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HOW MANAGERS APPLY WEATHER AND CLIMATE INFORMATION FOR DECISION-MAKING IN THE UNITED STATES

A THESIS APPROVED FOR THE DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL SUSTAINABILITY

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Abstract

As the climate continues to warm, precipitation events are projected to become more intense, leaving communities to prepare for potential increases in flooding. There is currently a wealth of weather and climate information available that practitioners can use to make decisions for their jurisdictions; however, this information can be hard to access, understand, and incorporate into standard operating procedures. To document the barriers to transitioning research into operations, the Prediction of Rainfall Extremes at Sub-seasonal to Seasonal Periods (PRES^{2}iP) project team established connections with different groups of natural resource managers from across the United States to understand how they think about and plan for heavy precipitation events. Through a stakeholder engagement workshop and conducting semi-structured interviews, the author of this thesis examines how practitioners use weather and climate information in their positions, additional factors that influence decision-making, and what weather or climate information practitioners wish they had when making decisions. Practitioners are more likely to be familiar with short-term weather forecasts than long-term climate predictions or projections, but they are willing to learn how to interpret and apply information for long-term planning. Additionally, other factors besides weather and climate information, such as budget constraints or the power of county officials, shape how practitioners make decisions. Overall, decision-making across timescales is a complex process where managers rely on multiple types of information.

Chapter 1: Introduction

As the climate continues to warm, precipitation events in the south-central United States are projected to become less frequent but more intense, meaning more precipitation will fall in shorter time periods (e.g., Kloesel et al. 2018; Brown et al. 2020a, Brown et al. 2020h). In cities and counties with aging infrastructure and reduced capacity to handle the problems climate change will bring, an increase in precipitation could push stormwater and floodplain management systems to the edge. It may damage roads and bridges, especially if this infrastructure is not designed to handle higher amounts of precipitation. Additionally, neighborhoods and parts of communities that do not experience frequent flooding may start having challenges with routine flooding. This increase in precipitation and flooding is expected to lead cities and counties to search for solutions, such as preparing resources ahead of a predicted flooding event or assisting residents with moving out of floodplains.

Outside of population centers, climate change and its impacts also are expected to cause issues for natural resource managers, such as those overseeing forests, fisheries, or water resources. For example, ecologists or biologists may have to manage water quantity and quality to ensure fish populations are able to survive (Callahan et al. 1999). An increase or decrease in precipitation amounts may affect how productive forests are, as could warmer temperatures (Janowiak et al. 2014). Water managers may have to deal with issues related to both supply and quality for their jurisdictions. Floodplain managers, who oversee development in their communities related to new buildings or infrastructure, are expected to have new challenges with stormwater or wastewater management (Association of State Floodplain Managers 2010).

There also are other types of practitioners who make decisions that are influenced by precipitation events, including emergency managers and tribal environmental professionals.

These practitioners can work in local, county, state, or tribal jurisdictions, and their communities may be impacted by increased precipitation in multiple ways. For example, emergency managers prepare their communities for all types of extreme hazards and manage response when an event occurs. Specifically related to flooding, they help coordinate emergency response to flash flooding in their community. Tribal environmental professionals can have a variety of responsibilities, including monitoring and managing water quality or supply, preserving riparian ecosystems for cultural practices, and stocking fish or other aquatic species for food and sport. While these are not the only practitioners that are impacted by heavy precipitation events, they represent some decision-makers who will have to deal with the repercussions of an increase in precipitation events. To make these decisions, practitioners may be able to apply weather or climate prediction information in their jurisdictions.

There already is a wealth of weather and climate information available to practitioners that can be used to plan for and respond to heavy precipitation events. When an event is ongoing, practitioners can use observations such as those from the Oklahoma Mesonet (McPherson et al. 2007), radar, and satellite to determine where precipitation may be occurring in their area. Using data from these sources and others (e.g., radiosondes flown by weather balloons), numerical models can produce different types of forecasts a few days before an event. For example, local National Weather Service offices provide forecasts for their jurisdictions that contain information about expected precipitation. NOAA's Weather Prediction Center produces quantitative precipitation forecasts for the entire country for one- to seven-day lead times. Beyond that, NOAA's Climate Prediction Center produces more qualitative precipitation outlooks for up to 12.5 months ahead of time. These outlooks provide probabilities of whether precipitation amounts will be above or below normal for different portions of the country. Lastly, looking farther into the future, different organizations produce climate projections, based on scenarios of possible future emissions, land cover, and societal conditions.

Some of this available information is used by decision-makers to prepare for precipitation events on shorter timescales, including current observations and weather forecasts. Given that these practitioner decisions influence emergency response, water availability, or future development in flood-prone areas, it is paramount that the atmospheric science community understand what information is most useful and informative for practitioners. For instance, some posit that with climate change projected to cause an increase in the intensity of precipitation events, practitioners will benefit from long-term predictions they can use to better prepare their communities for the impact of more precipitation (e.g., Butler et al. 2020).

Some decision-making frameworks emphasize the importance of place-based adaptation to help communities prepare for future climates (e.g., Cutter et al. 2008; Groulx et al. 2014; Pascua et al. 2017). This type of adaptation explains how managers can start thinking about climate change adaptation strategies that best match local conditions and identify solutions that would best suit their jurisdictions under the most likely future climate scenarios (Cross et al. 2012, 2013). These frameworks have already been applied in some scenarios (e.g., Murphy et al. 2017; Swapan and Sadeque 2021; Kamelamela et al. 2022; Shapira 2022), resulting in adaptation strategies that reflect community priorities, therefore making them more likely to be accepted and implemented successfully. Other research has focused on the importance of flexibility in managing adaptation and long-term planning (Janowiak et al. 2014), resulting in an adaptation framework that can accommodate diverse management goals and spatial scales. There are many strategies available to decision-makers when it comes to adapting to climate events, as long as they have access to climate information that they can understand and interpret for their jurisdictions.

However, just because a certain forecast exists does not mean it is useful to a practitioner. The information may be difficult to understand or apply at the local level, or it may be too challenging to adjust existing decision-making procedures within a jurisdiction (Bruno Soares and Dessai 2016). Practitioners also may not know what or how to access forecasts and other information that could help guide their decisions (e.g. Bolson et al. 2013; Bruno Soares and Dessai 2016), such as restricting development in areas projected to become more flood prone or designing new infrastructure to handle more intense rainfall events in the future. One approach to creating useable scientific products is to work with communities of practitioners to co-produce knowledge together (e.g., Lemos et al. 2012; Kirchoff et al. 2013; Howarth and Monasterolo 2017). Co-production occurs when scientists work with practitioners in interactive, goal-oriented relationships that recognize multiple ways of knowing to produce and develop new knowledge or methods for communicating (Norström et al. 2020a). By working with end users, forecasts are often easier to understand and filled with less scientific jargon. Practitioners are also more likely to trust co-produced products and implement them into their decision-making processes (e.g., Cash et al. 2003; Meadow et al. 2015).

However, despite opportunities to produce knowledge collaboratively, many meteorological and climatological forecast products are still inaccessible and out of touch with the decision-making processes of practitioners (e.g., Pagano et al. 2001; Taylor et al. 2015). My thesis research was designed both to engage in co-produced knowledge with natural resource managers and to interview floodplain managers about how they currently use weather and climate products. By listening to professionals, the atmospheric science community can learn what types of information they need for decision-making as an effort to bridge gaps between practitioners and scientists.

Ongoing research projects are attempting to better understand heavy precipitation events and how they can be better predicted, especially with longer lead times. For example, the Prediction of Rainfall Extremes at Sub-seasonal to Seasonal Periods (PRES^{2}iP) project, hosted at the University of Oklahoma, studies four main research questions: (1) What are the typical atmospheric patterns associated with sub-seasonal to seasonal heavy precipitation events in the United States?; (2) Does large-scale climate variability influence heavy precipitation events and, if so, how?; (3) How predictable are subseasonal-to-seasonal heavy precipitation events?; and (4) How can we create useful predictions of heavy precipitation events for practitioners? Throughout the project, the research team, which includes this thesis author, has engaged with three of the practitioner groups described earlier — water managers, emergency managers, and tribal environmental professionals — to understand how they prepare for heavy precipitation events and to inform development of educational and forecast products about these events.

To understand how these practitioners make decisions about heavy precipitation events, the PRES^{2}iP team planned three workshops. The first workshop was held in July 2018 in Norman, Oklahoma. The workshop consisted of four sessions and an interactive panel about Hurricane Harvey. Activities at this workshop included the following: (1) a discussion on how each participant defined extreme precipitation, (2) development of decision trees for decisions that participants would make related to extreme precipitation, (3) small group discussions on uncertainty associated with forecasts, and (4) an interactive role-playing activity where participants used existing forecast products to make decisions about a fictitious event. This workshop helped the PRES^{2}iP team refine research goals and confirmed that practitioners deal with a variety of impacts related to extreme precipitation and those who had attended the workshop were willing to learn about sub-seasonal to seasonal forecasts. However, it is possible these results are due to selection bias where practitioners uninterested in extended forecasts declined invitations to participate and the desires of the practitioners at the first workshop are not representative of all practitioners.

As part of my research assistantship, I helped plan and host the second PRES^{2}iP workshop, which was held virtually in October 2021. Many of the participants from the first workshop returned, though some new participants also joined. Building on what the PRES^{2}iP team learned in the first workshop, activities included a discussion on what forecast products participants currently use, an interactive session where participants had an opportunity to provide feedback on newly developed educational tools, and a discussion on uncertainty associated with sub-seasonal forecasts. When participants were explaining the types of forecast products they use to make decisions, it became clear that many of them were not planning far into the future; instead, they focused on short-term events and impacts they might experience in the next few days. Additionally, most of these practitioners did not incorporate seasonal forecasts or climate projections into their decision-making but wanted to learn how these long-term predictions could help them better manage water, emergency response, or tribal resources.

Although I was not present for the first workshop, I summarized the detailed session notes and agendas and served as lead author for a manuscript (Chapter 3) about the major findings. In doing this, I learned about existing challenges that practitioners face related to heavy precipitation events. Writing this manuscript and planning the second workshop led me to question how other practitioners might deal with heavy precipitation events, and if they would be more likely to use sub-seasonal forecasts in their jobs. Because of their unique position of regulating floodplains and the impacts that communities were likely to face as heavy precipitation events become more common, I chose to focus on the information usage by floodplain managers for the next step of my research. Through this research, my goal was to learn how a different group of practitioners uses weather and climate information to make decisions so I could inform the PRES^{2}iP team about new potential uses for their tools. Additionally, while prior research has focused on how other natural resource managers are addressing climate change impacts in their jurisdictions (Cross et al. 2012, 2013; Groulx et al. 2014; Janowiak et al. 2014), little research has focused exclusively on floodplain managers. Because they are responsible for overseeing future development and infrastructure, floodplain managers are acutely susceptible to the impacts of increased precipitation in their communities.

To investigate what weather and climate information floodplain managers use, I conducted interviews with managers across the state of Oklahoma. Because of the large, west-east precipitation gradient across Oklahoma, I was interested to determine if floodplain managers from different parts of the state used information differently. I was also curious to learn how floodplain managers make decisions and what information influences their decision-making process. Using the Protective Action Decision Model, developed by Lindell and Perry (2012), and knowledge from the first two PRES^{2}iP workshops, I wrote interview questions and completed interviews with floodplain managers across the state. In the process, I learned how floodplain managers use weather and climate information, barriers that constrain their decisions, and new types of information they wish were available.

This thesis describes challenges practitioners face related to heavy precipitation events, based on knowledge that I gained from workshops, interviews, and data analysis. Chapter 2 summarizes literature relevant to how water managers use weather and climate information.

Chapter 3 outlines the first PRES^{2}iP workshop and major findings. Chapter 4 describes the interviews with floodplain managers and results of those interviews. Chapter 5 contains key findings and recommendations for the weather and climate community moving forward related to producing useful forecast information.

Chapter 2: Literature Review

Heavy precipitation events and associated flooding cause substantial impacts to society annually. Each year, extreme precipitation events cause billions of dollars in damages, and impacts are felt in multiple sectors (White et al. 2017). These impacts affect transportation, with damage to roads and other infrastructure or delays in travel (Suarez et al. 2005). The economy also suffers during extreme precipitation and flooding events, particularly because of the costs associated with damages and business disruption (e.g., Kousky 2014; Allaire 2018). Food and water supplies can be impacted when growers cannot harvest or access their crops or if water becomes contaminated and unsafe to drink (Rosenzweig et al. 2002). Diseases are easily spread in the aftermath of a flood, and heavy precipitation events also often lead to loss of life (Ashley and Ashley 2008). As the climate warms, precipitation events are likely to become more intense, leading to larger extremes between sometimes longer dry periods around the globe, further exacerbating the impacts that are already felt by communities.

There are also multiple types of practitioners who deal with extreme precipitation and flooding, including water managers, emergency managers, or floodplain administrators. Floodplain administrators are particularly in tune with flooding because they are often responsible for overseeing community development within floodplains and managing who is allowed to build in given areas (Association of State Floodplain Managers 2010). Floodplain administrators also may coordinate and oversee public works projects in their jurisdictions to reduce flood risk and build resilience to future floods (Woodward et al. 2011; Tyler et al. 2019). However, given advance notice of possible heavy precipitation events, floodplain administrators can better prepare their resources and plan projects around potential impacts. By working with these decision-makers to develop new forecast tools and products, the weather and climate community can better support floodplain management and administration.

Section 2.1. Defining Different Timescales

Within meteorology and climatology, scientists often use a spectrum of timescales to conduct their research and operations. Figure 1 displays the typical timescales used in atmospheric-related sciences. For operations, these timescales range from forecasting the next hour’s weather to analyzing potential future climate scenarios and their implications on different regions and sectors. Each timescale provides different information that can be used by decision-makers to prepare for possible impacts, although each type of forecast, prediction, or projection has varying levels of uncertainty and skill.

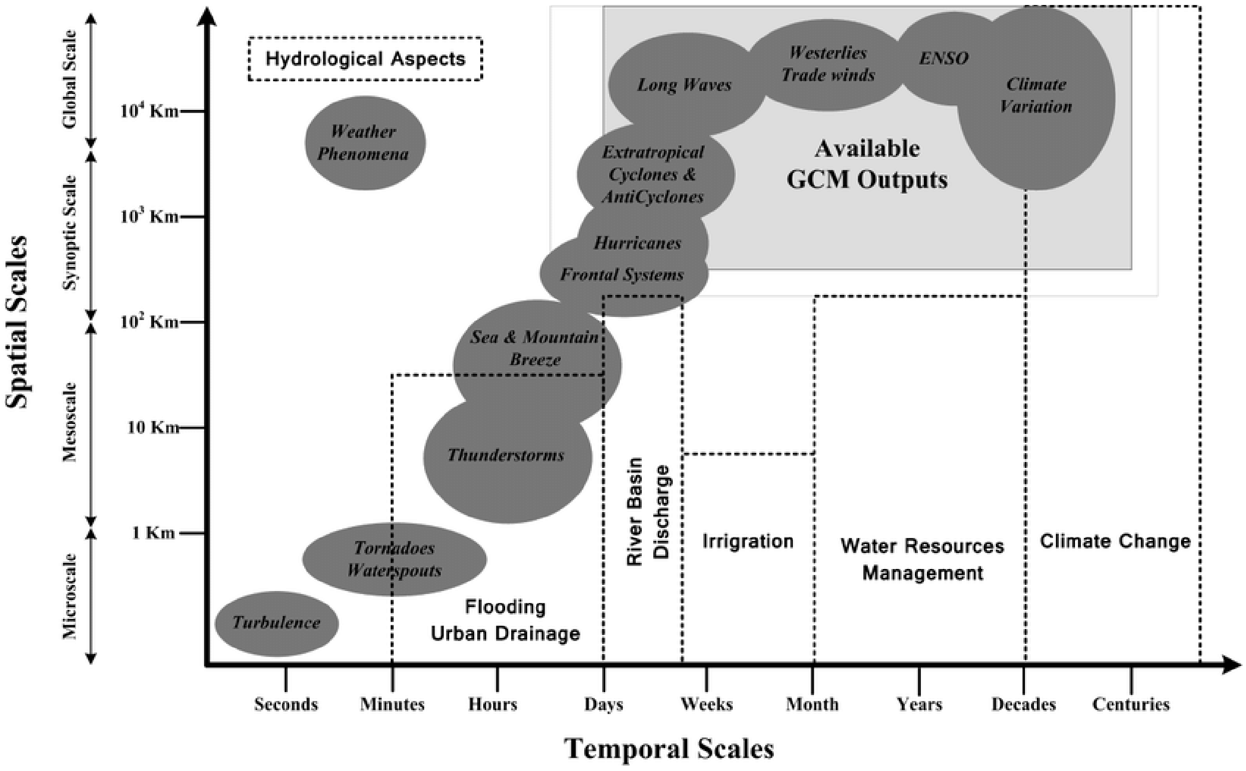

Figure 1: Common temporal and spatial timescales used in the atmospheric sciences (from Tavakolifar et al. 2017). GCM = global climate model or global circulation model. As the

temporal and spatial scales increase, predictions and projections cover larger areas and are less able to predict specific atmospheric phenomena. Instead, predictions and projections provide an idea of what future conditions in a broad region may be like, and these predictions can be used for long-term planning. At shorter temporal scales and smaller spatial scales, individual phenomena like a single thunderstorm can be predicted.

