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# Perceptions of Bark Beetle Landscape Disturbance Effects on Natural Resources and Drinking Water: Assessing Communication and Knowledge Exchange in the Rocky Mountain Region, USA

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## Abstract

Widespread changes to forested watersheds affected by the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic across western North America raised concerns about the effects of this climate-induced disturbance on drinking water and natural resources. Effective communication and knowledge exchange across scientists and stakeholders (*i.e.*, drinking water managers) is essential for constructively responding to such landscape scale disturbances, providing improved adaptive capacity through knowledge sharing. An assessment of stakeholder knowledge levels, information needs, primary concerns, and suggested communication strategies were conducted via an online elicitation survey and World Science Café workshops. Knowledge levels, assessed via a survey of local water managers and experts, were relatively low with approximately half of the respondents reporting little to no knowledge of the effects of mountain pine beetle on drinking water quality and quantity, thereby indicating limited knowledge exchange between scientists and drinking water stakeholders. Increased accessibility and dissemination of research findings pertinent to the mountain pine beetle epidemic's effects on drinking water quality and quantity is necessary for natural resource management. Recommendations for improved communication among scientists and drinking water stakeholders in particular and forest health in general include dispersal of non-academic research summaries, information exchange through existing media and community resources, demonstration projects, and information clearinghouses. This information provides a better understanding of the challenges, concerns, and first-hand experience of stakeholders of a landscape disturbance issue to apply this knowledge to enhance land management practice and how researchers on this overall project enhanced science communication efforts.

**Keywords**

Adaptive Capacity, Climate Change, Forested Watersheds, Water Quality, Water Quantity

## 1. Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (MPB) epidemic across western North America represents one of many ecological disturbances attributed to changing climate conditions [1] [2] and forest management practices including fire suppression over multiple decades [3] [4] [5]. This epidemic infestation killed trees on millions of hectares of forested watersheds. Such climate related ecological disturbances are increasingly identified as a threat to the resilience of social-ecological systems because these changes are outside the normal systemic functions [6] [7]. The widespread changes to forested watersheds resulting from this epidemic raise concerns about potential effects to drinking water resources [1] [8] [9]. Beetle-killed forests cause concern about the disturbance's effect on stream flow generation mechanisms, water quality and yield [8] [10] [11] [12] [13]. Potential effects to water quality include increases in nitrogen and phosphorous concentrations, dissolved and total organic carbon (DOC and TOC, respectively), increased concentrations of heavy metals, natural organic matter (NOM), and disinfectant byproducts (DBPs) precursors [12] [13] [14] with potential implications for unsafe drinking water.

Climate change induced ecological disturbances are increasingly recognized as a major 21st century challenge [4] [6]. Climate-induced ecological disturbances require adaptive capacity of social and ecological systems to effectively respond and adapt to such disturbances [15] [16]. This is especially true regarding drinking water resources in particular and forest health in general [17]. A key component of social adaptive capacity is knowledge exchange, with current research emphasizing the need for improved communication to increase knowledge exchange of current and potential effects of these ecological disturbances [18] [19] [20] [21]. Effective communication and knowledge exchange can support management responses and guide applicable research, thereby increasing adaptive capacity to landscape scale climate-induced disturbances [17].

Understanding the effects of the MPB epidemic on drinking water resources requires effective communication and knowledge exchange between research scientists and drinking water stakeholders. Potential changes to drinking water quality and quantity resulting from the MPB epidemic elucidate the need for increased adaptability of water resource management in response to changing ecological conditions of the landscape. Effective communication enables knowledge exchange between scientists, drinking water providers, and other stakeholders and is an important component of adaptation [6] [22] [23]. This paper reports social science findings from the second step in a larger five-year social-biophysical research effort involving the coupling of online elicitation survey data with World Science Café' workshop results. The biophysical research conducted by the Colorado School of Mines examined the biogeochemical effects of MPB to drinking water quality and forest health issues, while the social science at Colorado State University examines methods for improving scientist-stakeholder communication for enhanced knowledge exchange not only for water quality issues but forest management as well. The goal is to identify effective strategies for communicating scientists' research findings and drinking water manager perceptions of changes to water quality and wildland fire management due to bark beetle outbreaks and document collective efforts between the two research groups (School of Mines (COM) and Colorado State University (CSU)) for science communication.

