanding of the role of each user and their perspective on how they interact within each state's hydrologic system. Within the design process, these interviews and interactions are meant to develop trust, identify challenges, and empathize with each user's circumstance. During these interviews the design team captures key takeaways and themes using handwritten notes and recordings to shape knowledge goals for follow up site visits and further in-person interactions.

By strategically targeting areas which experience the largest impact from drought, the design team looks to understand how hydrologic data are currently used and identify opportunities to improve current indicators. Importantly, the team shadows stakeholder actions in the environments in which they operate to learn: what, when, where, and how decisions are made (Fig. 3). Interactions with participants spanned from offices, to water conveyance canals, and operational farms to discuss what data or information currently factors into the decision-making process. Overall, these experiences provide the necessary context to understand and observe the environments in which stakeholders operate and how drought imposes an emotional toll on these communities. To resolve the knowledge goals and prompt in-depth communication during in-person interviews, interactive techniques rooted in design research produce key insights where a user's pain points are as it relates to drought, the decisions they face, and the type of hydrologic or drought data they require.

Recent applications of coproduction invoke similar principals of end-user engagement to establish relationships, share knowledge, and incorporate stakeholders into the development process (Meadow et al. 2015; Reyers et al. 2015; Wall et al. 2017). However, the methods of design thinking differ from coproduction in two distinct ways: 1) by holistically exploring the root of the problem and 2) by employing steps of convergent and divergent ideation meant to push the boundaries of a problem's solution space. First, design thinking focuses on exploring and considering the true problem prior to science product generation (Brown 2009). Stages in this process, such as understand, empathy, and define, force reflection on the core issue to overcome during design. Design thinking utilizes interactions, such as introducing boundary objects or generative research tools, to identify the "pain points" experienced by end users (Sanders and Stappers 2012; Travis and Hodgson 2019). Second, design thinking differs from coproduction by divergent and convergent ideation. Divergent ideation encourages exploration of new concepts and ideas of how to approach the problem at hand to ultimately converge on the best ideas. While coproduction has similar goals, such as developing more useable scientific data products, the steps in design thinking dedicated to ideation and understanding the problem can lead to optimized solutions.

Interactive research tools, also known to the design industry as generative tools, bring end users into the design process by giving them a shared language and design to communicate directly and visually with each other (Stappers and Sanders 2003). This is an analog approach that enhances a design researcher's understanding of the dynamic and contextual user experience. The generative tools include timelines, flow charts, prioritization pyramids, and trade-off decks. Employing these methods pushes the limits of discussions by forcing end users to react to boundary objects, or sensitive subjects relating to their lives and allows designers to discover what lies below the tip of the iceberg (Lee 2007). This approach steers stakeholder interactions toward achieving knowledge goals intended to understand the broader problem and acquire a nuanced understanding of their behaviors and perspectives, including who makes decisions, what decisions are made, where are decisions made, when are decisions made, what factors drive decision-making, and why does a disconnect between drought indicators and stakeholders data needs exist (Fig. 4). For certain stakeholders, such as farmers and water managers, temporal-based generative tools such as timelines and flowcharts allow users to chart critical decisions made across a calendar year. This process uncovers any emotional connections and context with which data are used during major events for each stakeholder. For each visit, design researchers lead stakeholders through chronologizing key events during the course of a water year. Discussions prompted by this exercise focus on which pieces of drought information, if any, help inform their decision-making process. Timelines elucidate what decisions are made, who makes decisions, and when data availability mattered most for each stakeholder.

Flow charts link together dependencies of stakeholders across hydrologic systems, in addition to time factors. Stakeholders contextualize how drought impacts on up-system management alter down-system water users such as farmers through sketching how water flows through the system. Just as the effects of drought cascade through the components of the natural hydrologic system, drought changes to management actions also cascade through the hydrologic system. Flow charts help to link data decisions temporally across the stakeholder and user system. This provides a holistic perspective of how drought management actions affect water availability for multiple user groups. Furthermore, this exercise elucidates geographically where hydrologic data hold importance to each stakeholder.