Short-range weather forecasts are generally considered to be any forecast with a lead time of fewer than 10 days (e.g., Agudao and Burt 2013; Hoskins 2013). These products are produced by national meteorological centers, like the U.S. National Weather Service. Mathematically, these types of forecasts are initial-value problems, relying heavily on the knowledge of current weather patterns to produce a reliable forecast. They forecast specific conditions for a localized area at a given time and are produced by a range of numerical weather prediction models. Short-range forecast output for users can contain information about precipitation amount and timing, temperature, winds, and cloud cover, often at each hour within a forecast window. Short-range forecasts are based on initial atmospheric conditions (produced by earlier runs of the model) and recent observations that initialize the numerical model; then they apply the laws of physics to predict conditions at some point in the future (Ehrendorfer 1997). Observations can include radar and satellite data and measurements from radiosonde balloon soundings, ocean buoys, or surface weather stations. Therefore, the accuracy of short-range forecasts relates to the quality of observations; if observations are of limited or poor quality, the forecast is less likely to accurately predict future conditions (Simmons 2015).

Weather forecasts have improved significantly over time, especially as supercomputing capabilities have increased and knowledge of the physical processes affecting the atmosphere has improved. However, because weather forecasts are based on initial conditions, there are fundamental physical limits to how much more they can improve unless observations become more accurate and have higher resolution in space and time (Slingo and Palmer 2011). Additionally, even if observations were everywhere around the world and perfect, there would still be imperfections in forecasts, due to non-linear interactions (Lorenz 1963). The key to short-range weather prediction from a single model run is that the user is given output for a specific time and location — a deterministic forecast. In some cases, multiple runs of the same model or different models are combined in an ensemble, which produces a probabilistic forecast that can give a range of possible forecast outcomes (Gneiting and Raferty 2005).

At a slightly longer timescale, sub-seasonal forecasts (also called predictions) provide information with a lead time between 10 days and 30 days. These products are produced by national meteorological or climatological centers, such as the U.S. Climate Prediction Center (CPC). The sub-seasonal timescale, sometimes called the extended range, is coming into wider use in some forecasting centers across the globe and has the potential to provide decision-makers with more time to prepare for impactful events. However, this timescale is difficult to predict because forecasts are influenced by multiple factors.

Like weather forecasts, the amount and quality of initial atmospheric conditions and boundary conditions such as sea-surface temperatures, soil moisture, and sea-ice levels (White et al. 2017) influence the quality of sub-seasonal predictions. On a broader scale, the predictability of sub-seasonal forecasts are also influenced by large-scale atmospheric circulations such as El Nino Southern Oscillation (ENSO), the Madden Julian Oscillation (MJO), or the North Atlantic Oscillation (NAO) (Vitart et al. 2012). Predictability on the sub-seasonal scale results from the evolution of these and other large-scale circulations, which are coupled to energy and moisture fluxes over ocean and land. Sub-seasonal forecasts provide different information than short-range forecasts too. Because of their extended nature and limitations on predictability, sub-seasonal forecasts often provide information about changes in the *probability* of certain events compared to climatology (Vitart and Robertson 2018); hence, they are probabilistic rather than deterministic. These forecasts do not provide specific timing of precipitation or how much accumulation a certain location will receive. Instead, they paint a broader picture and give an idea of average conditions over a region.

Seasonal forecasts usually predict 1-12 months in advance, are exclusively probabilistic, and are produced by national climatological centers, such as the CPC. Initial conditions for seasonal forecasts include information about land cover and the ocean, and large-scale atmospheric circulations, similar to sub-seasonal forecasts. However, at these longer timescales, the accuracy of atmospheric initial conditions is less important than for numerical weather prediction. Instead, models need to initialize with observations of slower-evolving components of the climate system, such as sea-surface temperatures and snow and sea-ice coverage, and include boundary conditions like coupled land-ocean or land-surface processes and changes in radiative forcing (Hansen 2002; Hurrell 2008; Hoskins 2013). The predictability of seasonal forecasts is driven both by internal variability from large-scale atmospheric oscillations and the forcings provided by boundary conditions such as terrain or incoming solar radiation. As probabilistic output created from multiple runs of the same model or from combining different models, these products communicate how likely it is that a given area will experience conditions that are different than its normal climate (e.g., “Over two-thirds of the model runs indicate that this winter will be cooler than normal”).

Section 2.2. Decision-Making with Weather and Climate Information

Decision-makers in communities, tribes, government agencies, organizations, or businesses can apply each type of forecast or prediction according to their decision needs. Using weather or climate information to inform decisions can help practitioners better prepare for different hazards, reducing costs and damages, as well as protecting lives (National Research Council 2006). In the academic community, how these practitioners use the information to make decisions is understood through various decision-making theories or conceptual models. (Note: These *conceptual* models are different from those *physically based* models in the previous section.)

Section 2.2.1. Protective Action Decision Model

One such model is the Protective Action Decision Model (PADM), developed by Lindell and Perry (2012) to understand how people receive, interpret, and act on risk communication messages. In their work, they define “risk” as the probability of being impacted by a given hazard. Risk communication is defined two separate ways, depending on the immediacy of the event that is the focus of the communication. For imminent events, risk communication is called a warning, which contains information about an expected extreme event and aims to produce an emergency response in recipients. In our context, warnings result from current observations (e.g., tornado sighting) or short-term forecasts (e.g., for an ice storm in the next several hours). For long-term forecasts and predictions, risk communication is called a hazard awareness program, and aims for recipients to adopt long-term hazard adjustments, such as raising their home so it floods less frequently or choosing to move out of the floodplain entirely.

Researchers have applied the PADM to decisions regarding multiple hazards, including hurricane evacuations (e.g., Goodie et al. 2019; Alawadi et al. 2020), tornado warning response (e.g., Ripberger et al. 2019; Miran et al. 2020; Sherman-Morris et al. 2020; Walters et al. 2020) , tsunamis (e.g., Buylova et al. 2020; Wargadalam et al. 2021), and wildfires (e.g.,McCaffrey et al. 2020; Kuligowski 2021; Santana et al. 2021). Although it has been applied to flash flooding (e.g., Companion and Chaiken 2017), little prior research has focused on applying the PADM to flooding-related hazards that occur more slowly over time, such as those occurring on the sub-seasonal to seasonal timescales.

Outlined in Figure 2, Lindell and Perry (2012) describe the PADM as being an iterative process that begins when environmental and social cues, as well as warnings, start the "pre-decisional processes." These pre-decisional processes inform a decision-maker's perception of risk from a given hazard, determine possible protective actions that could be taken, and identify stakeholders who will influence the decision whether or not to take protective action. These stakeholders can be authorities or media personnel, as well as scientists, forecasters, or even medical professionals. Once the pre-decisional processes have occurred, perceptions about risks and the best possible actions that are available to a decision-maker provide the foundation for protective action decision-making.

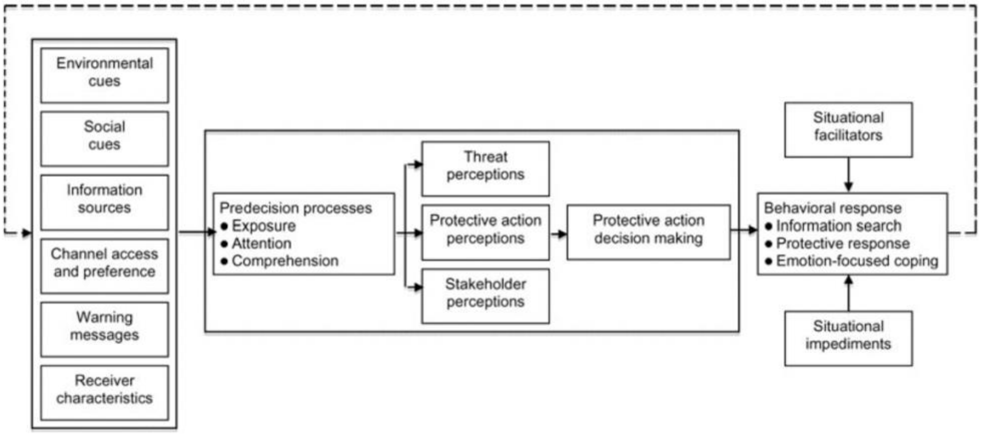

Figure 2: The Protective Action Decision Model (PADM), as outlined in (Lindell and Perry 2012). The left section describes environmental and social cues that initiate the PADM. The

center boxes are psychological processes someone goes through to assess their level of risk to a given hazard and determine which action they should take to protect themselves. The right section describes responses to the risk assessment, such as seeking more information or heeding a warning message. The sequence repeats iteratively until a protective action is taken.

Lindell and Perry (2012) define environmental cues (Fig. 2, left section) as any sights, sounds, or smells that can signal the onset of a threat to someone. For an extreme precipitation event, environmental cues could be experiencing street or river flooding. Social cues arise from observing the behavior of other people, for example, someone observing their neighbors preparing their home ahead of an anticipated hurricane. Warnings are messages about a potential hazard that are transmitted via a channel from a source to a receiver, and they may cause an effect in the receiver, depending on characteristics like their physical, social, or economic abilities. Warnings could be forecasts and predictions from the National Weather Service, communication from other government agencies, or conversations with professional colleagues. These warning messages are theorized to produce an effect in the recipients, including a change in the receivers' behaviors or beliefs.

Cues and warnings set the pre-decisional processes in motion, and these processes are necessary to produce a protective action. The first of the pre-decisional processes is exposure, which means people need to receive the information to take protective action. For example, a floodplain manager has to receive some type of weather forecast or climate prediction in order to act on it. The second pre-decisional process is attention, or whether people heed the information they receive; it is determined by a person's expectations, competing attention demands, and the intrusiveness of the information. For example, if a floodplain manager expects a hazard to impact them, they will likely pay more attention; if they have multiple responsibilities to tend to, they may pay less attention to information. The final pre-decisional process is comprehension, which is whether someone understands the information that is being conveyed to them. If the message or forecast is written in complicated, meteorological language that the recipient does not understand, it will be harder for them to act on the information that is being provided.

Protective action decision making is also influenced by a person's perception of threat, possible protective actions, and other stakeholders (Lindell and Perry 2012). Someone's perception of a threat is influenced by their assessment of the risk — the probability of something happening and the consequences of that outcome — and cognitive heuristics. These heuristics include prior experience with a hazard or threat, a tendency for someone to think they are less at risk than others, or a bias towards thinking in shorter timescales than longer ones (e.g., Tierney 2014). Threat perception is also influenced by someone's expected personal impacts, which are related to the recency, frequency, and intensity of people's personal experience with a given hazard. For example, if a water manager has recently experienced a hazard, or if that hazard happens often in their jurisdiction and is generally intense, they may have a higher threat perception.

After the three pre-decisional steps are completed and each of the core perceptions have been activated, the decision-making sequence turns to the decision stages identified in the PADM (Lindell and Perry 2012): risk identification, risk assessment, protective action search, protective action assessment, and protective action implementation. Each of the five stages has a key question associated with it that someone will ask themselves.

For risk identification, the question is: "is there a real threat that I need to pay attention to?" In risk assessment, the question becomes: "what are the personal impacts and do I need to take protective action?” Here, the immediacy of the threat matters, because people may continue seeking more information if they believe there is enough time before impacts begin. For example, a short lead-time weather forecast might prompt managers to act instead of seeking more information, compared to sub-seasonal or seasonal predictions that have longer lead times and allow for more information seeking.

The next stage, protective action search, occurs if people believe the threat is real and there is a high level of personal risk. In this stage, people will ask “what can be done to achieve protection?” and search for possible protective actions based on their own knowledge, the warning information, or from observing the social cues of others. In the fourth stage, protective action assessment, the question becomes “what is the best method of protection?” People will examine what the best available method of protection is, resulting in an adaptive plan that outlines which actions will be taken. The fifth and final stage, protective action implementation, involves asking the question of if protective action needs to be taken immediately. If someone answers no, they can place themselves at higher risk, especially for long-term hazard adjustments or decisions when there is no specific deadline a decision must be made by. When using long-term predictions, floodplain managers may understand the information they are receiving, but determine that protective action can wait, therefore creating more risk in their communities. Additionally, the decision to act may not be exclusively up to a manager. They may have to convince others of the need to take action, which can be difficult if those people are less directly connected with the issue. This difficulty is especially prevalent for long-term threats, where the potential impacts are far in the future, but action needs to be taken in the present.

At any given time in the PADM, someone who received a warning may realize they need more information before acting, especially if the protective action will involve the use of many resources. Additionally, forecast uncertainty can complicate decision-making and lead to seeking more information. This search for additional information begins with an information needs assessment, where people ask what information they need to answer a given question. Usually, more information is needed about the severity or immediacy of the threat (e.g., How intense will this flood be and when will it impact me? What actions are being suggested from authorities?). The next step of the information search is communication action assessment, asking "where and how can I obtain this information?" Sources of information can range from National Weather Service forecasters and forecast products, emergency responders in a community, local media personnel, or even social media. The final step of information search is the implementation of the communication action, when someone asks if they need the information immediately. If the answer is yes, people will actively look for information from the most appropriate and accessible source. If the answer is no, then information seeking will be less active and occur less often, especially if the location of a possible hazard is specific but the timing of when it might occur is not.

The PADM will repeat iteratively, driven by the communication action assessment. If someone does not believe they need to seek out additional information, the loop is not necessary; but in many cases, people search for more information about the threat, or how they should implement protective actions that have been identified. For hazards with longer lead times like those on the sub-seasonal to seasonal timescale, where impacts may be forecasted weeks to months ahead of time, a lack of urgency about those impacts may lead to someone delaying information search; for a hazard on the weather timescale, however, the information searching process may happen faster and more frequently until a protective action is identified.

While Lindell and Perry (2012) provide one model for decision making related to natural hazards, other social scientists have designed models and theories for how people receive and act on risk information. These include the warning response model (Mileti and Sorensen 1990), the theory of reasoned action (Fishbein and Ajzen 1975), the theory of planned behavior (Ajzen 1991), and protection motivation theory (Rogers 1983). Each of these models or theories identify components that may influence someone to make a decision, both within the weather and climate context and for risks in general.

Section: 2.2.2. Warning Response Model

The warning response model (Mileti and Sorenson 1990) outlines one way that people respond when they receive risk information and has been applied to multiple hazards, including wildfires (e.g., Lovreglio et al. 2021), floods (e.g., Smith et al. 2022), tornadoes (e.g., Johnson et al. 2021), or hurricanes (e.g., Lee et al. 2021). Compared to the PADM, the warning response process is more linear and less iterative, and people may not complete each of the six stages of the process.

Warning response begins with hearing, when someone is notified or receives a warning. Just because warning information is available, it is not always received, so this step is key to the remaining process. The next step is understanding, which occurs when the recipient gives personal meaning to the message. Each person can assign a different meaning to the warning and the expected outcome, for example if someone receives a flash flood warning, they can personalize the impacts and how they may be affected.

After understanding, the next step is believing. Even though someone may understand a warning, they might not believe that the hazard being described will impact them, or that the warning information is accurate. Confidence and trust in a forecast source or forecast itself plays an integral role in whether or not someone will react to a warning (Lazo et al. 2009). Therefore, if warning recipients do not trust the National Weather Service or the forecast information being provided, they may not act on the information. Ultimately, those receiving forecast information need to feel empowered to act on the forecast, which make them more likely to trust the forecast source, and forecast itself (McIvor et al. 2009).

In the personalizing stage of the warning response model, people will think about what the warning means for themselves, and the possible risks that they may face. This stage is key when it comes to people acting on a given warning, because if they do not believe a hazard will affect them, they may be less likely to act. Next is the deciding and responding stage, where the warning recipient will decide what they should do about the risk. The final stage is confirming, which occurs each time new information becomes available and the recipient is attempting to confirm prior information.

Although similar to the PADM in terms of how warning information is received and acted upon, the warning response model is generally used for shorter-term hazards, such as tornado or hurricane warnings. While the PADM can be applied to these hazards too, it also includes a focus on hazard adjustment adoption for hazards that can be extended over time, such as events that happen on the sub-seasonal or seasonal timescales. Additionally, the warning response model focuses more on the content of a given warning or risk message, and less on the specifics of how people are responding to take protective action based on those warnings.

Section 2.2.3. Expectancy Valence Models

The theory of reasoned action (TRA), theory of planned behavior (TPB), and protection motivation theory (PMT) all fall under the broad category of expectancy valence models, which explain how people develop their perceptions of risk and then take protective action. The TRA argues that someone's intentions are related to their attitude towards a behavior and subjective norms. Attitude is the thoughts someone holds about a behavior and whether or not it will lead to certain consequences. Social pressures and expectations, as well as motivation to comply with those pressures, comprise the subjective norms. Then, the intention to carry out a specific behavior is a function of both the attitudes towards that behavior and the subjective norms about it (Fishbein and Ajzen 1975).

Similarly, the theory of planned behavior builds on the theory of reasoned action and adds perceived behavioral control as one of the factors influencing the decision to act. Essentially, the theory of planned behavior states that if someone believes they are capable of taking a given action and they have a strong intention of doing so, they are more likely to successfully carry out that action (Ajzen 1991). Overall, these two theories provide foundational insight into the way that people can make decisions and factors that influence those decisions, but they are very broad and focus on many kinds of risks, not just those associated with natural hazards. Additionally, there is little discussion about how the factors influencing decisions can change over time, especially for decisions and behaviors that may not need to be carried out immediately.

The protection motivation theory is another example of a model for protective action decision making. The focus of PMT is to explain how people respond to dangerous, fearful situations. The PMT centers on fear appeals, which are defined as messages about a severe event that indicate to someone they are at risk while providing effective ways to avoid the threat (Rogers 1983). There are three key pieces of information that fear appraisals need to include: the magnitude of the danger of the predicted event, the probability the event will occur if no action is taken, and the effectiveness of a coping response. When a fear appraisal is received, these three pieces of information initiate corresponding cognitive processes: appraising the severity of the event, determining expected exposure to the event, and determining the efficacy of the recommended responses. Taken together, these three cognitive processes result in protective motivation if an event is deemed dangerous and likely to occur, and someone believes a recommended coping mechanism will prevent the threat from happening.