## 1.1. Background

### 1.1.1. Adaptive Capacity and the Role of Knowledge Exchange

Climate-induced ecological disturbances and forest management practices including fire suppression over multiple decades [24] [25] challenge the viability of social-ecological systems, particularly water resources [17] [26] [27] [28] in Colorado. While the adaptation of water resource management to the complexities of weather conditions has been established over time, where variations in weather and climate associated disturbances will occur within a "predictable envelope of variability" [29], the events associated with climate change disturbances occur outside this envelope and introduce a need for increased adaptation in water resource decision-making [28]. Such events occur outside predictable variability range and thus outweigh the existing resources and capabilities to successfully address the associated challenges resource managers will face [30] [31].

Adaptive capacity is the ability of a social-ecological system to adapt to disturbances and maintain ecological and/or social resilience [4] [26]. The United Nations Intergovernmental Panel on Climate Change (IPCC) defines adaptive capacity as "the ability to respond successfully to climate variability and change" [32]. Within social systems, adaptive capacity presents opportunities for adaptation through flexibility and learning in the context of ecological disturbances and uncertainty [6] [22] [33]. Limited knowledge of the effects of climate-induced disturbances such as the mountain pine beetle epidemic leads to high levels of uncertainty for water managers [26] although there is much science done in forest ecology alluding to the need for knowledge sharing. Through adaptation the negative social impacts of ecological disturbances to water resources are reduced and the primary functions of the system are maintained [17] [34]. Adaptive capacity is a function of the levels of information exchange, resources, and learning opportunities related to the attributes of the system, also known as knowledge exchange [29] [33].

Knowledge exchange through communication and learning opportunities among different parties enables information and resource exchange and is an important component of adaptive capacity [6] [22]. It is a necessary component for successful adaptation in the face of climate-induced disturbances, especially with respect to water resource management [17]. Successful knowledge exchange occurs when information from one entity transforms the actions or behaviors of another [35]. The incorporation of new information facilitates the adaptive capacity of water management systems to climate-induced disturbances [23] [28]. Improved knowledge exchange of scientific findings of the effects of climate-induced disturbances may provide drinking water providers the ability to prepare for potential changes to drinking water quality and quantity, if necessary, or prevent unnecessary actions from being taken if limited effects are identified [31] [36]. Knowledge exchange also provides relevant information for natural resource managers to share with local stakeholders and residents [37] [38]. In addition, knowledge exchange provides an opportunity for researchers to understand the challenges, concerns, and first-hand experience of stakeholders, which they can then apply to the formation and focus of their research and dissemination of results [17] [37].

Communication and therefore successful knowledge exchange among scientists and stakeholders is limited [17] [35]. Limited communication and knowledge exchange can decrease the effectiveness of science if it is not relevant to stakeholders, including water providers and natural resource managers, and in turn will limit the efficacy of stakeholder actions [37] [39] [40] [41]. Effective communication and knowledge exchange is limited by differing information needs, values and perspectives, and limited opportunities for communication amongst scientist and stakeholder populations [36] [37].

Investigations of knowledge exchange identifies how well society can effectively respond to climate-induced disturbances; but such studies of water management systems are relatively nonexistent [17]. To identify existing knowledge exchange and adaptive capacity there is a need to assess the current levels of knowledge and associated communication needs among water providers [17] [23] [42]. The MPB epidemic in the Rocky Mountain region provided the opportunity to assess current knowledge and the communication needs of drinking water stakeholders.