The prioritization pyramids and trade-off decks compelled interviewees to rank drought-related hydrologic data and discuss value and limitations of each dataset. During these rankings, stakeholders

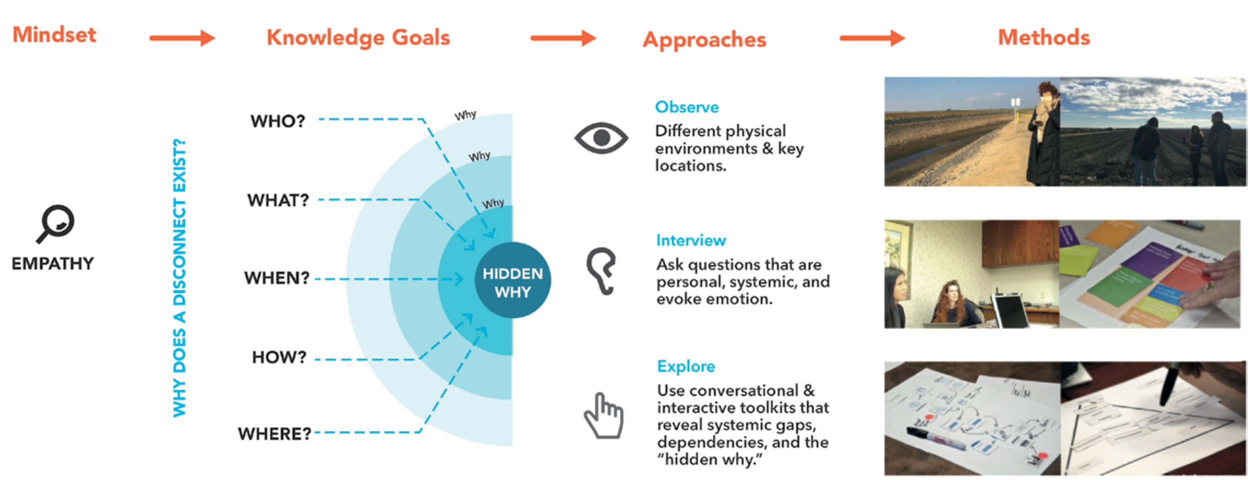

Fig. 4. Aligning design thinking tools and mindset to address knowledge goals of user interactions.

and user groups revealed certain information is more valuable during specific times of the year and how combinations of indicators are valuable to support decision-making. For example, farmers only require evapotranspiration and soil moisture data between planting and harvesting. During this period, evapotranspiration data, when used in conjunction with soil moisture and precipitation data, at the appropriate spatial scales can aid active management decisions related to cultivation including when and how much to irrigate (Fisher et al. 2017). Trade-off decks encouraged stakeholders to share what attributes make drought indicators valuable. Asking stakeholders to choose between cards of different indicator sources reveals how they perceive the value of ground observations, model estimates, and satellite datasets. This type of interaction allows conversations to touch on topics not covered by traditional surveys including why data attributes are valuable to specific decisions throughout the year and why certain cultural biases exist. Through these tools and interactions our team gathered the information necessary to distinguish different stakeholder group's needs and identify opportunities to improve drought and hydrologic data delivery to support water management.

Defining opportunity. During the "define" stage of design thinking, designers analyze and synthesize research from the previous stages in order to reframe and craft a meaningful human-centered problem statement. For drought indicators, this could be that *stakeholders need to use drought indicators to support short-term and long-term planning, assist decision-making, and mitigate the adverse ecological and economic effects of drought.*

Analyzing the information from interviews, generative tools, and site visits, designers collaborate with scientists to formulate new requirements and guiding principles. These steps provide a guide to address current deficiencies of drought indicators and improve their visual interface and experience design. The initial steps of this process include aggregating key takeaways from the interviews and interactions. One of the key synthesizing techniques is consolidating the insights from the research into contextual data journey maps that visually highlights the type and amount of drought data desired at certain points of the year. This practice of fusing qualitative insights into quantitative requirements has roots in market research where designers look to understand the human connection to a process (Dichter 1947). Clustering findings according to the identified themes and patterns is another technique used to organize the findings. Here, multiple insights are distilled into common threads that connect distinct stakeholders based on similar needs, such as farmers, local water managers, and state and federal water agencies. Our analysis of these qualitative insights reveals new data requirements from hydrologic models and observations and also uncovers new visual and experiential opportunities to improve drought information conveyance. The analysis is further refined by asking key questions related to stakeholder groups, including what drought indicators matter, what attributes make them useful, when are they needed, and how can the end-user interaction and experience be improved?