Overall, each of these theories and models provide insight into how people interpret risk information and make decisions. The warning response model is generally applied to hazards with short lead times, such as tornadoes or hurricanes. The PADM, on the other hand, can be applied to hazards with short and long lead times, like those associated with the sub-seasonal to seasonal timescale. The expectancy valence models (TRA, TPB, and PMT) are all broad and can be applied to many types of decisions, not just those associated with natural hazards, while the PADM and warning response models were developed to assess risk communication and how people respond to hazards. Although any one of these models could be used to understand how people make decisions about some type of risk, the PADM is the only one that mentions applicability to hazards with both short and long lead times, making it the best fit for studying forecast information use across multiple timescales.

Section 2.3. Current Uses of Weather and Climate Information

Weather and climate forecasts exist across a variety of timescales, serving different decision-making purposes. For water managers, and specifically floodplain managers, weather forecasts may influence emergency responses to flash flooding or flood risk management. At the seasonal timescale, floodplain managers may use climate information for long-term planning and decision-making about available resources. Taken together, all of the available weather and climate information can help water and floodplain managers better assess their risk of flooding and manage extreme precipitation events in their jurisdictions.

A 2013 report from the United States Army Corps of Engineers highlights different sources and types of weather and climate information that water managers used. Within the report, the Corps of Engineers defines three timescales that water managers use to make decisions: fine (hours to days ahead of time), medium (days to weeks ahead of time), and coarse (weeks to months, or even years ahead of time). These correspond to the weather, sub-seasonal to seasonal, and seasonal timescales that are commonly used in the weather and climate community.

The report (Raff et al. 2013) also identifies many types of information that water managers use to make decisions. In the short-term, this information can range from river gauge observations to precipitation predictions. The report identifies multiple existing forecast products that water managers use on the fine timescale, including precipitation monitoring from observation networks like Community Collaborative Rain, Hail, and Snow (CoCoRaHS) (Reges et al. 2016) or Snow Telemetry (SNOTEL) (Schaefer and Paetzold 2000). Additionally, precipitation analysis from the National Weather Service River Forecast Centers and stream gauge observations from the United States Geological Survey also aid real-time and short-term decision-making. Floodplain managers can use a combination of short-term forecasts and real-time monitoring systems for daily operational decisions or for emergency response during flooding events in their communities (Ingram et al. 2008).

On longer timescales, like those associated with seasonal forecasts (or coarse forecasts in the Corps of Engineers report), available forecasts often have lower spatial resolution and can provide less-detailed information about the extent or intensity of specific precipitation events. However, seasonal climate forecasts can be useful for long-term, strategic planning within organizations, including those related to water management (Bruno Soares et al. 2018). In the same Corps of Engineers report, the authors suggest water managers might use products on the coarse timescale for long-term water supply planning or to manage reservoir levels. Seasonal forecasts also can provide water managers with more operational flexibility and help them adapt to water supply variability (Pagano et al. 2001).

Current examples of seasonal climate forecasts that water managers use include seasonal precipitation outlooks produced by the Climate Prediction Center, water supply forecasts from the Natural Resources Conservation Service, and peak streamflow forecasts from River Forecast Centers (Lowrey et al. 2009; Raff et al. 2013). The Climate Prediction Center produces predictions related to temperature and precipitation and the U.S. Drought Monitor is updated weekly to give a snapshot of drought conditions across the country (Whateley et al. 2015). Outside of government forecasts, Columbia University's International Research Institute for Climate and Society also produces seasonal temperature and precipitation forecasts at the global scale (Mason et al. 1999). Although these seasonal forecasts and predictions are not updated as frequently as weather forecasts, they still provide water and floodplain managers resources to guide their long-term planning.

Between the weather and seasonal timescales, sub-seasonal to seasonal (or medium resolution forecasts) predictions can help fill the gap between detailed weather forecasts and broader, seasonal climate forecasts, allowing decision-makers to take action further in advance of an extreme precipitation event. The Corps of Engineers identify many types of information that are currently used at the medium timescale (days to weeks ahead) including quantitative precipitation forecasts from the Weather Prediction Center, predictions of streamflow from River Forecast Centers, or even some types of water-supply forecasts (Raff et al. 2013).

The Climate Prediction Center also produces sub-seasonal to seasonal precipitation outlooks for the entire country which highlight areas that are more likely to experience above- or below-normal precipitation in a three- to four-week time period (NOAA Climate Prediction Center 2022). Forecasts on the sub-seasonal to seasonal timescale often are used for broader operational planning and can provide a “heads up” to decision-makers about possible events that may impact them. This extra lead time can give practitioners additional time to prepare resources within their communities ahead of an extreme precipitation event.

Overall, there are many types of information that water and floodplain managers are using to make decisions related to water and floodplain management. These forecasts span timescales and can be both quantitative (e.g., quantitative precipitation forecasts) or qualitative (e.g., precipitation outlooks). Forecasts can help guide decisions from emergency flood response to long-term planning for water supply or development within floodplains.

Section 2.4. Common Barriers

Although using weather forecasts and climate information may benefit floodplain managers and other decision-makers, there are many reasons why this information might not be integrated into existing decision-making processes. There are many places to find weather and climate information and often, stakeholders are unsure of where to get exactly what they need (Carbone and Dow 2005; Rayner et al. 2005; Bolson et al. 2013; Bruno Soares and Dessai 2016). For example, the Climate Prediction Center of the National Oceanic and Atmospheric

Administration regularly issues sub-seasonal and seasonal forecasts focused on precipitation for the entire United States, but other organizations, such as the National Drought Mitigation Center or the International Research Institute for Climate and Society, also issue seasonal drought and precipitation forecasts. It is possible, therefore, that water or floodplain managers may be unfamiliar with all of the potential sources of information and how to access them, or which forecast is the most reliable for their region and decision problem.

Similarly, even if practitioners are able to physically access forecast information, they do not always find it easy to understand, as many forecasts use jargon uncommon outside of atmospheric sciences. They may also be unsure about how forecasts, especially at longer timescales, can influence their decision making. For example, managers of flood-control districts in the western U.S. that focus on long-term flood management (e.g., development or purchasing land) and short-term flood warnings did not immediately identify ways that seasonal forecasts could be useful for them (Pagano et al. 2001). In a survey of 50 European decision-makers from a range of sectors, including water management, tourism and energy, seasonal forecasts were perceived as more useful than understandable, and not very user-friendly (Taylor et al. 2015). In the same study, weather forecasts were considered much easier to access and understand than seasonal forecasts, though both were considered to be useful for decision-making. Practitioners may know that sub-seasonal or seasonal forecasts exist and believe they are useful, but not understand how to interpret the information contained in a forecast. Therefore, it is imperative for scientists to convey forecast information more clearly and in a way that is understandable to end-users. Additionally, scientists could work with practitioners to educate them on using the types of weather and climate information and how that information can be brought into existing decision-making processes (Coelho and Costa 2010).

Another possible barrier is the limitations of spatial and temporal scales of different kinds of forecasts. Given adequate initial conditions, weather forecasts provide spatial and temporal details about where precipitation is likely to occur. However, this granularity and specificity are not currently possible at longer timescales, so skillful predictions cannot provide specific rainfall amount, location, or timing at the sub-seasonal or seasonal scales. Often, practitioners want forecast information at localized scales, for example a particular watershed that they work within, or they may want the forecast translated into specific impacts, such as whether or not their local community will experience flooding (Bruno Soares and Dessai 2016).

Practitioners in previous studies found it difficult to identify how sub-seasonal or seasonal forecasts would help solve problems they faced in their profession (Rayner et al. 2005). They were able to see how weather forecasts could be used to prepare for a possible storm or how climate projections could be applied to plan for the future, but they struggled to identify how information about sub-seasonal and seasonal climate variability could help them. For example, water and floodplain managers are often making decisions about reservoir levels for an upcoming season or year and they need forecast information that can aid those decisions (Hartmann et al. 2002).

Practitioners also may consider weather and climate forecasts unreliable, making them less likely to use forecast information (Carbone and Dow 2005; Bruno Soares and Dessai 2016). Despite the calculated forecast skill[1], practitioners often desire high accuracy (the forecast being right x% of the time) to consider using them for decision making. In a role-playing game, Crochemore et al. (2021) found that forecasts of high reliability were linked with an increase in water management decisions taken. Especially at longer lead times, this level of skill is difficult,

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[1] A statistical evaluation of the accuracy of forecasts (American Meteorological Society 2012)

if not impossible, to attain; yet practitioners still say they will not use information unless it meets their levels of reliability.

The misconception that forecasts are unreliable can arise from multiple sources. First, decision-makers view forecasts and their accuracy differently than forecasters, viewing a forecast as either “right” or “wrong” instead of one outcome among a range of possibilities (Steinemann 2006). Although probabilistic forecasts are becoming more prevalent, these forecasts bring their own sets of challenges for decision-makers, such as interpreting what “above normal” or “below normal” means and the probability of those circumstances occurring (Davis et al. 2016). Another misconception about forecast reliability stems from the accessibility of forecast skill information. This information may be available for decision-makers to find but is usually not presented in a way that is easy to understand and interpret (Taylor et al. 2015). Even if information about forecast skill were available, decision-makers may not understand what skill means for them (Callahan et al. 1999; Rayner et al. 2005).

Besides challenges surrounding the actual forecasts themselves, decision-makers often work within complex institutions that have their own barriers to navigate. One challenge is the fragmentation and specialization associated with water and floodplain management (Rayner et al. 2005). Water is usually overseen by multiple departments within a jurisdiction, with many governments (e.g., tribal, municipal, state, federal), intergovernmental agencies (e.g., departments of water resources, environmental protection, natural resources, tourism), and nongovernmental offices (e.g., industries, local water advocacy groups) making decisions related to water use, quality, or consumption. Fragmentation leads to institutional complexity and a broad network of practitioners making decisions about water management. New water managers need time for learning how to navigate their individual jurisdictional policies and also the intricacies of its physical environment. Additionally, being a water or floodplain manager often is not someone's only job, especially in small communities or tribes. Instead, the person holding these roles can have other responsibilities within their jurisdiction, giving them less time to focus on overseeing water or floodplain issues and seeking out new sources of climate information.

Another component of working within complex institutional systems is the difficulty associated with changing established policies or practices (Rayner et al. 2005, Steinemann 2006). Often, policy changes are reactive and in response to a crisis or disaster, instead of being done proactively (Pagano et al. 2002). Additionally, floodplain managers, especially those working in local government, may have little control over policies and practices that influence how they do their jobs. Decision-makers also may not want to incorporate new, detailed scientific information into their practices, especially when they might not understand its use or the benefit of using it (Morss et al. 2005; Bruno Soares and Dessai 2016). Instead, they will continue using existing information because it is "good enough" and does not require changing existing practices. It also can be difficult to integrate new information if it comes from outside of the decision-makers' organization. Information from within an organization generally is trusted more than information that originates outside of the organization (Feldman and Ingram 2009). Therefore, forecast information that is produced in-house may be considered more trustworthy than forecasts from external partners like the National Weather Service or commercial forecasters.

Finally, money is a significant factor when it comes to decision-making. Another challenge is financial resources and practitioners' budgets, as they can influence how likely managers are to take risks and invest in long-term improvements or plans (Ramos et al. 2013; Arnal et al. 2016). Practitioners and governments may not have the money to invest in gaining access to new forecasting resources or developing and updating existing decision-making plans

(Bruno Soares et al. 2016). It is also easier for agencies and governments to wait and “fix on failure,” after a flood damages infrastructure, instead of trying to reduce flood risk broadly ahead of an event (Pagano et al. 2001). Additionally, if there were few resources to prepare for a hazard, or if there were no institutional incentives to do so, taking action may be a lower priority for practitioners compared to other management tasks (O’Connor et al. 2005).

Research suggests ways to overcome these barriers that floodplain managers may experience related to using weather and climate information. First, it is imperative for end-users to be trained in using the types of weather and climate information that is produced by scientists and how that information can be brought into existing decision-making processes (Coelho and Costa 2010). This training can be accomplished by developing stronger partnerships between the scientists producing forecasts and end-users using them to make decisions. Longer range forecasts also can be post-processed to smaller spatial scales such as the watershed scale, because this localization can make the information more useful to water and floodplain managers (Coelho and Costa 2010; Baker et al. 2019). However, downscaling techniques can cause systematic biases to propagate from larger scales to local scales, influencing the output of forecasts (Coehlo and Costa 2010). Finally, providing information about forecast skill can help floodplain managers understand what a given forecast can and cannot provide to them. Overall, there are many barriers that can prevent managers from using weather and climate information in their jobs.

Section 2.5. Summary

Floodplain management and administration is an incredibly nuanced specialty, and professionals in these roles face a variety of challenges when making decisions. Weather and climate forecasts can provide vital information for floodplain managers across a variety of temporal and spatial scales, ranging from a few days ahead of time (the weather timescale) to many months or even years into the future (the seasonal timescale or climate projections). There are currently multiple forecast products available to help floodplain managers; however, these products are largely on the weather or seasonal timescales. The sub-seasonal to seasonal timescales offer an opportunity for forecast advancement to provide managers and decision-makers more lead time to prepare for potential extreme precipitation events and their impacts.

Chapter 3: Listening to Stakeholders: Initiating Research on Sub-seasonal to Seasonal Heavy Precipitation Events in the Contiguous U.S. by First Understanding What Stakeholders Need

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Section 3.1. Abstract

Heavy precipitation events and their associated flooding can have major impacts on communities and stakeholders. There is a lack of knowledge, however, about how stakeholders make decisions at the sub-seasonal to seasonal (S2S) timescales (i.e., two weeks to three months). To understand how decisions are made and S2S predictions are or can be used, the project team for "Prediction of Rainfall Extremes at Sub-seasonal to Seasonal Periods" (PRES^{2}iP) conducted a two-day workshop in Norman, Oklahoma, during July 2018. The workshop engaged 21 professionals from environmental management and public safety communities across the

contiguous United States in activities to understand their needs for S2S predictions of potential extended heavy precipitation events. Discussions and role-playing activities aimed to identify how workshop participants manage uncertainty and define extreme precipitation, the timescales over which they make key decisions, and the types of products they use currently. This collaboration with stakeholders has been an integral part of PRES^{2}iP research and has aimed to foster actionable science. The PRES^{2}iP team is using the information produced from this workshop to inform the development of predictive models for extended heavy precipitation events and to collaboratively design new forecast products with our stakeholders, empowering them to make more-informed decisions about potential extreme precipitation events.

Section 3.2. Introduction

Heavy precipitation (rain or snow) poses significant risks to society (Pielke and Downton 2000, Adeel et al. 2020), including damage to and disruption of transportation systems (Suarez et al. 2005), water contamination (Curriero et al. 2001; Exum et al. 2018), economic losses from flooding (Rosenzweig et al. 2002), and loss of life (Ashley and Ashley 2008). In 2019, flooding and extreme precipitation caused an estimated $20.3 billion in damages across the United States (NCEI 2020). With advanced notice of an impending event, individuals and groups can take protective actions sooner, limiting losses and costs. However, few forecast products exist to inform stakeholders two weeks to three months —the subseasonal-to-seasonal timescale — prior to an extreme precipitation event. Actions at this timescale may include adding insurance protections, releasing water from a reservoir, updating evacuation plans, increasing public outreach, or preparing an emergency response plan and other resources. White et al. (2017) discuss sectoral applications of S2S predictions, including humanitarian aid, public health, energy, water management, agriculture, and emerging sectors such as retail, marine fisheries, and wildfire risk management.

The Prediction of Rainfall Extremes at Sub-seasonal to Seasonal Periods (PRES^{2}iP) project, funded by the National Science Foundation (NSF), is designed to address this forecast gap. The research team is examining the following questions: (1) What are the typical atmospheric patterns and common characteristics associated with sub-seasonal to seasonal extreme precipitation events in the United States?; (2) Does large-scale climate variability influence extreme precipitation events and, if so, how?; (3) How predictable are subseasonal-to-seasonal extreme precipitation events?; and (4) How can we create informative predictions of extreme precipitation events that are easily communicated to policymakers and other stakeholders? Here we describe a workshop that begins addressing the latter question.

When stakeholders are included in product development, the resulting products are more likely to be used and viewed as legitimate and trustworthy by decision-makers (Cash et al. 2003; Meadow et al. 2015). Information tends to be clearer to final users because it is communicated in familiar terms without complicated jargon (Jasanoff and Wynne 1998). Also, co-developed products are generally easier to use and integrate into existing decision-making processes (Lemos et al. 2012).

Researchers also need to understand *how* stakeholders make their decisions (Dilling and Lemos 2011). Stakeholders have regulatory, institutional, political, and resource constraints that can hinder them from using scientific information (Morss et al. 2005). They make decisions in complex settings that change rapidly and are rife with the uncertainty that an event will occur in their jurisdiction *and* lead to substantial impacts (Lindell and Perry 2012).

In July 2018, as the PRES^{2}iP project began, the research team engaged participants whose jobs required decision-making, planning, response, or recovery work related to local or regional flooding. We held a two-day stakeholder workshop in Norman, Oklahoma, to determine how participants defined ‘extreme precipitation’ and used weather or climate prediction products in their professions. The background section details why this workshop was needed, and the methods section explains the workshop design, choice of participants, and workshop implementation. In the results section, we highlight workshop activities and the information we gathered. Finally, we will summarize how we used the information in our broader research agenda and discuss future plans.