#### 1.1.2. Mountain Pine Beetle and Drinking Water

Insect outbreaks have affected large, North American forests in recent decades. The primary insect of focus in this paper is the mountain pine beetle (MPB) in Colorado, an endemic bark beetle normally infesting and killing a small percentage of lodgepole pine trees [4] [5] [9] [14] annually. However, since 1997, widespread MPB caused tree mortality has affected more than 42 million acres of forested watersheds in the western United States [43]. This is attributed to warmer temperatures in the winter that led to increased MPB populations in epidemic proportions in concert with increased susceptibility of trees to MPB because of drought-related stress [25] [44] [45]. The extensive beetle-killed area raised concerns about the epidemic's effect on drinking water quality and quantity from these forested watersheds that supply water to over 30 million people [8] [11] [12] [13] [43] [46] as the effect of reducing tree density on water quantity has been expected to increase water yield [47] [48], which might be relevant in semi-arid or arid environments, yet Penn *et al.* 2016 [49] found limited evidence of increased water yield in MPB effected headwater watersheds in Colorado. Potential water quality effects include changes in nutrient concentrations in water due to a loss of vegetation uptake [14], increased heavy metal mobility from soils due to increased dissolved and total organic carbon (DOC and TOC, respectively), and the formation of potential disinfectant byproducts (DBP) from chlorination of water with higher concentrations of natural organic matter (NOM) from all the dead vegetation [12].

This research encompasses the second phase of a social science component of a larger project investigating potential water resource changes resulting from the MPB epidemic to identify feedback between climate change, insect driven forest disturbance, biogeochemical processes and management (e.g., forest and water treatment) practices [13]. The landscape covered in the overall study included northern Colorado and southern Wyoming where more than four million acres of forest were affected by the MPB [13] [50]. More specifically, the Platte River and Colorado River watersheds included supply water to over 30 million Colorado and Wyoming residential water users and 3.5 million acres of irrigated agricultural land [46]. We had four objectives for this study: 1) gauge knowledge levels and information needs about MPB effects on drinking water resources among drinking water resource stakeholders, 2) identify stakeholder concerns and potential solutions about MPB effects on water quality, 3) determine important topics about MPB and drinking water resources to communicate with the general public, and 4) identify mechanisms to improve communication across drinking water professionals (e.g., managers) more generally at a broader scale and to document evidence of the science communication efforts by the research teams from COM and CSU.

## 2. Materials and Methods

The qualitative mixed methods reported is the second phase of the social science component of a larger project funded by the National Science Foundation-Water Sustainability and Climate Program (NSF-WSC) investigating potential water resource changes resulting from the MPB epidemic and the associated drinking water management response to define feedbacks between climate change, insect driven forest disturbance, biogeochemical processes and management (e.g., forest and water treatment) practices [13]. We used a qualitative elicitation survey online and World Science Café workshops to collect data for this phase of the project. The population of interest was drinking water stakeholders (experts at national and regional water conferences) and water-related professionals in Colorado and Wyoming regarding the MPB disturbance effects to drinking water resources in particular and forest health in general. Drinking water stakeholders include drinking water providers, community watershed group representatives, local government, drinking water consultants (e.g., engineers, restoration professionals), and state and federal agency representatives. The scientists referred to in the paper are our research team representing the biogeochemists and hydrologists at Colorado School of Mines (COM) (n = 16) and the forest and social scientists at Colorado State University (CSU) (n = 11).

## 2.1. Qualitative Survey

We conducted two qualitative surveys using SurveyMonkey online software [51] in phase 1 of the study [13]. The online survey used an elicitation method to collect and summarize expert knowledge for a specific topic of interest [13] [52] [53] [54]. The elicitation methodology has increasingly been used to guide decision-making and inform future research endeavors in environmental and social sciences [53] [55]. The dispersed attributes of the internet-based survey approach provide respondents the necessary flexibility and time to submit their responses and reduces potential bias that may arise through group discussions [56]. The elicitation approach was identified as an effective method for measuring knowledge levels and communication needs [20].

### 2.1.1. Survey Development

A literature review of public perceptions of MPB effects on forest health and drinking water resources was used to develop online survey questions. The survey included five open-ended questions concerning respondent knowledge of science and research on MPB, perceived drinking water quality issues and challenges, and suggestions to improve communication and outreach about MPB effects on drinking water and demographics. Qualitative analysis was used to obtain more detailed individualized responses and unexpected phenomena otherwise unattainable through closed-ended questions [57] [58]. We pilot tested the survey spring 2013 with colleagues to make any necessary revisions before its release.