What drought indicators matter? Drought data requirements vary for each stakeholder (Fig. 5). Understanding what types of data are useful can lead toward consistent, reliable drought indicator data sources for decisions support (Table 1). Higher-level management, such as federal and state agencies (e.g., U.S. Bureau of Reclamation, California Department of Water Resources) may operate dams and pumping stations along water conveyance projects and, most importantly, determine surface water allocations in many states. Current water levels in reservoirs, the snowpack and soil moisture in reservoir drainage basins, and projected precipitation provide valuable information to support stakeholders' responsibilities. Many of these agencies rely on customized tools made by internal scientists and engineers to assist this process. Unfortunately, these tools are often private or may be removed from the local needs of irrigation districts, farm advisors, and farmers where water is managed at much smaller spatial scales.

Irrigation district managers combine information on grower demands and changes in allocations to decide when to fulfill deliveries to their farming customer contracts. On-farm decisions are supported by indicators that track changes of evapotranspiration, vegetation status, and soil moisture. These data can help farmers identify problem spots within their fields and determine when and how much to irrigate. Farm advisors and farmers rely on up-system information about water allocation to aid long-term decisions such as planning which crops to grow. While differences in data requirements are apparent from federal and state agencies compared with farmers, drought information supporting higher governance agencies has inherent value for planning and management at lower levels (Fig. 5). On top of the differences in hydrologic data needs for each stakeholder group, certain attributes distinguish the value of each indicator.

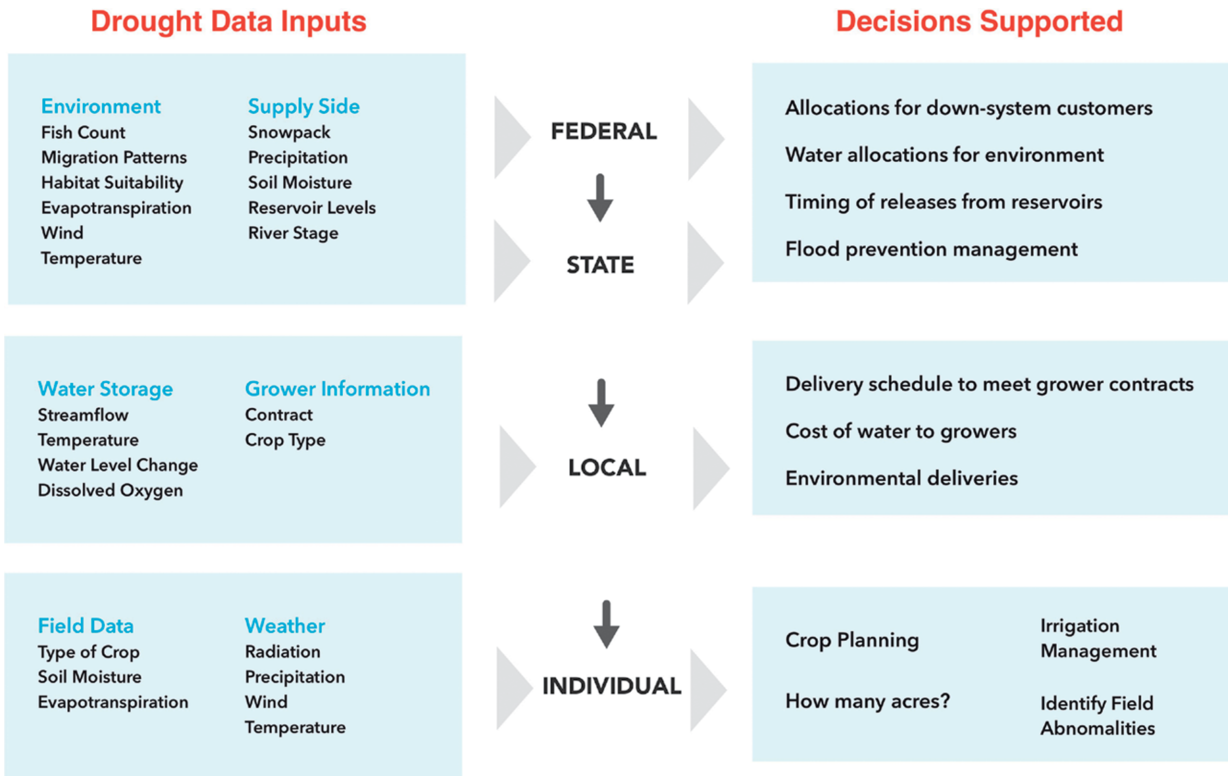

Fig. 5. Data dependencies for agencies in the hydrologic system. Inputs show opportunities to provide newly designed drought indicators that can impact various levels of water management.