Section 3.2. Background

Despite its impacts, there is no universally accepted definition of extreme precipitation (Pendergrass 2018). Meteorologists, for example, may have numeric definitions, such as if a month’s worth of rain falls in a single day at a given location (NOAA 2018). Stakeholder’s definitions, on the other hand, tend to vary based on precipitation impacts, policy constraints, decision type, or experience (Dourte et al. 2015). To develop a useful extreme precipitation product for a range of stakeholders, researchers must understand how the users define the term ‘extreme precipitation,’ which can be accomplished through scientist-stakeholder relationships.

Beneficial scientist-stakeholder relationships take time and intentional work to develop before they benefit both groups through information creation and use (McNie 2007). Previous research highlights how these relationships can be fostered. For example, communication, which is the process whereby information is exchanged and socially contextualized between stakeholder and scientist (Weaver et al. 2013), is critical. Frequent communication helps to build credibility of the researcher, making it more likely that the stakeholders will use final products and trust their information (Cash et al. 2003; Kahan et al. 2012). Through discussion, stakeholders can express their needs so that researchers can make their products most useful and further explain their process and outputs to stakeholders.

Subseasonal-to-seasonal (S2S) prediction (i.e., two weeks to three months) has been a growing area of research in the past decade (e.g., Robertson et al. 2015; White et al. 2017; National Academies of Sciences, Engineering, and Medicine 2017). The World Meteorological Organization notes this timescale is important for developing early-warning systems of high-impact weather events, such as extreme precipitation, and that better predictions could bring substantial societal benefits (WMO 2013; White et al. 2017). Forecasts within the S2S timescale have been tested or implemented in the United States (e.g., Baker et al. 2019; DeFlorio et al. 2019). Europe (e.g., Bruno Soares and Dessai 2016), Australia (e.g., White et al. 2015), Africa (e.g., Andrade et al. 2020), and other countries. Opportunities also exist for enhancing predictions of meso- to synoptic-scale precipitation events at the S2S timescale (Gershunov and Cayan 2003; Mallakpour and Villarini 2017) by taking advantage of expanded understanding of modes of climate variability across the Atlantic and Pacific Oceans (e.g., El Niño-Southern Oscillation, Madden–Julian Oscillation). As prediction experiments attempt to address this recognized research gap (e.g., Pegion et al. 2019), the time is ripe to engage stakeholders who may use any future predictions in conversations about their decision-making needs as related to future S2S forecasts. Hence, the PRES^{2}iP team began to examine how to create informative predictions of extreme precipitation events that could be easily communicated to stakeholders by gathering insight into a sampling of decision processes.

Section 3.4. Methods

To gather information from a range of experts, the PRES^{2}iP team hosted a two-day, face-to-face workshop in Norman, Oklahoma, in July 2018. This activity helped the PRES^{2}iP team prioritize which subseasonal-to-seasonal extreme precipitation events to study and establish multi-directional communication pathways among PRES^{2}iP researchers, guest forecasters, and invited decision-makers. Our team planned the logistics and content of workshop sessions from November 2017 to July 2018.

We selected three primary user communities: water resource managers (6 participants), tribal environmental professionals (2 participants), and emergency managers (9 participants), though we also added a few representatives (4 participants) from other sectors (e.g., education, energy). We recruited experts using purposive sampling (Tongco 2007) and snowball sampling (Goodman 1961), contacting those who had worked with a PRES^{2}iP team member and gathering recommendations from them. Some invitees were recommended by other colleagues or through direct contact via email listservs or website personnel directories. Because tribal environmental professionals do intensive fieldwork during the summer, we were unable to recruit many who could leave their jurisdictions. We also invited three guest speakers or observers from the National Weather Service (NWS), including the Climate Prediction Center (CPC), to ensure our research progress was consistent with operational products and services. On July 12-13, 2018, our 19 PRES^{2}iP team members welcomed 21 participants to the first PRES^{2}iP workshop – the *Research Priorities Workshop*. Participants represented different jurisdictions (tribal, state, metropolitan, rural) and physical geographies (mountainous, coastal, plains, riverine) across the Lower-48 States (Fig. 3). In their individual professions, they experienced different types of extreme precipitation events: heavy wintertime snowfall, springtime floods along rivers, landfalling hurricanes, severe convection from isolated or quasi-linear systems, or monsoons.

Figure 3: Geographic distribution of workshop participants.

The workshop had four sessions, briefly described in Table 1, each designed to gather specific information. For Sessions 1–3, participants were grouped based on their sector: (1) water managers, (2) emergency managers, and (3) tribal environmental professionals and other experts. For Session 4, participants were sorted randomly into four smaller groups. Notetakers recorded the information exchanged within each group, and a facilitator at every table summarized the main points after each session's discussion. Facilitators and notetakers were members of the PRES^{2}iP team, including faculty, staff, postdocs, graduate students, and undergraduates.

Table 1: Description of workshop activities and goals.

Workshop Session	Activity	Session Goal
Session 1: What does extreme precipitation mean to you? Day 1 – 75 minutes	Participants watched a short video of scientists from the National Weather Center who were asked about their own definitions of extreme precipitation. The video initiated small-group discussions among PRES2iP participants about what they considered to be extreme precipitation events.	To clarify what spatial and temporal scales of extreme precipitation concerned the participants.
Session 2: How do the participants make decisions? Day 1 – 75 minutes	We prompted participants to think about all decisions for which they were responsible as related to extreme precipitation. Each then selected one decision process and created a decision tree to document its evolution and the information they used to make that decision.	To learn what decisions participants made in their professions regarding extreme precipitation.
Session 3: Impacts and uncertainty Day 1 – 75 minutes	Participants were assigned to small groups, led by a PRES2iP facilitator, and asked questions about how they dealt with uncertainty and the impacts of extreme precipitation events.	To learn how the participants used forecasts to prepare for extreme precipitation events, how they considered forecast usefulness and uncertainty during the decision-making period, and how the impacts of short-term versus long-term events differed.
Session 4: Roleplaying activity Day 2 –120 minutes	Groups assessed multi-day forecast products, discussed their interpretation, and collaborated to make a recommendation to the mayor of a fictitious city. Workshop participants assumed the role of Emergency Managers, and PRES2iP team members assumed roles of NWS Forecasters and Mayors.	To learn how participants interpreted different types of forecast products commonly used for S2S precipitation events.

Session 1 focused on defining ‘extreme precipitation’ from each participant’s perspective, as different definitions could lead to different interpretations of the same event (e.g., Ćwik et al. 2021). To initiate conversations among participants we created and played a video of researchers and forecasters from the National Weather Center in Norman, Oklahoma, answering the question: what does the term ‘extreme precipitation’ mean to you? Next, we asked the participants a series of questions: How much precipitation in a month would be considered extreme?, Does the duration of an event or the intensity of an event matter more to you?, and Is extreme precipitation over a large or small area more impactful? These questions fostered discussions among participants and the PRES^{2}iP team about how the participants defined ‘extreme precipitation’ and its associated temporal and spatial scales.

Understanding stakeholder’s decision-making process is key to developing a useful product (e.g., Klemm and McPherson 2018), so Session 2 focused on what types of decisions workshop participants made before, during, or after an extreme precipitation event. Facilitators prompted the participants to think about a *specific* extreme precipitation event (of any duration or intensity) they had experienced that required them to make complex decisions. Participants brainstormed a list of their decisions, such as supplying sandbags or choosing to postpone or relocate scheduled events. Next, facilitators asked them to select one decision and describe their decision-making process, beginning from when they first learned that extreme precipitation was forecast for their area. Each participant created a ‘decision tree’ and included who they interacted with (i.e., their event-related social network), what information sources they consulted, what actions they took, and when these interactions or decisions occurred in the event timeline. We concluded by discussing similarities and differences in everyone’s decision-making processes.

In Session 3, conversation focused on forecast impacts and uncertainty. Our goal was to determine how participants used forecasts to prepare for extreme precipitation events, how they considered uncertainty when making decisions, and how potential impacts differed over varying time periods. First, facilitators from the PRES^{2}iP team asked questions about what forecast products participants currently used to make decisions and how their product usage varied for long-term and short-term forecasts. Participants also answered prompts about how uncertainty affected their decision making and how skillful a forecast needed to be for them to use it.

For stakeholders, uncertainty needs to be conveyed in a way that allows end users to effectively solve problems (National Research Council 2006). One solution is to increase the usage and prevalence of probabilistic forecasts, allowing end users to make better and more informed decisions (Ramos et al. 2013). Probabilistic forecasts can improve decision quality by showing a range of potential scenarios (Joslyn and Leclerc 2011) from which a most probable, best case, and worst-case scenario can be highlighted (Marimo et al. 2015). These three scenarios help stakeholders to identify potential impacts and prepare for them. Stakeholders also want information on uncertainty and want their forecasts compared to prior years; in other words, they want context for how a future event resembles an event they already endured (e.g., Klemm and McPherson 2017). Yet, stakeholders can struggle to apply uncertainty information that is included in forecasts when they first encounter it (Berthet et al. 2016). Therefore, we wanted to know if workshop participants had similar concerns.

Lastly, the PRES^{2}iP team asked the participants how their jurisdictions were susceptible to extreme precipitation events and if impacts varied for long-duration versus short-duration events. For example, we wanted to know if 10 inches of rainfall over two days would be more impactful than 20 inches of rainfall over 30 days.

In Session 4, participants were engaged in a role-playing game to examine how well they understand, interpret, and act on existing forecast products, such as the Weather Prediction Center’s (WPC) Excessive Rainfall Outlook or the Climate Prediction Center’s 1–2 week precipitation forecasts. Role-playing scenarios allow stakeholders to practice using products and become comfortable doing so (Rosendahl et al. 2019) and enable participants to observe how the products are used and interpreted. In our activity, we provided a simulated setting for workshop participants to interpret forecast products and make choices while playing the role of an emergency manager in a given scenario. The activity allowed PRES^{2}iP researchers to see what features of forecast products are straightforward or difficult to interpret.

At each table, individuals played one of three roles: the Expert Meteorologist (role played by a PRES^{2}iP facilitator), the Mayor (also a PRES^{2}iP facilitator), and Emergency Managers (all workshop participants). Mayors requested recommendations from the Emergency Managers, established constraints for them to follow, and collected input from the team. Expert Meteorologists facilitated discussions with Emergency Managers concerning their thoughts about forecast products, answered questions that arose during the scenario, and, if necessary, explained the forecast products to the participants. Five to six Emergency Managers examined possible flooding impacts on transportation, utilities, first responders, and school services. They had to interpret the forecast products, integrate that information into their decision process, and make recommendations to the Mayor about how to handle an upcoming event (e.g., sports tournament, music festival) under the threat of extreme precipitation.

Two scenarios were used: (1) the August 2016 Southern Louisiana flood event (impacting central Louisiana, including Baton Rouge) and (2) the Spring 2011 Mississippi River flooding (affecting Memphis, Tennessee, and New Orleans, Louisiana). These events were chosen to contrast some sources of extreme precipitation. The Southern Louisiana flooding was caused by a weak tropical system while the Mississippi River flooding was due to heavy precipitation on top of melting snowpack. Dates were removed from the forecast products to reduce the chances that familiarity with the actual events would impact discussions. We did not analyze the skill of any of the events' forecasts, as the exercise was focused on learning from the participants about how they interpreted and acted on various forecast products.

In the activity, participants were presented with the CPC's seasonal outlooks at three-month and one-month timescales; one- to two-week precipitation products from both the CPC and WPC; and, sequentially, five-, three-, two-, and one-day WPC precipitation outlooks. As simulated time approached the predicted event, we provided shorter-term forecast products and discussed those before moving forward. Finally, depending on what questions the Emergency Managers asked or additional products they requested, participants also viewed WPC excessive rainfall outlooks, 850hPa and 500hPa synoptic maps, or radar or satellite imagery. The Emergency Managers discussed what they thought each product described, and if they interpreted a product incorrectly, the Expert Meteorologist explained what the product meant. In each time period, the Emergency Managers discussed how each product's information might influence their recommendation to the Mayor.

At the end of this exercise, we asked participants about each of the forecast products to learn what information they were gathering from each product and how they interpreted the associated uncertainty. We asked them what decisions they made based on each product, how comfortable they felt interpreting the product, and if there were challenges associated with using a given forecast product. Throughout the exercise, a notetaker documented major discussion points for each product, including misinterpretations that participants had made.

Because the workshop initiated a larger research project on S2S prediction of extreme precipitation events, we were limited in the types of forecast products we could show the participants and in the number and backgrounds of participants invited. We did not yet have experience developing experimental products and needed to keep the discussion groups small in order to have time for in-depth questions. We sought a variety of perspectives but limited the representation to only a few sectors so as to hear common messages. As a result, our results are not representative of all sectors, populations, or stakeholders in the contiguous U.S.; rather, they offer examples of issues that experts have with forecast products associated with extreme precipitation events.

Section 3.5. Results

Over four sessions, the PRES^{2}iP team gathered a large amount of information, especially through face-to-face table activities for complex topics and side conversations during the breaks that promoted trust and deepened understanding between PRES^{2}iP researchers and workshop participants.

Section 3.5.1. What does 'extreme precipitation' mean to you?

As expected, 'extreme precipitation' had different meanings to the participants. Most noted that the amount of precipitation was less important than whether it caused damage; thus, heavy precipitation that caused no damage, injuries, or fatalities was not considered an extreme event. Although many agreed that a precipitation rate of 1-2 inches per hour likely would cause impacts, no single threshold identified the amount of rain over a given time period that was considered 'extreme precipitation.'

However, most participants did use threshold values when they described situations in their jurisdiction. These threshold values were rates of precipitation (e.g., 6 in of rain over 3 h) and not statistical thresholds based on climatology (e.g., 95th percentile). They knew how much rain resulted in flooding of a given low-water crossing, for landslides and building damage to occur, or for inundation of stormwater systems. These place-based thresholds depended on antecedent precipitation (i.e., with extremely dry or saturated soils leading to more severe impacts), seasonal timing (e.g., spring rains on frozen soils), soil type (e.g., clay soils), terrain (e.g., steep valleys), land cover (e.g., fire burn scars), and land use (e.g., urbanization). Several participants also mentioned wind speeds associated with the precipitation (e.g., wet downbursts, freezing rain or snow with high winds) or the precipitation type (especially freezing rain or hail) affected their definition.

All participants identified high-intensity, short-duration events as those most difficult to respond to effectively. Many had different concerns for long-duration events, as their impacts could be harder to identify in a damage survey (e.g., seepage into basements) or increased future risks (e.g., potential debris flows). Longer-duration events or more time between events spread the impacts over time, enabling more proactive solutions. Participants also noted that events with little precipitation could still affect vulnerable people. For example, vehicle owners with bald tires find wet roads particularly dangerous, and specialty crop producers with no insurance can lose their business in a minor hailstorm.

For the PRES^{2}iP team, the key message was that no single threshold for a precipitation amount over any duration was going to satisfy the participants. We needed to focus on *where* heavy precipitation events might occur and *how likely* they are, then trust local experts to do their jobs.

Section 3.5.2. How do you make decisions regarding extreme precipitation?

For stakeholders, decision making is a balance among multiple, sometimes conflicting, factors. Session 2 focused on the types of decisions that participants make when extreme precipitation threatens, the processes of decision making as captured in decision trees (Fig. 4), and comparisons of similarities and differences among decision processes. Participants' decisions ranged from enhancing local monitoring and preparing resources to communicating with the public and implementing safety plans. Table 2 lists the participants' decisions, which are mostly local and place-dependent.

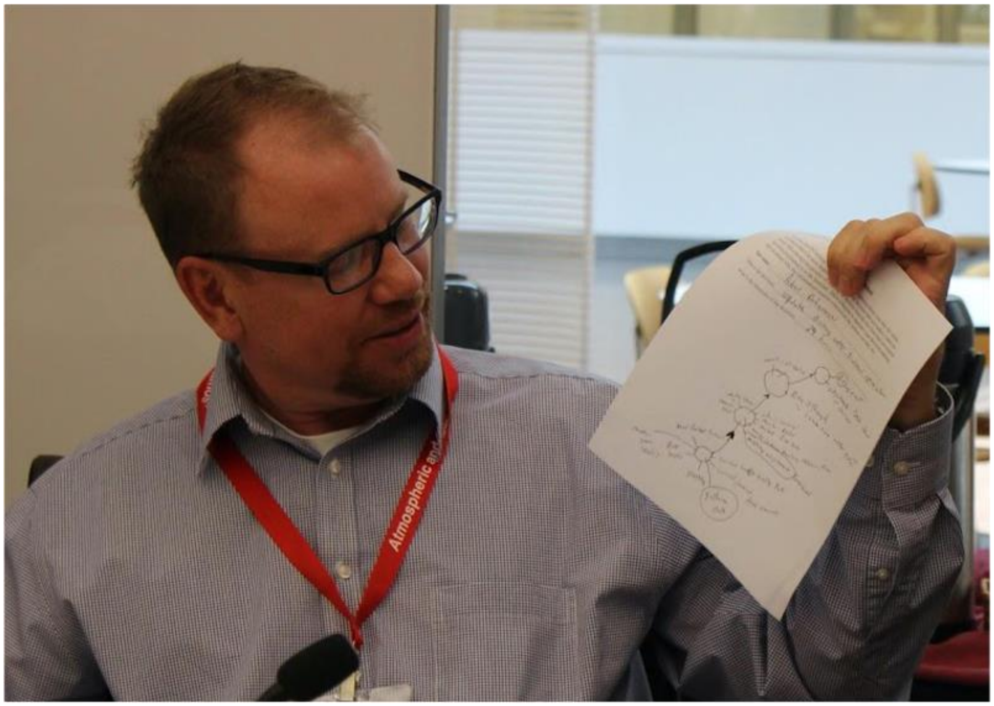

Figure 4: Robert Bohannon from the Department of Public Works in Moline, Illinois talks about his decision tree during workshop session 2.

Some participants apply seasonal forecasts to anticipate impacts in the coming months while others wait until specific events are predicted before implementing plans. At two to three months out, forecasts are primarily useful to influence resource and spending decisions. Weeks prior to a forecasted event, participants may survey their infrastructure, begin conversations with local and state governments or regulators, and check staff availability. For most participants, extensive planning that required time and energy usually did not occur until several days before the event, when uncertainty was diminished. Only then did participants begin engaging in common actions, including conversations with trusted forecasters, moving emergency vehicles outside of floodplains, readying resources, preparing to close schools, or evacuating vulnerable populations. Other considerations participants noted were desiring longer lead times during holidays, when they worked in environments with more than one level of government making decisions, or if their emergency plans required more time to execute. One participant, however, worried about staff “burning out” if concern was heightened weeks in advance. Several experts mentioned considerations of forecast accuracy or false alarms. When referencing CPC forecasts in general, another participant explained that they “do not need longer forecasts, [rather, they] need more accurate forecasts.”

Table 2: Decisions regarding extreme precipitation events identified by workshop participants during decision tree activity

Planning Decisions (Months to Weeks Before Event)				
Choose locations for weather stations	Train or retrain employees	Decide who is given weather information within the tribe	Pre-position resources	Order sandbags
Monitor water sampling and frequency	Monitor upstream water quality	Calibrate flood models and monitor water levels	Monitor water sampling and frequency	Check pump equipment
Calculate percentile storm event volumes for the amount of water permittees are allowed to discharge	Stockpile / prepare additional chemical water treatments	Coordinate with river operations center	Coordinate with power generation desk about potential excess hydrogeneration	Update drinking water treatment options
Response Decisions (Days to Weeks Before Event)				
Brief governor	Social media messaging before, during and after events	Prepare road crews for salt or sand / downed trees (winter precipitation)	Warning partners (Public works, regional counties, school districts etc.)	Evacuation of hot spot areas
Emergency Operations Center activated	Decide how much information should be shared with the public ahead of time	Initiate email communications to inform upper management and hydrologists about potential flooding	Work with public works and transportation ahead of time to clear culverts	Open or close county buildings
Brief power plants in area	Move staff to dams for 24-hour coverage	Establish hotel, food, fuel supply for utility repair crews and contractors	Identify alternative routes, ensure those routes are cleared and accessible	Transport juveniles / inmates
Coordination calls with FEMA/Office of Emergency Management / sheltering agencies if long-term impacts are expected	Bring hydrologists in for 24-hour shifts	Work with contractors who may be working on dams to prepare them for heavy rain	Road closures	Take wells out of service before an event

Section 3.5.3. Impacts and uncertainty

During Session 3, we asked participants how they dealt with forecast uncertainty during their decision-making process. They all highlighted the importance of their relationships with NWS forecasters. Relationship building enhanced communication and trust between the groups, generated a mutual understanding of each other's terminology and responsibilities, and increased the participants' understanding of and comfort in discussing forecast uncertainty. Without these relationships, forecast products seemed to be used less often or effectively. For example, several participants mentioned having relationships with local forecast offices but not the national centers (e.g., Weather Prediction Center), causing them to lean on products generated by local offices when making decisions.

This session's discussion showed how participants might leverage these relationships with NWS forecasters to better understand and apply forecast uncertainty and gather information that was not communicated in products posted to public-facing websites. This communication also created an opportunity to seek clarification, ask challenging questions (e.g., if you were me, would you order 10,000 sandbags?), or identify subtle cues about the event. For example, the words used by forecasters can convey uncertainty, as can the timing of forecast products. One participant noted that if the NWS scheduled a webinar more than a few days in advance, they knew the forecasters had higher confidence in the event occurring. Consistency over time also provided uncertainty information; a consistent forecast was interpreted as more certain and easier to use for making decisions. Participants noted that they needed forecasters to be frank, include probabilistic information, and discuss confidence or uncertainty regarding the forecast.

Effective communication of uncertainty mobilized participants to use forecasts in different ways. For example, they could use a worst-case scenario to prepare for an upcoming event when catastrophic impacts were possible, even if forecast confidence was low. Some participants noted that their public communication focused on the most-likely scenario, which might change over time. Yet, as another participant noted, uncertainty could be used to prolong public engagement and education about a possible event because, typically, when people became certain about an event's outcome, they stopped listening. Different scenarios enabled participants to apply their local knowledge, education, and experience to best serve their jurisdiction.

Finally, the participants discussed forecast accuracy in detail, with PRES^{2}iP team members posing the question: "Would it be helpful if we were only correct X percent of the time when forecasting a heavy rainfall event of any duration, more than two weeks ahead of time?" In one group, six of seven participants said 75 percent was their threshold for useability, while one participant said 50 percent was their threshold. Another group had lower thresholds for events 3-4 days in advance, ranging from 30-50 percent to start any actions. The third group did not identify threshold values but discussed situations that would result in different answers to the question. These contextualized situations depended on location (i.e., "we always get heavy rain"), event type (e.g., hurricane vs. extratropical cyclone), terminology (e.g., "extreme" vs "record rainfall"), and risk tolerance (e.g., cultural or political differences). Overall, participants desired higher accuracy for not only subseasonal-to-seasonal forecasts, but also forecasts that would fall within the typical weather timescale. They felt that this increased accuracy would allow them to make decisions with higher confidence of the forecasted outcome occurring in their area.

Section 3.5.4. Understanding, interpreting, and acting on forecast products

The role-playing activity required participants to solve a complex problem together, using their varied understanding of the forecast products dispersed by the Expert Meteorologist. For the groups using the central Louisiana flooding case, participants played the role of Emergency Managers in Baton Rouge, Louisiana; for the Mississippi River flood case, they played Emergency Managers in Memphis, Tennessee (Fig. 5). To begin, they received the 3-month, then the 1-month, seasonal temperature and precipitation outlooks from the CPC (Fig. 6). After noting what public event they were planning, the Emergency Managers started discussing the outlooks.

Figure 5: Nelly Smith from the Environmental Protection Agency Region 6 participates in the role-playing activity.

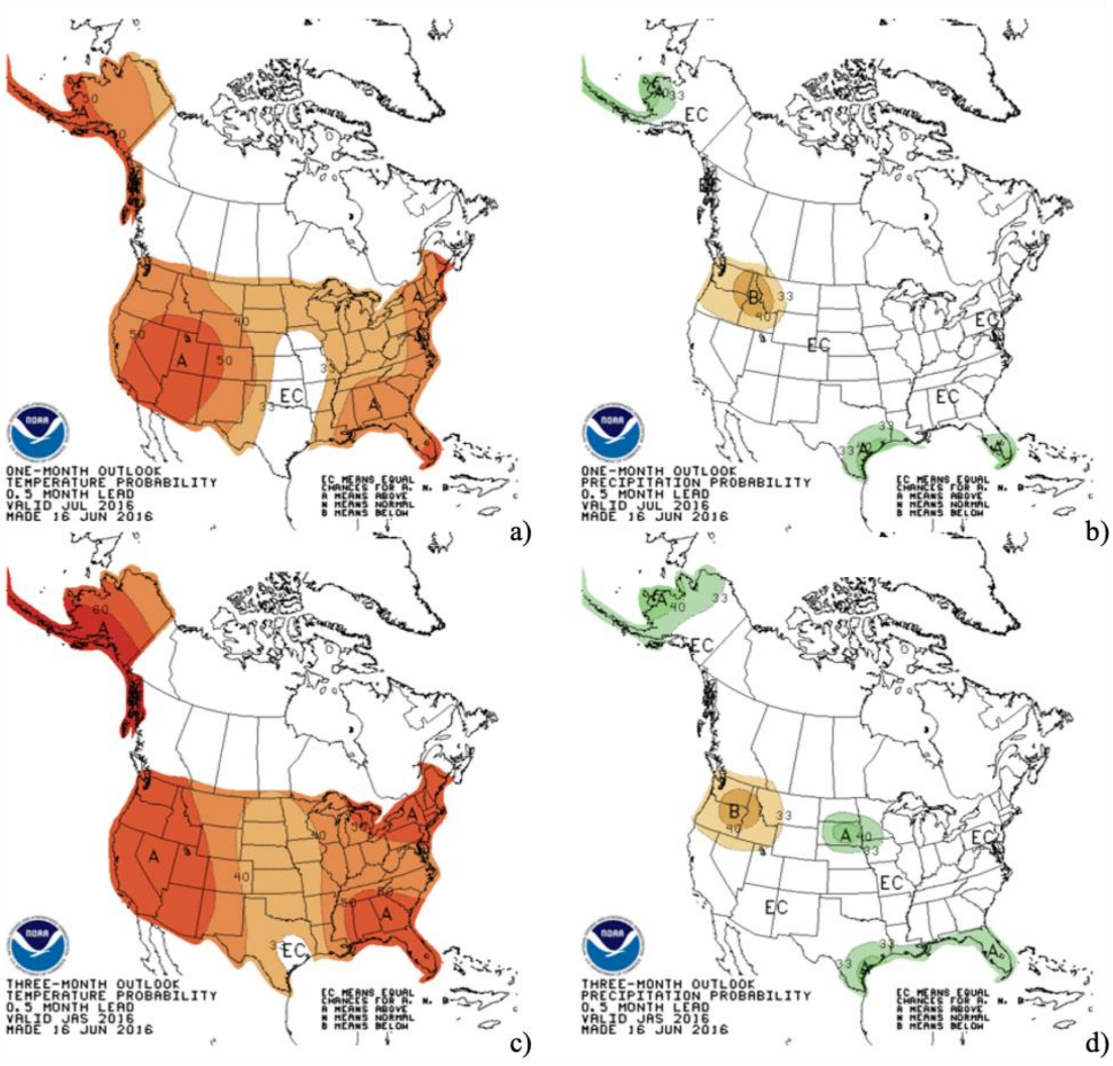

Figure 6: Examples of Climate Prediction Center a) One-month seasonal temperature forecast, b) One-month seasonal precipitation forecast, c) Three-month seasonal temperature forecast and d) Three-month seasonal precipitation forecast provided to Emergency Managers during workshop role playing activity.

There was general confusion about the CPC products, with several wondering what "EC" (equal chance) meant, what lead time meant, and what the confidence levels were in the different categories. Several participants discussed the difference between probability and confidence levels, with many wishing the legend used clearer language, that terminology was defined (e.g., what does ‘enhanced’ mean?), or fonts were larger. As one stated, “I thought [they] would talk in layman’s terms, not just put things out for us to interpret;” another said, “I want to know how to interpret this.” In one case, a participant was concerned that the product had numbers labeled on it, as they felt it conveyed more certainty than actually existed. Most indicated that they would take no action with these seasonal outlooks.

At one-month lead time, we asked the Emergency Managers what additional information would be helpful to them. A variety of products were named: a map of the normal temperature and precipitation for that time of year, a hurricane outlook, a river stage outlook, and soil moisture conditions. One group wanted a list of potential precipitation amounts above normal (e.g., 3, 5, 8 inches above normal) and the associated probability that these amounts would occur. All groups noted that CPC seasonal outlook products should include a text explanation in layman’s language.

As we moved ahead in time to 14, 7, 5, and 3 days before the event, the Expert Meteorologist presented quantitative precipitation forecasts (QPF). Participants were concerned about the color key changing among products, what colors were chosen to depict rainfall, what the timeframe was, and whether any rainfall rates were implied in the products. Several wanted to know the likelihood that the precipitation amount would occur, the accuracy of the model(s) used, or how much confidence the forecasters had. Other product enhancements included: a worst-case scenario, potential rainfall rates, potential storm type, and duration of the rainfall. Many participants noted that during this time, the centroid of the event or the forecasted rainfall consistently trended in one direction, giving them a higher confidence in the forecast over time. A few participants noted that, by two-weeks in advance, they would not trust the CPC forecast over QPF forecasts of the Weather Prediction Center. By five to seven days before the event, the Emergency Managers started recommending actions to the Mayor, including activating the Emergency Operations Center, alerting schools, increasing staffing at critical facilities, preparing evacuation orders, and communicating with the community.

By one to two days before the event, the Emergency Managers had high confidence in their planning decisions and moved to full-scale implementation of their plans. Receiving more detailed products helped answer their questions about intensity, location, and likelihood of the event, increasing their confidence. These products included: WPC's one- and two-day precipitation forecasts and excessive rainfall outlook, as well as radar and satellite imagery. At this point, some people asked what the exceedance maps meant and how to interpret them. One asked why the color scale of the QPFs were so similar to that of the CPC outlooks, as they displayed different information. Others were frustrated by the number of products and what each could add to their decision-making process.

The closer we moved toward the event, the more comfortable the participants became with the products. It was clear that they were used to applying short-term weather forecasts, satellite and radar imagery, and rainfall measurements. With a few exceptions, they were not comfortable with products beyond five days. Participants with water quality, longer-term water planning, or electrical utilities careers found the outlooks more useful to their actual jobs than their simulated jobs in this role-playing activity.

The participants were least familiar with the CPC's products and either had many questions about how to interpret them or made assumptions based on the wording. For example, one group initially interpreted "EC" (i.e., equal chances) as a prediction of a 50/50 chance of normal precipitation. Several participants were concerned about how to interpret percentages above normal without knowing the normal value. On the three-month CPC predictions, probability and forecaster confidence were sometimes conflated.

Overall, participants wanted to see more explanatory text that included confidence levels associated with each product. They also wanted probabilities as best, worse, and most likely scenarios, though some indicated they wanted probability values directly on the maps. Others noted that they would ignore actual values if they saw words like “high” or “low” on a map. All but one participant wanted probability information for all forecasts, not only extreme events.

The exercise ended by bringing all groups together to discuss the main outcomes. Their main point was that they were willing to work with technical plots, but those were only useful with a narrative explaining the forecasters’ thinking. Their personal experience using the product and their relationship with the forecasters who created the product were the two most important aspects to having confidence in a product.

Section 3.6. Summary

This workshop advised the PRES^{2}iP team how participants experience and make decisions regarding extreme precipitation events. Through discussions and activities at the workshop, we confirmed that no single threshold of precipitation was used to consider an event “extreme.” Instead, participants focus on the impacts of an event and make an array of decisions on differing timelines before an extreme precipitation event. Pre-existing relationships with NWS forecasters play a crucial role in decision-making because they can give participants more information and insight into what a forecaster is communicating, which can alleviate some of the challenges in dealing with forecast uncertainty. Finally, participants were largely unfamiliar with long-range (5+ days) forecast products, but they were willing to try these products as long as they included layperson, narrative explanations and consistency among graphics.

Information gathered from this workshop allowed the PRES^{2}iP team to center our research goals on stakeholder needs. This includes connecting statistical definitions of extended (i.e., 14-days to 3 months) extreme precipitation with impacts on the ground through resources such as the NCEI Storm Events Database (https://www.ncdc.noaa.gov/stormevents/). The PRES^{2}iP team also has applied knowledge generated by the workshop participants to investigate atmospheric conditions before, during, and after extreme events with the lead times identified by the stakeholders in mind (e.g., Jennrich et al. 2020). Work is ongoing to understand uncertainty and false-alarms in forecasting such events, as well as rainfall rates and types within events (Bunker 2020, Schroers 2020).

In the future, the PRES^{2}iP team plans to hold two additional workshops, the Product Definition Workshop (originally scheduled for Summer 2020 but delayed due to COVID-19) and the Testbed Activity Workshop (at the end of the five-year project). The Product Definition Workshop aims to clarify how research results can be translated into operational forecast products. For the Testbed Activity, participants will engage with the PRES^{2}iP team in the NOAA Hazardous Weather Testbed, where they can test our predictive tools, discuss their strengths and weaknesses, and provide the feedback needed to transition products from research to operational use in the future.

Looking back, the PRES^{2}iP team recognizes the vast value we have gained by engaging colleagues from tribes, cities, towns, counties, and states across the contiguous U.S. at the start of our research. When we have different paths the research can take, we return to these conversations to ground us. When we discuss the design of products, we think about what our colleagues said about their decisions in the field. In particular, the graduate and undergraduate students know some of the real people who both struggle with and rely on the products that our community develops. Although we have not completed our research, the value of these conversations is clear to us. We encourage others to add some aspect of stakeholder engagement into their research and development efforts too.

Section 3.7. Acknowledgements

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Chapter 4: What Floodplain Managers Want: Using Weather and Climate Information for Decision-Making

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Section 4.1. Abstract

Due to climate change, extreme precipitation events are likely to become more common in Oklahoma. Within communities, there are many types of practitioners who are responsible for overseeing planning for the future and may be able to integrate weather and climate information into their decision-making. Floodplain managers from across Oklahoma were interviewed to learn what information they currently use and how it informs their decisions. When making decisions in the short-term, floodplain managers were likely to use weather forecasts. For long-term decisions, other factors such as constrained budgets or the power of county officials had more influence than specific climate predictions or projections. Overall, weather and climate information is just one component of floodplain managers' decision-making process, and the atmospheric science community could work more collaboratively with practitioners so they can make more informed decisions about the future.

Section 4.2. Introduction

Since 1980, flooding and heavy precipitation events have caused an average of four billion dollars in damage per year in the United States (NOAA National Centers for

Environmental Prediction 2020). These heavy precipitation events impact transportation (e.g., Suarez et al. 2005), public health (e.g., Exum et al. 2018), agriculture (e.g., Rosenzweig et al. 2002), tourism (e.g., Craig and Feng 2018; Meseguer-Ruiz et al. 2021), and more. Because they often make decisions related to development and infrastructure in their jurisdictions, floodplain managers are uniquely situated to be impacted by heavy precipitation events and flooding. Floodplain managers are responsible for understanding physical processes related to flooding; managing how human interactions and development change floodplains; developing policies, guidance, or plans for their jurisdictions; and overseeing infrastructure design and construction (Association of State Floodplain Managers 2010).