What drought indicator attributes make them useful? An indicator's level of importance is different with each different user within a hydrologic system. Higher-level water management typically prefer datasets to be aggregated to spatial and temporal scales relevant to the decisions that they make. For example, both state and federal agencies who manage reservoir operations prefer timely data already aggregated or subset to basin and watershed scales. Additionally, managers prefer near-real-time updates on snowpack, soil moisture, and precipitation. These qualities are important to most accurately model the reservoirs that feed mountain runoff. Many agencies already customize hydrologic models to ingest near-real-time observations and trust these data because they are creating it themselves. However, these agencies are generally concerned about particular geographic areas such as watersheds that feed into the reservoirs under their management. Therefore, many of these tools are not directly applicable to support the affected down-system stakeholders whose water might come from multiple reservoirs. Irrigation district managers also benefit from spatially and temporally aggregated data sources to support planning water deliveries to meet customer requests. Farmers, on the other hand, almost universally prefer spatially explicit data at subfield scales to identify abnormalities. Near-real-time data at these fine spatial resolutions provide farmers the opportunity to mitigate potential loss in yield. Common across all stakeholders is a desire for highly accurate data during times when hydrologic data can support their activities.

When and where do drought indicators matter? Systems-thinking strategies facilitate a mapping out of when stakeholders make decisions, the interdependencies across different agencies, and where these behaviors take place. Water management decisions often align to local climate and seasonality in water availability and demand. As drought progresses across each component of the hydrologic cycle—precipitation/snow → soil water storage/snowpack → runoff → reservoir water storage → water delivery → summer crop/ecosystem consumptive water use/evapotranspiration—information on the state of each component has value for different stakeholders at distinct times of the year. Supply-side indicators (precipitation, snowpack, water storage) are particularly useful to support decisions during times of water supply, while demand-side indicators (e.g., environmental flows, evapotranspiration) are more important during the active growing season and dry seasons (Fig. 6).

Table 1. Drought indicator attribute requirements across multiple levels of governance across supply- and demand-side indicators. NRT is near–real time.

	Variable	Agency	Spatial resolution	Frequency	When	Latency
Supply-side indicators	Snow	Federal	Watershed (tens of km^2)	Daily to weekly	Winter/spring	Days/weeks
		State				
	Precipitation	Federal	Watershed	Daily	All year	NRT
		State				
		Irrigation district	Basin (tens of km^2)	Daily	Summer	NRT
		Farmer	Field (<1 km^2)	Hourly to daily	Irrigation	NRT
	Streamflow	Federal	Discrete	Hourly to daily	All year	NRT
		State				NRT
		Irrigation district	Discrete	Hourly to daily	Summer	NRT
	Reservoir	Federal	Discrete	Daily	All year	NRT
		State				
	Groundwater	State	Basin	Monthly	All year	Monthly
		Farmer		Monthly	All year	Monthly
Demand-side indicators	Evapotranspiration	Federal	Watershed/basin scale	Monthly	All year	Days/weeks
		State				
		Irrigation district	Multifield	Daily	Irrigation	Daily
		Farmer	Field	Daily	Irrigation	NRT
	Temperature	Federal	Watershed	Daily	All year	NRT
		State				
		Farmer	Field	Daily	Irrigation	NRT
	River flow and temperature	Federal	Discrete	Hourly to daily	All year	NRT
		State				
		Irrigation district	Discrete	Hourly to daily	Summer	NRT

Supply-side indicators are important at higher levels of governance to inform decisions such as setting surface water allocations throughout a region. These indicators hold potential value for longer-term planning decisions, as they reflect water availability in the system. In mountain-sourced water regions, snowpack and reservoir levels dictate spring and summertime water deliveries to irrigation districts and growers. To inform their decision, higher-level agencies ask how much water will be available later in the year. Integrated indicators of precipitation, snow water equivalent, hillslope soil moisture storage, and runoff can support surface water allocation decisions. Unfortunately for farmers, often times decisions about cropping schedules have to be made prior to the water allocations being set. Since down-system stakeholders are dependent on the decisions of higher-level management, knowing what indicators are being used could support long-term planning. Probabilistic indicators accounting for precipitation, winter snowpack, and reservoir storage may serve as a useful tool to support both stakeholders. These examples primarily focus on winter-dominant precipitation such as the western United States, but the timing of data requirements remain geographically consistent. In regions sustained by rain-fed agriculture, farmers are simultaneously dependent on both supply-side and demand-side indicators during warmer months.