The decisions floodplain managers make depend on meteorological forecasts, because in the short-term, these forecasts can provide advanced notice of heavy precipitation events that may impact, for example, daily road paving activities. In the long-term, projections indicate what conditions may be like in warmer climates with higher moisture-carrying capacity. As meteorological predictions become more skillful, especially at longer lead times such as those associated with the sub-seasonal or seasonal timescales (about two weeks to three months), floodplain managers may be given more advanced notice of impending precipitation events, empowering them to take action ahead of time and prepare their communities.

There are multiple types of predictions available related to heavy precipitation events. Short-range weather forecasts generally are any forecast with a lead time of less than 10 days and are produced by both National Weather Service local offices and national forecast centers. These forecasts provide specific information about precipitation amount and timing, as well as impacts across the country, and can be either deterministic (i.e., exact conditions at a specific time) or probabilistic (i.e., probability of an event occurring at a specific time or range of times).

Forecasts for slightly longer lead times, usually between 10 days and 30 days, are considered sub-seasonal forecasts. In the United States, NOAA's Climate Prediction Center (CPC) produces sub-seasonal forecasts that communicate which portions of the country may experience above or below average conditions related to temperature and precipitation. Finally, seasonal forecasts, also produced by the CPC, have a lead time of 0.5 to 12.5 months and are exclusively probabilistic. These products communicate how likely it is for a given area to experience conditions that differ from its normal climate.

These different types of predictions can play a key information role for decision-making and planning, especially for those working in fields related to resource management, such as floodplain managers. Previous research has identified multiple methods of conceptualizing this decision-making process related to weather-related alerts, including the Protective Action Decision Model (PADM) developed by Lindell and Perry (2012). The PADM has been applied to multiple short-term hazards, including tornado warning response (e.g., Ripberger et al. 2019; Sherman-Morris et al. 2020), flash flooding response (e.g., Companion and Chaiken 2017), or wildfire response (e.g., Kuligowski 2021; Santana et al. 2021). While the PADM has been applied to some water-related hazards, little prior research has focused on applying the model to long-term precipitation hazards that evolve more slowly over time, such as those on the sub-seasonal to seasonal timescales.

The PADM (Figure 7) is conceptualized as an iterative process that begins with environmental and social cues (e.g., experiencing street flooding or observing the behavior of other people), as well as warnings (e.g., receipt of a weather forecast). The next step is the pre-decisional processes: exposure, attention, and comprehension (Lindell and Perry 2012). First, a floodplain manager has to be exposed to the cues or warnings, then decide to heed the information, as long as they comprehend the information. After the pre-decisional processes, someone making a protective action will face the protective action decision-making portion of the model, which consists of five stages: risk identification, risk assessment, protective action search, protective action assessment, and protective action implementation. Theoretically, by the end of these stages, a decision-maker will have assessed the risk they face, decided among possible actions to take, and implemented one of those actions.

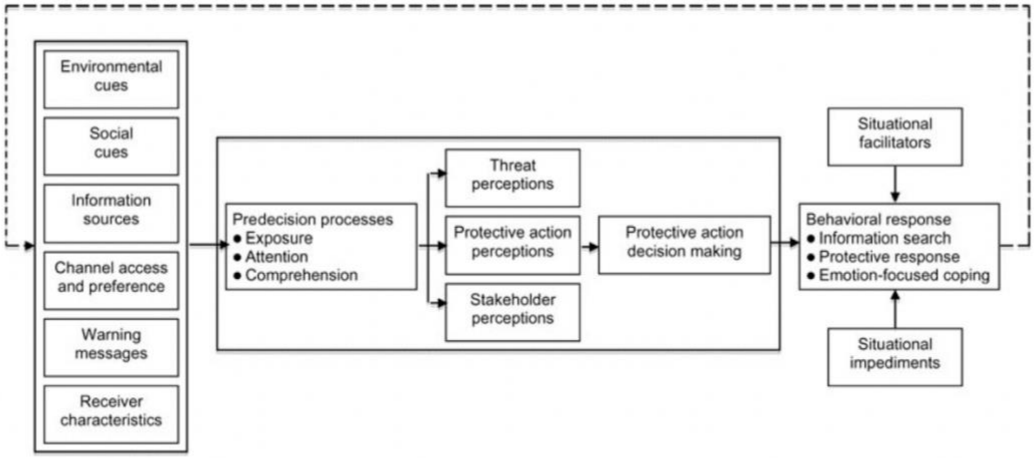

Figure 7: The Protective Action Decision Model (PADM), as described in (Lindell and Perry 2012). Environmental and social cues (left section) are two types of information that can initiate protective action decision-making. A message recipient will face psychological processes (center) to assess their level of risk to a given hazard and determine which action they should take to protect themselves. Then, they will respond to the risk assessment (right) by seeking more information or heeding a warning message. The sequence repeats iteratively until a protective action is taken.

This process of searching for a protective action will repeat, driven by the communication action assessment portion of the PADM (Fig. 7) In many cases, people will search for more information to guide how they respond to a hazard. The types of information that floodplain managers search for varies widely and is not always related to weather forecasts. For hazards such as flooding or heavy precipitation events on the sub-seasonal or seasonal timescale, a lack of urgency about hazard impacts could lead floodplain managers to continue searching for information and wait for more certainty in the forecast, instead of acting ahead of time when long-term forecasts become available.

Given the variety of weather and climate information available for decision-making, there are many potential applications to water and floodplain management. In 2013, the United States Army Corps of Engineers compiled a report that details different types of information water managers use for making decisions. In the short-term, this information includes river gauge observations or precipitation predictions. It was common for water managers to obtain this information from observational networks such as state mesonets or the Snow Telemetry Network (SNOTEL) which is used to monitor snowpack, precipitation, and temperature (Schaefer and Paetzold 2000). Information on the sub-seasonal timescale was used less frequently, although water managers did use quantitative precipitation forecasts from NOAA's Weather Prediction Center. On longer timescales, such as those associated with seasonal forecasts, water managers used the U.S. Drought Monitor or outlooks produced by the Climate Prediction Center to make decisions regarding long-term water supply. Overall, forecasts used by water managers covered a range of timescales and were used for decisions such as responding to flooding or planning for long-term water availability in their jurisdictions.

Even though there is a wealth of weather and climate information available to inform decisions, that does not mean forecasts are always used by decision-makers. Many barriers exist to using these forecasts. For example, practitioners may be unsure of where to get the exact information they need (e.g., Carbone and Dow 2005; Rayner et al. 2005; Bolson et al. 2013;

Bruno Soares and Dessai 2016). When practitioners can access the information they need, it is not always easy to understand (e.g., Pagano et al. 2001; Coelho and Costa 2010; Taylor et al. 2015). Potential users can view forecasts as unreliable or inaccurate and, therefore, not trustworthy enough to be used for decision-making (e.g., Carbone and Dow 2005; Bruno Soares and Dessai 2016; Crochemore et al. 2021).

In addition to problems accessing and understanding forecasts, floodplain managers often work in complex institutional systems that add a layer of complexity to their decision making. One challenge is the fragmentation associated with water and floodplain management, because water is often overseen by multiple agencies or departments within a jurisdiction (Rayner et al. 2005). Additionally, being a floodplain manager is often one component of someone's job, and they will have other responsibilities to balance. Another challenge is a floodplain manager's inability to change policies and procedures in their jurisdiction (Steinemann 2006) or reactive policy changes that only arrive after a community has experienced a disaster (Pagano et al. 2001). Finally, budgets and financial resources in a jurisdiction significantly limit which floodplain management strategies are implemented and how likely a community is to invest in long-term improvements and plans (e.g., Ramos et al. 2013; Arnal et al. 2016). Because of the multiple challenges that a floodplain manager may experience in their position, it can be difficult for them to act on weather and climate information, even if they are able to access it and interpret it for their local area.

Drawing on this literature and a prior stakeholder engagement workshop, the purpose of this study was to understand how floodplain managers in Oklahoma currently use weather and climate information to make decisions and opportunities for future use. Building on the Protective Action Decision Model, I developed three research questions: (1) What forecast information do floodplain managers use to plan for extreme precipitation events and where do they obtain this information from?; (2) How do different forecasts influence the decision-making timeline of a given floodplain manager?; and (3) What types of forecast information do floodplain managers wish they had when making decisions in their jurisdictions?

Section 4.3. Methods

Section 4.3.1. Context

In 2018, the Prediction of Rainfall Extremes at Sub-seasonal to Seasonal Periods (PRES^{2}iP) project hosted a three-day workshop at the University of Oklahoma with water and emergency managers and tribal environmental professionals from around the country (VanBuskirk et al. 2021). During this workshop, the PRES^{2}iP team learned how different practitioners plan for and make decisions regarding heavy precipitation events. According to workshop participants, practitioners are likely to focus on short-range forecasts, even if long-range forecasts are available to them. Because of this response to heavy precipitation events, I investigated if other practitioners may be more likely to use forecasts on the sub-seasonal to seasonal timescale. I chose to focus on floodplain managers, as their job responsibilities may affect long-term development and planning in their jurisdictions (Association of State Floodplain Managers 2010) and are affected by heavy precipitation events. To understand how Oklahoma floodplain managers are making decisions using weather and climate information, I conducted interviews with floodplain managers across the state.

Section 4.3.2. Sampling

The climate in Oklahoma varies widely. Western Oklahoma receives 20 to 30 inches of precipitation annually, on average, whereas eastern Oklahoma receives 40 to 50 inches of precipitation per year (Oklahoma Climatological Survey 2011). My goal was to recruit participants from across the state to reflect this gradient in precipitation. To do so, I used both purposive sampling (Tongco 2007) and snowball sampling (Goodman 1961), as follows. Initially, I emailed county floodplain managers to recruit potential interview participants using a list maintained by the state water agency. After exhausting this list of county floodplain managers, for a second round of recruitment I emailed county emergency managers to ask if they could connect me with floodplain managers in their community. Additional participants were recruited from a list of presenters at a recent Oklahoma Floodplain Managers Association conference and personal recommendations. My goal was to interview 5-10 people, as recommended by Creswell and Poth's guidelines (2018) for qualitatively assessing phenomena—in this case the decision-making process of floodplain managers—and ultimately, I conducted 8 interviews. Participants were the decision-makers regarding severe weather and precipitation within floodplains who might use weather or climate information to make their decisions.

Section 4.3.3. Interview guide

I designed my interview guide—composed of questions to directly answer my research questions—based on findings from the PRES^{2}iP workshop and the Protective Action Decision Model (Lindell and Perry 2012). For instance, at the stakeholder workshop described above, participants indicated they used a variety of weather and climate information to make decisions, so interview questions asked participants to state what types of information they use (Table 1, RQ1). Additionally, the PADM addresses how recipients utilize forecasts to make decisions in response to natural hazards, so I wrote questions to understand how floodplain managers use and act on different weather and climate information (Table 1, RQ 2 and 3). My goal was to understand what information floodplain managers use to make decisions and how they are coming to those decisions. Table 3 displays the research questions.

Table 3: Research questions and associated questions from interview guide

RQ1: What forecast information do floodplain managers use to plan for extreme precipitation events and where do they obtain this information from?	**RQ2:** How do different forecasts influence the decision-making timeline of a given floodplain manager?	**RQ3:** What types of forecast information do floodplain managers wish they had when making decisions in their jurisdictions?
1. What forecast products do you use when making decisions? 2. In what ways has this forecast information been useful to you? 3. Where do you get forecast information from? 4. When and how often do you use these forecasts? 5. How do you use the forecast information to prepare for flooding?	1. When and how often do you use these forecasts? 2. How do you use the forecast information to prepare for flooding? 3. Who do you talk to when making a flooding related decision? 4. How do your discussions with these individuals shape your decisions? 5. Can you give me an example of a time one of those conversations led to a specific decision? 6. Your area experienced a flood in X year. Has your usage of forecast information changed since then?	1. Based on your previous experiences with flooding, in preparing for a future flood, what forecast elements would be most useful to you? 2. Is there information that you don’t currently have that you wish existed when making decisions related to floodplain management?

Section 4.3.4. Data collection and sample description

Prior to contacting potential participants, my study was reviewed and approved by the University of Oklahoma’s Institutional Review Board (study number: 13548). To recruit participants, I emailed individuals from the sources listed earlier (Section 4.3.2), describing the purpose of the study, commitment required, timeline for scheduling interviews, and required paperwork to be completed. Interviews were semi-structured, leaving room for follow-up questions to participants’ responses as needed. All interviews took place via Zoom and, on average, lasted between 45 minutes and 1 hour. I recorded and transcribed interviews. I did not compensate participants for their time.

Section 4.3.5. Analysis

I analyzed my data using thematic analysis, first developing codes, then creating code categories, and synthesizing codes into themes about the data (Figure 8). First, I read each transcript, coding text relevant to my research questions and developing codes as I read—a process known as open coding (Braun and Clarke 2006). I conducted my first round of coding based on the content of my interviews, where statements about different topics were coded together. This process resulted in 35 codes of two types: characteristics of the data and descriptive statements. Characteristics of the data included: (1) types of information that floodplain managers used, (2) sources of weather and climate information, and (3) types of decisions being made. Descriptive statements included: (1) someone explaining their role and experience in floodplain management and (2) challenges floodplain managers faced in their jobs.

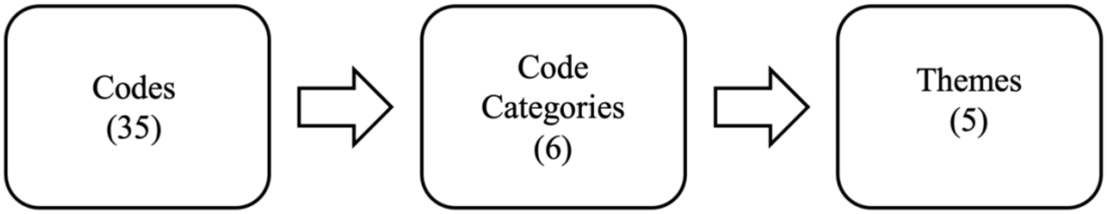

Figure 8: Coding and thematic analysis process. Interview quotes were categorized into codes describing different characteristics of the data, such as statements about budgets, challenges managers faced in their positions, or about specific information sources like the National Weather Service, email, or professional colleagues. These codes were then grouped into six categories based on shared characteristics, and the categories were then collapsed into five themes describing research results.

After initial coding, I completed a second round of coding to combine the 35 codes into six different categories: types of weather/climate information, sources of weather/climate information, practitioner partners, types of decisions, decision making factors, and desired information. I then inspected and analyzed these categories in light of my research questions and theory, collapsing them into five themes (Saldaña 2009). These themes described findings to address my research questions and added new insight from the interviews regarding the Protective Action Decision Model.

Section 4.4. Findings

I completed 8 interviews with floodplain managers, who represented decision-makers at the city, county, and state level (Figure 9). I interviewed participants in two main regions: the Oklahoma City metropolitan area and eastern Oklahoma, both of which experience more precipitation and flooding than western Oklahoma. All interviewees were current or former floodplain managers, though current occupations varied slightly across the sample. Five participants were active floodplain managers, one was a consultant, one was an emergency manager, and one was an engineer. The consultant, engineer, and emergency manager were all responsible for decisions related to floodplains and development.

Most of my analysis was focused on my research questions and themes; however, there are other findings worth mentioning, particularly the influence of climate change on floodplain management. During the interviews, some floodplain managers discussed climate change and how they are dealing with its impacts in their jurisdictions. All floodplain managers who discussed climate change were aware of its impacts but did not use specific forecast products or climate projections to make decisions related to long-term planning. Instead, these decisions were shaped more by existing problems, such as routine neighborhood flooding, and not potential future climates. Grappling with climate change was a challenge for some floodplain managers; for instance, one interview participant said:

> "At the county level as far as climate change goes, that is probably a newer topic. You know, it's not something we've really addressed as of yet. I think it's something that the more and more it's talked about, it's something that we're going to have to address at some point. I don't know how as the county we can do that just because the county we're a lot more, I'd say financially constrained than cities."

My main analysis that addressed my research questions resulted in five themes: (1) *Types of decisions:* types of decisions that floodplain managers make, (2) *Information overload:* types and sources of information used by floodplain managers, (3) *Social network:* people involved in the decision-making process, (4) *Outside factors:* additional factors that influence decisions, and (5) *Wishful thinking* desire to use forecast information that may not be available yet. Table 4 summarizes the themes and codes.

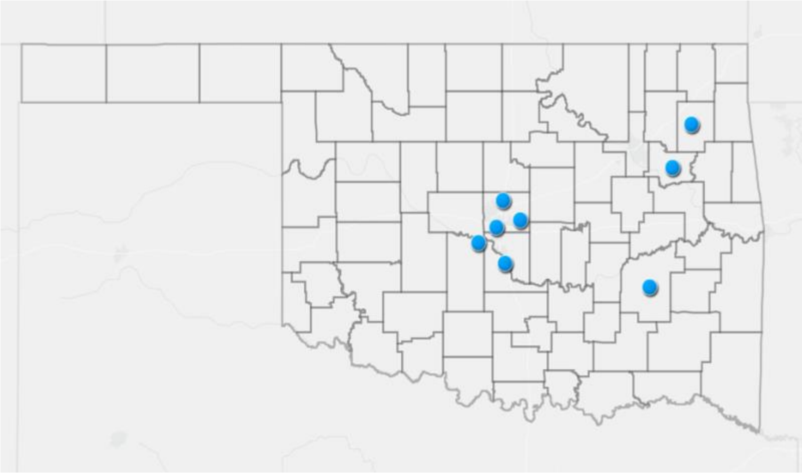

Figure 9: Location of interview participants.