During the spring and summer seasons, demand-side indicators hold more value for down-system water management decisions. Evapotranspiration and weather datasets can provide irrigation district managers with an idea of when and how much water farmers require. For farmers, the most data-dependent time is during irrigation. During this window,

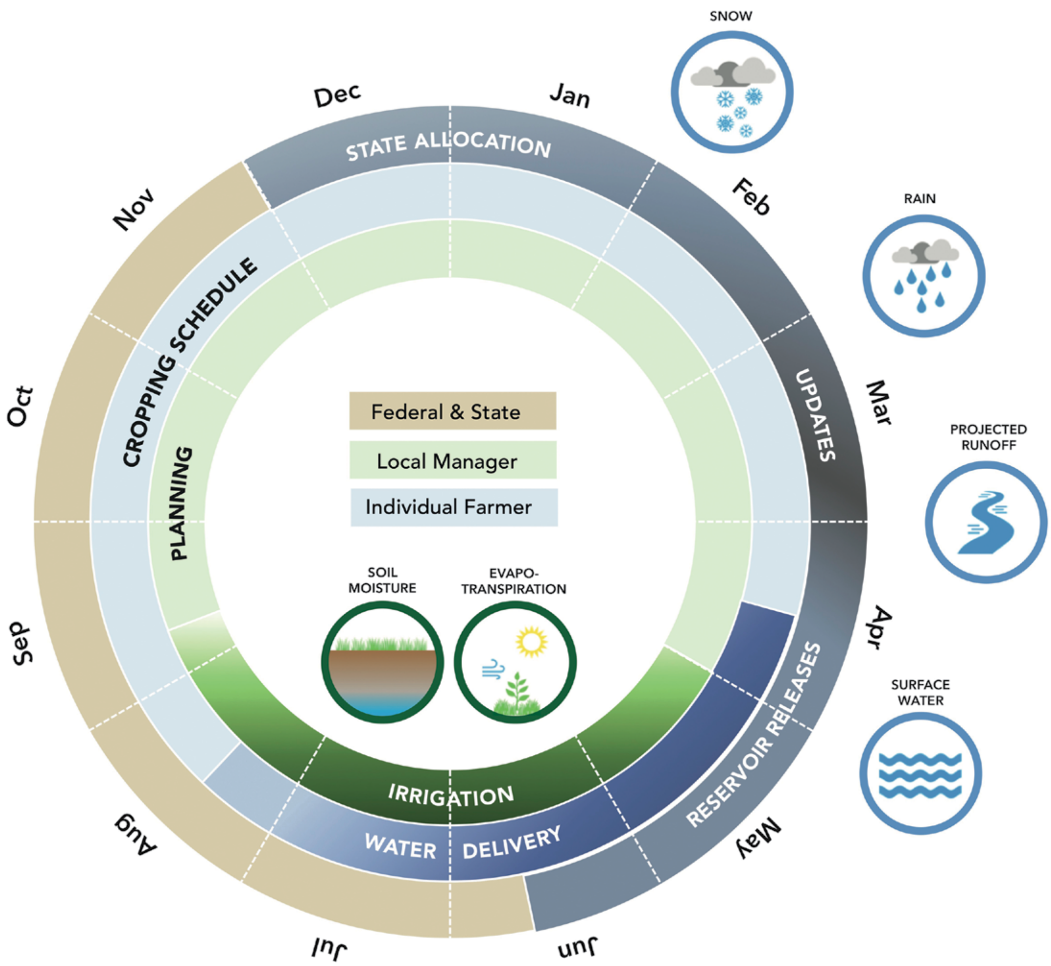

Fig. 6. A layered multi-stakeholder timeline can visually indicate the time-dependent interconnected dependencies across levels of governance. Outer rings are higher system actors, while inner rings are down-system stakeholders. Color and intensity depict when data are most useful for each stakeholder group.