Section 4.4.1. Theme 1: Types of decisions

Throughout the interview process, each person described different types of decisions that they are responsible for making in their position. Decisions occurred across a variety of timescales, ranging from responding to events in real-time, to long-term planning for their jurisdiction. In the short-term, decisions often were being made as a response to the onset of precipitation or the expectation of a precipitation event within the next two to three days. Most frequently, participants were responsible for planning construction or road paving activities that could be impacted by any type of precipitation. For example, they could have to decide how far to pave a road one day such that they could complete both sides of the road if precipitation was expected the next day. Additionally, weather forecasts could be used to prepare job sites ahead of precipitation, ensuring topsoil was protected or clearing storm drains ahead of precipitation. Weather forecasts also were used to prepare within a community, by staging barricades for closing roads or notifying residents they may need to evacuate depending on the intensity of impacts.

Participants were less likely to make decisions on the sub-seasonal to seasonal timescale. Many were not making those types of decisions at all, rather only focusing on much longer timescales. When participants were making decisions within these longer timescales, they often did not consult different predictions or projections for their jurisdictions. Instead, their decisions were shaped and guided by experiential knowledge they had about rainy or dry seasons in their area.

For those who did make sub-seasonal to seasonal decisions, they mentioned scheduling more staff during the time most impacts were expected or preparing resources to respond to flooding. Others described that they may send crews to clear ditches and remove debris around creeks or storm drains to alleviate any potential flooding. These activities depended on the availability of employees and what other projects were in progress. At the seasonal timescale, floodplain managers mentioned planning construction projects or other large-scale developments around the spring and fall rains that they commonly experienced each year.

Floodplain managers also frequently made decisions for their communities related to long-term planning and development. These decisions included preparing for facility maintenance, or monitoring and maintaining canals within a jurisdiction, making repairs as needed. Other decisions were related to addressing flooding issues in localized areas, with some floodplain managers seeking funding from the federal government to relocate neighborhoods that flooded often. Others addressed persistent roadway erosion due to rivers and streams in their jurisdictions and made plans to move or redesign roads as needed. The engineer who was interviewed designed and planned the construction of new infrastructure and bridges throughout the state. Finally, floodplain managers also worked with others in their jurisdictions to develop multiple types of long-term plans related to community development. These documents included master drainage plans, rezoning and development plans, stormwater plans, and hazard mitigation plans.

Overall, floodplain managers were responsible for decisions across multiple timescales in their jurisdictions. These timescales could range from responding to precipitation events as they are happening or preparing for the long-term impacts of heavy precipitation events. Decisions were influenced by multiple factors, including different types of weather and climate information, shared information within a floodplain manager’s social network, or even other factors such as a community’s budget, all of which will be discussed in depth below.

Table 4: Summary of themes (left), their descriptions (center), and associated codes (right) from thematic analysis of participant interviews.

Theme	Description	Codes in Theme
Theme 1: Types of decisions	Practitioners make a variety of decisions across timescales	Short timescale decisions, extended range (s2s) decisions, long-term planning decisions, climate change
Theme 2: Information overload	Multiple types and sources of weather and climate information are used to make decisions	Weather information, extended range (s2s) forecast information, precipitation, temperature, radar/satellite, soundings, seasonal forecasts, historical data, face to face communication, web, NWSChat, NWS, mesonet, TV/media, email
Theme 3: Social network	Multiple people and relationships influence how decisions are made	External partners, internal partners, commissioners, stakeholders
Theme 4: Outside factors	Other factors, such as budgets or amount of authority, influence decisions	Financial challenges, job related challenges, forecast accuracy, lessons learned, day to day management/job responsibilities, public awareness, past experience, role/experience, frequency
Theme 5: Wishful thinking	Practitioners want information and forecasts that cannot be physically predicted	Desired info, forecast accuracy

Research Question 1: What forecast information do floodplain managers use to plan for extreme precipitation events and where do they obtain this information from?

Section 4.4.2. Theme 2: Information Overload

Floodplain managers used a variety of weather and climate information from multiple sources to make decisions in their jobs regarding all types of hazards, not only extreme precipitation events. Information ranged from real-time observations and short-term weather forecasts to seasonal forecasts. These observations and forecasts covered multiple atmospheric variables, such as temperature, wind, and precipitation. Specific information included precipitation and temperature forecasts, radar and satellite products, atmospheric observations from weather balloons, and even historical precipitation observations and stream gauge data.

Floodplain managers received weather and climate information from multiple sources. Information came from the Oklahoma Mesonet (a network of surface observation stations across the state), broadcast meteorologists, email blasts, other government agencies such as the Federal Emergency Management Agency (FEMA) or the United States Geological Survey (USGS), and face-to-face communication with National Weather Service forecasters via NWSChat (a messaging tool used by the NWS to communicate during high-impact weather events). Participants with emergency management experience were more likely to use more technical information (i.e., satellite data or atmospheric conditions) than those without emergency management experience.

Section 4.4.3. Theme 3: Social Network

This theme encompasses all the ways that participants described how colleagues in their network help them make decisions. For example, practitioners relied on their networks to receive and interpret weather or climate information. Often, colleagues in neighboring communities served as sounding boards ahead of an event and provided an outside perspective on what impacts a given community might experience. As explained by an emergency manager:

> “He’s [emergency manager in a nearby city] pretty much a weather geek. So, he’s a really great resource because he stays on top of all of this, and I like to just get his opinion on what he thinks is going to happen. I’ll make my own decision, but I’ll certainly seek input from those people whose judgement I’ve learned to trust.”

In this instance, both emergency managers had access to the same forecast information, but their discussions could reinforce how each person was interpreting the forecast and preparations could be made accordingly.

NWS forecasters were also crucial sources of information for floodplain managers, especially in the few days leading to an event. Some floodplain managers had close relationships with specific forecasters at their local weather service office and would call the office ahead of an event to discuss forecast details. Others accessed forecasts on their own from the NWS website. Overall, it was clear that the NWS was a key source of trusted forecast information that floodplain managers utilized.

Section 4.4.4. Theme 4: Outside Factors

Prior experience with a flood also influenced how a floodplain manager made decisions for their community. Every floodplain manager who was interviewed had experience with flooding in their community that either caused them to change policies or affirmed that previous changes to policy were beneficial. For example, one manager described how a flood in 2016 had led their community to develop a canal-wall mitigation plan to monitor whether canals needed maintenance. When another flood impacted the community in 2019, this plan had helped identify possible failure points in the canals and did maintenance ahead of time, so the community had no canal failures in the second flood. A different floodplain manager described how a series of floods proved that home buyouts in part of their jurisdiction were helpful because homes that previously had flooded routinely were moved out of the floodplain. By taking previous experiences and incorporating them into new policies or practices, floodplain managers were able to be better prepared for the next flood that impacted them.

Research Question 2: How do different forecasts influence the decision-making timeline of a given floodplain manager?

Section 4.4.5. Theme 2: Information Overload

Floodplain managers often used information in real-time to respond to impacts their community was experiencing. For example, one floodplain manager stated: “I’m looking and seeing what the radar predictions are from the news channels and the Weather Channel and then I'm watching real-time radar as it's happening. I'm using real-time data." During an event, real-time observations helped guide emergency response and where additional resources would be needed.

Besides radar and satellite products, another source of these real-time observations was the Oklahoma Mesonet (McPherson et al. 2007) which was frequently mentioned by interview participants. Floodplain managers used the Mesonet to assess impacts in neighboring communities and then applied their localized knowledge to determine what impacts their jurisdiction could face. One participant stated: "I think the Mesonet is great too, because even on flooding events, if I look at the sites that are in the South Canadian Basin, I can get a pretty good idea of if we're going to have a flood here on the South Canadian River." Mesonet data also were used after precipitation events occurred to develop reports and quantify impacts, or even to incorporate into regression formulas used for planning and bridge design.

Although not every floodplain manager interviewed used forecast information at all timescales; many mentioned using weather forecasts, seasonal climate forecasts, or some combination of both. Short-term forecasts were also important for decision-making and planning before events to help floodplain managers prepare. Prior to a precipitation event, predictions were used to assess what areas of a given jurisdiction might be impacted. Weather forecasts were helpful for day-to-day operations, diagnosing what conditions crews working in the field might experience, or planning to close roadways and prepare infrastructure for impacts of a potential hazard. For example, one floodplain manager described how weather forecasts were used to plan road paving activities, saying:

> "The rain, it influenced us by determining our paving schedule. It determined how far we went one day so that we could at least finish the other side of the road in case the rain

> came that afternoon. If the rain did come, it halted our work, but we had planned and changed the length of our half of the road paving based on the predicted rainfall."

At longer timescales, floodplain managers discussed seasonal forecasts that gave them an idea of conditions for a few months from now, but also mentioned these forecasts lacked the detail required to act on them. Instead, they were used "as a guide to help us pay attention to what might be coming." Floodplain managers also knew typical precipitation patterns associated with the seasons, stating, "I try to look out by the seasons. We've got the spring rains, we've got the fall rains, that dictates our construction season." This climatological knowledge about when precipitation was more likely did influence when projects were initialized. In general, weather forecasts were used more often to make specific decisions and seasonal forecasts were used as an alert for possible future conditions.

Finally, some floodplain managers were dealing with decision-making and planning on much longer timescales, handling recurring flooding problems that lasted decades or longer in their communities. While these floodplain managers did not use specific climate projections to assess impacts their jurisdictions might face in the future, they knew which areas of their jurisdiction were susceptible to routine flooding and thus took steps to alleviate the impacts. These actions included seeking FEMA funding to help residents move out of floodplains, re-designing infrastructure to handle more intense precipitation events, or developing new stormwater or drainage plans. For example, one floodplain manager noted: "Another thing that the city did, we developed a master drainage plan. I believe it took 6 years and it identified several hundred stormwater projects within the city and came up with a project list that was able to prioritize them." These long-term projects helped determine priority areas for floodplain managers and often aimed to make communities more resilient to flooding impacts.

However, while weather and climate information are a key component of decision-making, they are only one factor that shapes how floodplain managers make decisions. Social networks and other outside factors, such as a jurisdiction’s budget, the responsibilities and authority a given floodplain manager has, the desires of county commissioners, and public awareness about flooding issues also influence how floodplain managers are making decisions in their communities.

Section 4.4.6. Theme 3: Social Network

Multiple people in each jurisdiction have influence over issues related to floodplain management. Floodplain managers frequently discussed collaborating with their social network, including stormwater managers, county or city engineers, the public works department, emergency managers, or the transportation department. As one floodplain manager said: “When I’m seeing things that need to be done, I talk to the mayor, the director of public works, our city planner, our code inspector, maybe our emergency manager, and our street superintendent. Every one of those people are involved in some way with stormwater or floodplain management from an administrative or technical point of view.” Floodplain managers are not acting in isolation when it comes to floodplain issues. Instead, they work with colleagues and other professionals to develop plans and solutions to problems that arise.

Finally, public awareness and public input played a role in the development and implementation of some floodplain-related projects, like building new bridges, creating new stormwater facilities, or identifying flooding problems in a community. Thoughts from members of the public were described both positively and negatively, as they can be sources of new ideas or help identify issues in a community. Dealing with public frustrations, however, was a challenge for floodplain managers, for instance one floodplain manager explained:

> “And that’s the problem with floodplain management and stormwater management. When there’s an event, everybody says, right away, ‘let’s fix this stormwater problem.’ But two weeks later, all they care about is the street in front of them because it’s got a pothole. So, my business and everybody that’s in my business, we’re always struggling to help educate the people on why we are doing this.”

However, keeping public attention on flooding for a long period of time can be difficult, but many floodplain managers noted that recent floods enable progress with new facilities or projects because members of the public are reminded of the impacts of flooding. Despite this, it can still be difficult to sustain passion for change, especially when residents realize the cost of fixing stormwater or floodplain issues.

Section 4.4.7. Theme 4: Outside Factors

Besides working in complex networks of other practitioners and the public, floodplain managers also deal with other complicating factors when it comes to decision-making. One of the biggest challenges expressed by participants was their jurisdiction’s budget. Nearly every participant mentioned how their ability to implement solutions was constrained by the availability of funding. Even if a solution to a floodplain issue was identified, it was not always possible for that solution to be put into practice, as described in the following quote:

> “The problem is that it all takes money. Everything comes back to money. And they [the county commissioners] can say ‘We don’t have the money to do that. We understand what you’re saying, we know you can come up with a technical solution. But that solution costs money, and where is that money going to come from?’”

Identifying funding sources and applying for external grants were large obstacles that participants must overcome.

Additionally, some participants lacked the authority and agency to make their own decisions. Floodplain managers had to get approval from those in their social networks for decisions, including those related to personnel and field operations, and large-scale decisions related to long-term planning or development. As one interview participant explained, “I’m very limited on my authority. Not only in the field, but when it comes to city personnel too. I cannot dictate and tell crews what to do. I can make suggestions and run it up the chain of command. And for the most part everyone is on board because no one wants to see flood damage.” The added layer of complexity associated with running decisions by others with more authority was a common point of frustration for participants, especially when they felt capable of making those decisions themselves.

Outside of weather and climate information or professional colleagues, there are other factors that influence the decision-making of a given floodplain manager. Although not directly related to weather or climate, these factors also play a large role in shaping decisions. County commissioners were key players in decision-making, and, in some cases, they were able to use their authority to determine the scope of floodplain management projects. As one participant explained: “I also work with the commissioners, who are basically the bosses of the county.” These leaders had power over which projects were funded at the county level, and floodplain managers frequently had to communicate updates or new plans with them. Commissioners also could dictate which projects occur in their jurisdiction and provide suggestions for future construction projects. Then, floodplain managers would be responsible for determining how to implement those projects within existing rules and regulations, as exemplified by one participant: “Obviously if there’s something they [the commissioners] want to do, you’re going to try and find a way to make it happen.” Another floodplain manager explained:

> “At the end of the day, it’s up to the commissioners. Pretty much everything we do has to go to the Board of County Commissioners. So, it’s public meetings, and they vote on topics. At the end of the day, it’s their decision of either making it happen or not.”

Overall, even if a floodplain manager was able to use weather or climate information and their professional network to come to a decision, whether that decision moves forward was reliant on commissioners' ultimate approval.

Other challenges were mentioned as well, though less frequently than those related to budgets or authority. For example, one participant had multiple responsibilities outside of floodplain management, such as hiring new personnel, dealing with insurance claims, or overseeing training for employees. Others mentioned how hard it could be to navigate the rules and regulations surrounding development within their communities and at the state level. Local politics associated with funding projects and resource allocation were also challenges, especially for those working at the county level. Finally, some interview participants mentioned that in their communities, stormwater and floodplain management are afterthoughts to their superiors in the decision-making hierarchy, so it could be difficult to make progress on projects.

Overall, floodplain managers were not solely relying on weather or climate information to make decisions. Instead, they were working within complex social networks with multiple colleagues and practitioners involved in developing and seeing a project through. County commissioners could dictate which projects are funded—if money were available at all for floodplain-related issues. Even if the best weather and climate information were available, floodplain managers may not be able to use it to develop solutions to problems they face because of these other outside factors.

Research Question 3: What types of forecast information do floodplain managers wish they had when making decisions in their jurisdictions?

Section 4.4.8. Theme 5: Wishful Thinking

While there are multiple types of forecast information currently available with which to make decisions, floodplain managers also desired new kinds of forecasts to guide decisions in their jobs. However, floodplain managers desired some forecast products that the meteorology and climatology communities cannot physically predict, given the current state of forecasting. Floodplain managers want forecasts at precise locations, stating “Of course, it would be great for them to pinpoint precisely what square mile where the rain is going to hit” or “Getting more localized is always a good thing.” Beyond a few hours ahead of time, it can be challenging to pinpoint precise precipitation amounts at the county level or more localized spatial scales.

Floodplain managers also wanted more localized, long-term forecasts as well. These desired forecasts could be used to guide bridge design or stormwater plan developments for specific infrastructure or projects. One engineer even explained that it would be helpful to have forecasts for specific rivers or watersheds far into the future: “It would be cool if there was some sort of prediction you could count on. And if that prediction could say ‘well we need this bridge bottom beam elevation to be here because in 20 years, they’re predicting an increase in water surface elevation and it’s 99% accurate.’ That’d be great.” Currently, these types of predictions with such a long lead time and spatial precision are not possible (Dessai et al. 2009). However, the climatology community does produce different climate projections that provide a range of possible future conditions under different scenarios (IPCC 2021). These projections are generally produced for the entire globe with global climate models operated by multiple national and international agencies. Projections are then downscaled for use at local levels (Barsugli et al. 2013) by the agencies that produce them as well as universities or other research institutions.

Finally, floodplain managers identified additional types of information that would be helpful to them in their positions. One explained that having contact information for other decision-makers in their jurisdictions (e.g., other professionals in floodplain management) would be helpful for growing their professional network and discussing challenges. Better real-time data was also highly requested, with multiple participants desiring more Oklahoma Mesonet stations or USGS river gauges so they could have higher spatial resolution of observations. Additionally, participants wanted easier access to historical rainfall data, with some noting that the data were available, just not always in a format that was easy to use. Much of this desired information is difficult for the atmospheric science community to provide under current funding and priorities.

Section 4.5. Discussion and Conclusions

Floodplain managers use a variety of weather and climate information from multiple different sources when they are making decisions within their jurisdictions. Besides this information, other outside factors influence how decisions are made, such as inadequate availability of funding, desires of county commissioners, and limited authority of the floodplain manager. Often, these outside factors are more influential than a given weather forecast or climate prediction. Additionally, even if the best forecasts were available, floodplain managers may not be able to act on them. Finally, when making decisions, floodplain managers desire forecast information that the atmospheric science community may not be able to predict given the current state of forecasting, indicating a disconnect between the people producing forecasts and those who are using the forecasts to make decisions.