observations of soil moisture, evapotranspiration, and precipitation can greatly support farm decisions. Figure 6 depicts when data are most useful for each stakeholder group across the calendar year. End-of-growing-season indicators reveal the effects of drought across the hydrologic system and support longer-term planning. Indicators such as water use and water supply at aggregate temporal scales facilitate evaluating how the ecological and economic impacts from drought are geographically distributed. These indicators support disaster relief efforts by states and farmers through determining the eligibility for insurance claims. End-of season indicators also have potential to expose areas of groundwater overreliance. Overall, the actual value of each drought indicator for a stakeholder depends on the time of year and the decisions that they face (Fig. 6). Improving the availability and timing of data delivery can help to improve the user experience.

How can the end-user interaction and experience be improved? Beyond uncovering the relevant data and attributes for each stakeholder group, design thinking creates more usable indicators by considering the context in which stakeholders use them. Data requirements driven by a human-centered design approach deliver the necessary content, but how end users interface with and experience drought indicators determines the magnitude of their impact. The methods of human-centered design move beyond solely aesthetic considerations such as pretty color bars and elegant fonts. Instead, understanding core user demands drive the ways in which designers formulate technical requirements to address current gaps in service. In addition to the opportunity to improve end-user interaction, there is also a way to enhance the overall end-user experience by improving the system in which stakeholders use, customize, and collaborate with indicators. In general, all types of stakeholders want simplified access to drought

Table 2. A design traceability matrix aligns design features with opportunities to meet drought data user needs.

Need	Stakeholder	Design features	Indicators
Compare current year's precipitation or snowpack to similarly dry or wet recent years	Individual farmer Local manager	Incorporate time series of current year's cumulative precipitation and snowpack with similar dry or wet years and the average year	precipitation snowpack
Identify intrafield abnormalities to target management actions and mitigation	Individual farmer	Link temporal anomalies of soil moisture and vegetation indices to a map of high-contrast easily identifiable hot spots	soil moisture vegetation indices
Know when and how much water to irrigate crops	Individual farmer	Link satellite-modeled evapotranspiration and soil moisture data to "ideal" crop-specific evapotranspiration; move design beyond time series to deliver information through a calendar	evapotranspiration soil moisture precipitation weather forecasts
Find all relevant indicators for "me" in one place	Federal and state Local manager Grower	Provide system indicators based on hydrologic connectivity (natural and managed); incorporate geographically relevant areas with interactive "clickable" options to access more specific information	all indicators
Simplified access to indicator data relevant for decision-making	Federal and state Local manager Grower	Use simple, clean, visual cues to minimize clutter when displaying information; include automated geolocation to minimize navigation steps	all indicators

indicators and want their drought data visual experience to be quickly interpretable. Farmers and growers want very specific transformations or information extraction from data, such as the current year's data compared to similar years, a tool for guiding the amount to irrigate, and the ability to link temporal anomalies to "hot spots" within their fields.

Designers use specific technical functionalities of perception and visualization to prioritize and deliver key user experience features that address user needs (Table 2). For example, in order to improve drought indicator interfaces, we focus on combatting user pains related to drought information and data overloads by simplifying the way drought data are visualized and accessed. To maintain simplicity, drought indicators should only display data relevant to each stakeholder. Adaptable indicator designs might include the ability for an individual user to input a set of requirements that results in a tailored indicator aligned exactly to their needs. However, some of these inputs, such as identifying the hydrologically relevant regions, can be automated by geolocating the user's IP address or smart phone location to enhance the user experience. Other design features including shading the background for areas outside of a stakeholder's region of interest draw in the user's focus to the relevant region.

For farmers, drought indicators should include indicator features that link time series, which distinguish when drought conditions take hold, to maps, which point to where droughts are potentially affecting yields. Additionally, farmers want to see how the current year's precipitation compares to similar years historically. This information can be easily extracted from datasets and presented in visually compelling and relevant forms to provide context for decision-making. Last, designers can increase the value of indicators by presenting systems of hydrologically interconnected indicators relevant to each stakeholder. Combined together, the technical and design requirements provide a framework to develop new indicators adept at fulfilling unique, but interconnected, stakeholder needs across the hydrologic system.

The steps of the design thinking process of understanding, empathizing, defining, and analyzing produce a new set of criteria to ideate, prototype, and test the new drought indicators. These parameters include only providing relevant indicators with the appropriate attributes (spatial, temporal, data sources) at the relevant times and simplifying the visual interface form in order to contextually enhance the user experience. These criteria, driven by stakeholder needs, serve as guiding principles for the development of new drought indicators.

Iteration through ideation, prototyping, and testing. Ideation, prototyping, and testing balance pushing the boundaries of innovative solutions with adhering to technological capabilities. Through a highly iterative process, designers develop a range of low-fidelity maps, graphs, and tables that portray potential drought indicators (Fig. 7). During these stages the design team negotiates the newly defined drought indicator parameters and user needs with data availability. Within the ideation

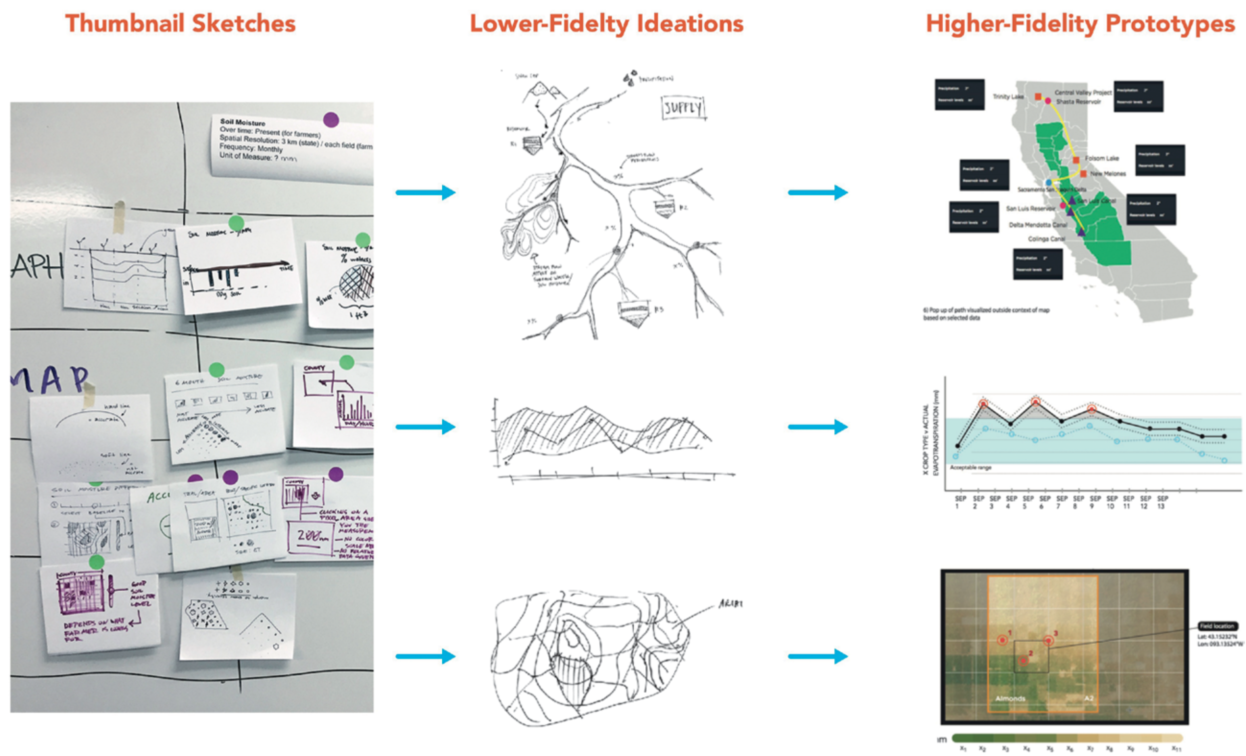

Fig. 7. The methods of design incorporate low-fidelity thumbnail sketches and ideation before advancing to higher-fidelity digitized prototypes. These steps make time for "out of the box" ideas and expand solution space. The evolution to digitized versions undergo user testing and evaluation.

phase, time is dedicated to expanding the solution space of the problem by generating as many ideas as possible with the given context. To be inclusive of extraordinary ideas, concepts were not constrained by criteria at this particular step. In this activity, called divergent thinking, the quantity of ideas takes precedence over quality of one idea. After ideas are exhausted, designers group and prioritize concepts based off the aforementioned criteria and guiding principles. Whiteboard sketches acted as quick first-pass iterations of potential drought indicator interfaces. Frequent communication between designers and scientists provide immediate avenues to check the feasibility of each prototype based on the availability of certain datasets and the capability of digital drought indicator distribution frameworks.