Four of the five themes resulting from the interviews align with one or more of the environmental and social cues or sources in the Protective Action Decision Model (Lindell and Perry, 2012). *Information overload*, describing the types of weather and climate information floodplain managers use and where they obtain this information, relates to the environmental cues and information sources described in the PADM (Table 5). *Social network* (i.e., the people floodplain managers work with to make decisions) are types of social cues in the model. *Wishful* *thinking* is associated with PADM's information sources, with floodplain managers identifying new types of forecast information they would like to receive. All of these different factors can contribute to someone seeking protective action against heavy precipitation events.

Table 5: PADM elements (left) and overlap with themes (right)

PADM Elements	Themes
Social cues	Social network
Environmental cues	Information overload
Information sources	Wishful thinking
Decision process and information search	Types of decisions

Additionally, *types of decisions* are related to a different portion of the PADM – the decision process and information search – where forecast recipients seek out additional information about a hazard and make decisions based on that information. Lindell and Perry describe a specific type of decision–hazard adjustments – or hazards with longer lead times, like those on the sub-seasonal or seasonal timescales. Although long-term forecasts are available and can provide substantial advanced notice, floodplain managers were likely to continue waiting until an event got closer in time before making decisions. However, for recurring problems like routine neighborhood flooding, some floodplain managers did take action. These decisions related to recurring problems were not necessarily influenced by different forecasts or predictions. Instead, they were influenced by public pressure to limit flood damage or the knowledge that flooding would continue to be a problem if not addressed.

Lindell and Perry (2012) include multiple inputs into the PADM, such as social cues or information sources, and the model assumes that people are seeking protective action based solely on relevant forecast information or social and environmental cues. However, none of the inputs of the PADM are defined to include outside factors that may also influence protective action decision-making and the model should be adjusted to include these factors. While forecasts and predictions are one important component of decision-making, they are not the sole piece of information that influences floodplain management. Often, forecasts and predictions are used to supplement decisions that are dictated by budgetary constraints or the desires of county officials with more authority. Although Lindell and Perry acknowledge situational impediments (e.g., lack of access to a personal vehicle to evacuate) at the behavioral response stage, the outside factors that I describe here could contribute to our understanding of structural impediments to decision-making. Overall, the influence of weather and climate information as well as social networks fits well with social and environmental cues in the model, however, the model fails to account for outside factors that also influence decisions and should be amended to include these factors.

When asked about types of information related to heavy precipitation that they would like to have but currently do not, multiple floodplain managers asked for very specific forecasts at localized levels (i.e., within a given square mile), with long lead times (multiple years ahead of time). While this level of specificity is not necessarily possible to provide, it is important for the atmospheric science community to understand the needs of their various stakeholders when producing new forecast information.

One way to strengthen the content of cues and warning messages in the PADM is by working with stakeholders to co-produce scientific knowledge and new forecasts. Knowledge co-production has multiple benefits, including an increased likelihood that final products will be used and considered trustworthy (Cash et al. 2003). Additionally, co-produced knowledge is often more easily understood and clearer to final users because it is written and communicated in familiar language (Jasanoff and Wynne 1998). Finally, co-produced forecast information is easier to integrate into the existing decision-making processes that stakeholders have (Lemos et al. 2012). By working with floodplain managers to use and interpret different types of forecast products—such as through the workshop described earlier—the atmospheric science community can explain components of the forecast. Then, combining forecast information with their localized expertise on flooding, floodplain managers can apply knowledge to make more informed decisions for their communities.

Even if floodplain managers were to have perfect weather and climate information, other factors often stand in the way of applying it. Because budgets are usually limited, managers are not always able to implement technical solutions to floodplain management problems, even if they know what actions need to be taken. Additionally, county commissioners can control which projects move forward in their jurisdiction, leaving floodplain managers to figure out how to make those projects happen, even if those projects are not the most pressing issues in a jurisdiction. Overall, these constraints mean that climate-informed floodplain management often does not happen, and communities are not taking advantage of the wide variety of forecast information available, leaving them vulnerable to changing conditions future climates.

Section 4.5.1. Study Limitations and Future Directions

This study highlighted how floodplain managers in Oklahoma use weather and climate information to make decisions for their jurisdictions. However, the research had limitations. First, the participant pool did not capture decision-makers from the entire precipitation gradient across Oklahoma. Floodplain managers in the wetter, eastern portion of the state may have to use different management strategies than floodplain managers in the drier, western portion of Oklahoma. Additionally, parts of Oklahoma will face different types of climate change impacts, requiring floodplain managers to adapt in a variety of ways. Second, the study only included participants from one U.S. state. Oklahoma has its own guidelines and regulations for floodplain management; these vary by state and influence how decisions are being made. Third, no floodplain managers who oversee tribal jurisdictions were interviewed, yet the region encompasses lands of 39 tribes, each with their own government and set of policies. Large tracts of land where tribes manage their own natural resources also will face the impacts of climate change, often with fewer resources than non-tribal land. Therefore, future research should expand this work to issues affecting tribal land. Future work also could investigate how floodplain managers might use climate projections in their area for long-term planning or increase communication between floodplain managers and those making predictions to provide contextualized, local information that can be used in decision-making.

Section 4.5.2. Conclusion

As the climate continues to become warmer, and in some locations, wetter, Oklahoma will face new issues related to floodplain management. Precipitation events are projected to become less frequent, but more intense, meaning more precipitation will fall in a given event (Kloesel et al. 2018). The increase in intensity of precipitation events may exacerbate existing flooding issues. For example, outdated stormwater infrastructure could be overwhelmed by a larger volume of water in the system. Areas that did not previously flood may begin to experience flooding more routinely when more precipitation falls, and neighborhoods may need to be relocated, as one interviewee noted. Existing infrastructure (i.e., roads and bridges) may not be built to withstand increasing precipitation amounts. These impacts affect the decisions that floodplain managers make, so it is imperative these practitioners are engaging in climate-informed, long-term planning for their communities.

By improving floodplain management measures now, communities can be better prepared for the future and reduce the impacts of flooding. There appear to be gaps between what research suggests are best practices for floodplain management and what floodplain managers actually do. First, in some conversations with practitioners (VanBuskirk et al. 2021), managers have mentioned working with their professional networks to establish stronger connections between departments in their jurisdictions, thereby implementing a cross-government approach. For example, floodplain managers who regularly interface and collaborate with public works or stormwater management could use those existing relationships to explore long-term solutions for dealing with water and flooding. Second, city councils and other elected bodies could review the distribution of power to ensure that floodplain managers have the authority necessary to move forward with climate-informed decision-making.

Floodplain managers are not the only people who are impacted by communities not using climate information for long-term planning, and residents or other community members also face impacts. Climate change will disproportionately impact those that are already most vulnerable and have the fewest resources in communities, leaving them susceptible to the impacts of more routine flooding. However, floodplain managers and climate-informed floodplain management could help reduce vulnerability. For example, managers could assist vulnerable residents with moving out of floodplains or other flood-prone areas. Additionally, integrating floodplain management with other jurisdictional practices and processes could lead to better and more holistic decision-making. Climate change is one of the biggest issues facing communities across the world, and ensuring practitioners are making more-informed decisions for their jurisdiction enhances resilience and leaves them better able to absorb the shocks of a warmer world.

Chapter 5: Conclusions

Section 5.1. Key Findings

The work in this thesis can be summarized in two parts: (1) the description of a stakeholder engagement workshop hosted by the PRES^{2}iP project and (2) the study of floodplain managers in Oklahoma. At the PRES^{2}iP workshop, emergency managers, water managers, and tribal environmental professionals from across the United States discussed how they conceptualize and make decisions regarding sub-seasonal to seasonal heavy precipitation events. For the study of floodplain managers in Oklahoma, I conducted interviews with eight floodplain managers from across the state, representing city and county decision-makers. The interviews focused on what types of weather and climate information floodplain managers used and how it informs decision-making.

The aim of both studies in this thesis was to understand how different practitioners use weather and climate information to make decisions regarding heavy precipitation events. By engaging with water and emergency managers and tribal environmental professionals through the PRES^{2}iP workshops, as well as interviewing floodplain managers in Oklahoma, I have learned how practitioners across the country prepare for the impacts of precipitation events in their communities. Although weather forecasts are used routinely for making short-term decisions, often practitioners are not using sub-seasonal to seasonal forecasts or climate projections to make decisions and plan for the future. Instead, their long-term planning is influenced more by time constraints and a lack of financial resources, as well as the political environment and desires of their county commissioners. Consequently, even if the atmospheric sciences community can develop excellent long-term forecasts or climate projections, practitioners may not use them in their decision-making.

Thoughtfully engaging with practitioners can involve committing to the principles of knowledge co-production, informing practitioners of research results, consulting them during the research process, or allowing decision-makers to help set research agendas and goals (e.g., Bamzai-Dodson et al. 2021). Often, researchers approach practitioners with pre-designed forecast products or new tools and ask for their input, but those tools may not actually meet the needs of the practitioners. Instead, allowing practitioners to bring their needs and questions to the table and framing research agendas around those ideas can foster beneficial co-production of knowledge that benefits those attempting to use weather and climate information for decision-making.

Additionally, as prior research has shown, involving practitioners in the process of developing new tools has multiple benefits, including an increased likelihood that the tools will be used for decisions (e.g., Dilling and Lemos 2011; Norström et al. 2020). Finally, conveying information and research outputs to practitioners through already established channels, such as professional networks (e.g., Oklahoma Floodplain Managers Association, Federal Emergency Management Administration) or boundary organizations (e.g., Climate Adaptation Science Centers or Regional Integrated Science Assessments), may mean that they are more likely to receive the information, instead of relying on practitioners to actively seek out forecasts (Kirchhoff et al. 2015).

Keeping this in mind, engaging with practitioners can help researchers better connect their products to those using them for decision-making, as there are no guarantees practitioners will use research products to make decisions. This collaboration could involve physically meeting practitioners where they are when hosting workshops or meetings, as it could be difficult for some people to travel or take multiple days off work at a time. Additionally, the time of year when research activities are held is an important consideration and factor that can limit practitioners' ability to participate. This scheduling conflict was an issue for the PRES^{2}iP team, specifically when recruiting tribal environmental professionals, as many of our research activities were hosted in the late summer and early fall, which is a peak time for field work. Through all of the work contained in my thesis, I learned the importance of thoughtfully engaging with practitioners to produce research outcomes that can help inform decision-making. Additionally, I learned that power structures and institutional systems constrain decisions much more than whether a given practitioner has access to weather and climate information, and in the future, the research community could further interrogate these systems and how managers work within them to prepare for warmer climates.

Section 5.2. Implications

An issue that the weather and climate community regularly contends with is the notion that their output products are not the most influential factors in how practitioners make decisions on weather events. While weather forecasts did play a role in short-term decision-making for some practitioners, other factors like financial resources and the political desires of county commissioners were more important for long-term planning. In some cases, communities had not considered climate change in their planning processes; therefore, they did not seek long-range forecasts or climate projections.

Practitioners also do not always have the time to plan for more than a few days ahead of the predicted onset of an event, whether that be due to available staff, waiting to feel more confident in a forecast, or having other responsibilities that take precedence. Overall, even if long-range forecasts are available, practitioners are often working in complex institutional systems that can limit their ability to prepare for precipitation events more than a few days ahead of time.

When producing new forecast products or information, the atmospheric science community could begin research projects with stakeholder engagement workshops to set project goals and possible outcomes that are based in practitioner needs. Doing so would allow scientists to hear directly from the practitioners that would be using new products and shape research projects accordingly. Additionally, the atmospheric science community would benefit from becoming familiar with other constraints or barriers that practitioners contend with. These barriers shape how practitioners are able to apply any new forecast products that are developed and how managers are planning for the future in their jurisdictions.

Finally, atmospheric scientists should seek out interdisciplinary research partnerships and work with social scientists to understand not only how weather and climate information is being used, but also investigate different funding mechanisms for climate adaptation or public policy. While it is important to advance the science of weather and climate, producing better forecast products relies on understanding human behavior and social structures, which comes from working with social scientists. Ultimately, the weather and climate community has to reckon with their products not being the most important factor in decisions, and instead continue seeking out ways to produce new knowledge in collaboration with stakeholders.

Section 5.3. Limitations

While my work resulted in engagement with multiple types of practitioners, there are many other decision-makers who are not represented. For example, practitioners working in agriculture, forest management, or with wildlife also may benefit from using extended forecasts or climate projections. However, in order to have in-depth, focused conversations at the PRES^{2}iP workshops, the research team chose to focus on a subset of natural resource managers to determine if there were common messages or questions that decision-makers had regarding heavy precipitation events. Additionally, engagement with tribal environmental professionals was relatively limited because the workshops were hosted during peak field work season for those practitioners. In Oklahoma specifically, individual tribes manage large areas of land and waters. The perspectives of floodplain managers and other decision-makers working on tribal land were not represented in this work, though these communities also will face their own challenges when it comes to adapting to future climates.

Another limitation is the scope of both research projects. Each of the studies focused on how one or more groups of practitioners use sub-seasonal to seasonal forecasts related to heavy precipitation, and only considered other factors that influence decision-making if those factors were brought up by participants. While many participants did mention other challenges associated with their positions, not all of them did, so all the issues practitioners face may not be represented in this work.

Section 5.4. Future Research

This work also leaves open many possibilities for future research. As climate change continues to be an issue communities face, it will be imperative for practitioners of all types to use seasonal forecasts and climate projections. One area of research could focus on partnering with different practitioner fields and encouraging the integration of weather and climate information into existing decision-making practices. This collaboration could be accomplished through workshops or outreach events similar to the ones hosted by the PRES^{2}iP team, where practitioners are able to learn more about information that is available and how they could use it in their own jurisdictions. Another option could be researchers working directly with professional organizations to understand the needs of various practitioner groups and using the existing organizations to disseminate information. Finally, future work could focus solely on other factors that influence decision-making and the constraints that practitioners work within while planning for their communities.

Another challenge and area of future research identified by this work is the disconnect between the atmospheric science community and the practitioners who might use forecasts. In my interviews with floodplain managers especially, it was evident that some managers did not know the limits of meteorological predictability and the accuracy or skill of different types of forecasts. However, the weather and climate community often fails to understand how practitioners make decisions and use forecast information, so both sides would benefit from future work that aims to better connect research and practice.

One avenue of connecting research and practitioners is through boundary organizations. Tasked with sharing climate science with different types of decision-makers, boundary organizations play a critical role in how climate adaptation is done across the country. Going forward, these organizations could work to build stronger partnerships with resource managers who will have to make decisions that are influenced by precipitation events by hosting webinars and presentations, gathering input from practitioners via focus groups or surveys, including practitioners on advisory boards, or empowering them through scenario planning (Bamzai-Dodson et al. 2021). It can be difficult for practitioners who are far from the locations where boundary organizations are located to get connected with these organizations, as they may not know they exist. Additionally, small communities with fewer resources may not be able to get the attention of boundary organizations like larger cities or counties are able to. This limitation could further perpetuate inequality in climate adaptation and planning as smaller cities could be less able to adapt because of the unequal access to organizations that can assist with planning.

In addition to sharing climate science with practitioners, boundary organizations are also able to provide more context for decision-makers. By investing in the development of new partnerships, boundary organizations could increase the number of practitioners who have access to contextualized and localized climate information. Practitioners from the PRES^{2}iP workshops explained that they could see the value in long-range forecasts, but they were unsure of how to interpret and use them in their daily decision-making practices. Boundary organizations can play a key role in facilitating the uptake of long-range forecasts and climate projections if they are willing to put in the work to connect with new groups of practitioners. This, in turn, will help more communities prepare for the impacts of climate change.

Besides better connecting stakeholders and scientists, future work could also consider the implications of the decisions that practitioners are making and the conditions that shape those decisions. Although the work in my thesis provides insight into how decisions are made about floodplains and precipitation, it does not investigate how decision-making processes vary across jurisdictions or the impacts of the decisions being made. The context that decisions are being made in is important, and future work could consider the social, economic, and political conditions that would allow practitioners to engage in better long-term planning for their communities. This could include researching how budgets and other funding mechanisms could be used to fund better floodplain or water management infrastructure or how strict jurisdictional boundaries influence natural resource management and climate adaptation planning. Finally, the outcomes of these decisions and planning will not just affect the managers who are implementing changes. The ability of one community to adapt could vary greatly compared to a neighboring community, based on available funding or political desires within each location. Future research could investigate disparities in adaptation practices between communities and how inequities in natural resource management or planning may negatively impact residents.

Section 5.5. Conclusions

Heavy precipitation events will continue to occur in communities across the country, and all types of practitioners will have to contend with the impacts of those events. As aging infrastructure may struggle to handle increased precipitation amounts, and jurisdictional budgets continue to shrink, there will be fewer resources available to respond to climate change. It will be critical for researchers to work with cities, counties, and tribes to help them identify how to maximize their response to weather events and prepare for future climates with limited funds. One way to do this could be connecting practitioners with other resources and organizations that can help with implementing adaptation measures such as other government agencies or county departments, private sources of funding, or public-private partnerships. One role that researchers can play beyond information dissemination is in connecting cities and counties with other types of resources, such as evaluation tools, professional networks, or funding opportunities.

Overall, whether dealing with sub-seasonal to seasonal precipitation events or changing precipitation patterns due to climate change, heavy precipitation often leads to flooding and significant economic impacts within communities. It is no secret that climate change will disproportionately impact people who are already overburdened, and a lack of long-term planning in cities exacerbates that vulnerability. To minimize the harms that communities face, it is imperative for the weather and climate community to build partnerships with practitioners and actually listen to their needs, then work collaboratively to help inform decision-making. A more just, equitable, and resilient future depends on this collaboration.

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