Prototyping and testing is a cyclic process embedded within design thinking after the iteration phase. Scoped down ideas feed into the first pass of prototyping and testing in which designers work with collaborators, stakeholders, and end users to solicit feedback. This direct feedback mechanism allows designers to gain new empathetic insights into the user interactions and informs the next pass of prototyping until the solution inhibits all old and new criteria.

Low-fidelity prototypes are digitized into higher fidelity. The first stage of prototypes are created to provoke collaboration between scientists and designers. In design thinking, low-fidelity prototypes elicit noncommittal creative behaviors that allow empathetic openness to feedback. Higher-fidelity concepts are created as a means to provoke conversations with end users within the testing phase. Figure 7 showcases how ideations transition to low-fidelity sketches and then evolve to higher-fidelity digitized prototypes. End users provide new feedback that might not have been captured during the previous stages of drought indicator development. Multiple iterations informed by feedback lead to new and refined drought indicators better aligned with stakeholder requirements.

CONCLUSIONS. The methods of design thinking provide a new and complimentary approach to advance drought and climate data communication, and support management decisions. Previous research into drought indicator design has existed at two extreme ends of user engagement: no end-user involvement or targeted coproduction. These extremes generate data products that are ill suited for general water management needs or very customized for a narrow user group. By investing time to understand the problems and empathize with users in the water management system, the stages of design thinking provide designers and scientists the necessary context to the development of more usable drought indicators for multiple user groups. These steps help overcome culturally ingrained biases of stakeholders to broaden the impact of climate and drought data (Janetos and Kenney 2015). While many of these insights—such as providing drought data users with data they directly require, when they specifically need it, and in a form that is easy to access and easy to understand—may seem obvious, the design thinking methodology and approach provides a robust framework to create new, more efficient drought indicators.

Leveraging strengths of multidisciplinary collaborations is important to move drought, weather, and climate applications forward. Scientists are trained experts in doing science, but not product design. As scientists are increasingly called upon to support societal applications, collaboration with product designers can extend the influence of their valuable data. The process of design thinking can transition useful drought indicators into a system of useable drought indicators better suited to fulfill varying stakeholder needs within complex sociopolitical, climate-dependent hydrologic systems. While this approach is helpful, a stakeholder still must actually use the new drought indicator (Lemos et al. 2012). Water, ecosystem, and resource managers perceive using new data as risky (Osgood et al. 2018; Rayner et al. 2005). Furthermore, sometimes other factors constrain the application of new data sources or prevent application of certain datasets or data sharing, such as internal organizational policy (Dilling et al. 2015).

The design thinking process mitigates stakeholders' potential perception biases through empathy and collaboration on drought indicator design. This process helps identify gaps where current data availability is insufficient and forms parameters to shape new drought indicators that address user demand. Stakeholder involvement through interviews, generative tools, and design feedback makes this a friendly, transparent, and participatory process where stakeholders can cocreate with designers by refining prototypes into more useable and effective indicators (Norton et al. 2012). Maintaining long-term relationships across ethnographic space can enhance the value of indicators as stakeholder become invested in their development (Norton et al. 2012). Widespread buy-in takes time, but working with and listening to end users will only improve drought indicator usefulness (Meadow et al. 2015). Last, challenges remain to appropriately quantify the benefits of end-user engagement (Wall et al. 2017). Building from quantifiable strengths and limitations of this process will only further refine interaction techniques to increase end-user buy-in and develop better drought indicators.

KEY TAKEAWAYS FOR THE SCIENTIST.

- The methods of design thinking have the potential to deliver key insights on technical and design requirements and to uncover new opportunities to shape more applicable drought indicators.
- Leveraging expertise from design can complement existing strengths in science to elevate the potential of scientific datasets to support stakeholders by breaking through barriers of ingrained cultural biases.
- Context matters—dedicate time to discern nuances in stakeholder needs.
- Applied sciences projects that leverage the strength of multidisciplinary teams and prioritize end-user interaction can increase user willingness to use new data sources.

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