### 2.1.2. Study Population and Sampling Procedures

Respondents were selected as a purposeful sample [59] representing drinking water stakeholders in the study area. Email addresses were identified "through attendance lists from the June 2013 American Water Works Association (AWWA) Annual Conference and Exposition in Denver, Colorado and the AWWA Rocky Mountain Region Section conference, held at Keystone, Colorado in September 2013" [13]. The second set of respondents were identified from attendees of the Sustaining Colorado Watersheds Conference (SCWC), which included representatives of community watershed groups, state and federal agencies, and consulting firms, and was hosted by the Colorado Watershed Assembly, Colorado Foundation for Water Education, and Colorado Riparian Association in Avon, Colorado in November 2014. Non-probability sampling was used including inclusion and exclusion criteria to acquire a sample of 682 invited respondents from the list of conference attendees. Inclusion criteria included drinking water providers and water professionals from the Rocky Mountain Region that were involved in the provision of drinking water resources and provided their consent to participate in the research [13]. Exclusion criterium included attendees working outside the study region and not involved in drinking water provision or management. Reminder emails were sent to non-respondents within two weeks of the initial invitation. The survey was open online for three months (September to November 2013) [13] [60].

Of the 229 who began the elicitation surveys (34% response rate), a total of 122 completed questions relevant to the analysis reported here. Approximately 81% of respondents' drinking water systems provide water for over 10,000 households. Most respondents (67%) reported surface water as their systems' drinking water source, 18% reported a blend of groundwater and surface water, and 16% reported groundwater as the primary drinking water source. The majority (75%) reported their drinking water source comes from MPB affected watersheds.

The 2013 survey sought information from participants of the national and the Rocky Mountain Section of the American Water Works Association (AWWA) conferences. Fifty-three percent of those respondents were drinking water providers and 27% were water resources consultants. Other respondents (20%) to the AWWA survey were associated with academic institutions, state or federal land agencies, or community watershed groups. The 2014 survey collected information from participants of the Sustaining Colorado Watershed Conference (SCWC). Twenty-three percent of the SCWC survey respondents were community watershed group representatives, 19% were associated with local government (state, county), and 15% were with federal agencies. The remainder of respondents to the SCWC survey (43%) included drinking water providers, consultants, scientists, water educators, and state or federal employees.

#### 2.1.3. Analysis

Using QSR NVivo (version 10) software, a thematic analysis organized data into key themes [59]. Themes and categories were identified *a priori* including information needs, watershed management issues, and drinking water challenges. Open and axial coding was used to determine themes and sub-themes not previously identified [57] [58] [59]. Qualitative responses were categorized and independently coded by the members of the CSU research team. The relevance of identified themes was based on the proportion of respondents identifying each theme; therefore, findings reported here are those identified by most respondents.

## 2.2. Beetle Café Workshops

The World "Science" Café [61] was used to create a dynamic network of conversation and knowledge sharing organized around critical questions for this study [62] as phase 2 coupled on the phase 1 survey results. This workshop approach which we called the Beetle Café for our purposes, organizes groups of people together to discuss a specific topic, providing an opportunity for concepts generated from small group discussions to be confirmed and strengthened by the larger group.

The Beetle Café supplemented data from the elicitation surveys providing greater detail via experiences, insights, and ideas about the effects of MPB-induced tree mortality on drinking water quality and quantity through two workshops. The workshops, entitled the Beetle Café, were held at the 2013 Joint Annual Conference of the Rocky Mountain Section of the American Water Works Association (RMSAWWA) and the Rocky Mountain Water Environment Association (RMWEA) in Keystone, Colorado and the 2014 Sustaining Colorado Watersheds Conference. The Beetle Cafés were used specifically to identify potential water resource changes resulting from the MPB epidemic and how information related to drinking water resources should be communicated. The Café format included small groups for participants to identify challenges related to MPB affecting drinking water quality and supply, discuss potential solutions, and identify stakeholder communication needs through an interactive process involving: 1) an initial brainstorm to plot key thoughts, 2) clarification of key ideas and grouping into thematic areas, and 3) discussion of the thematic areas, posed to the entire group. A graphic illustrator was used during the workshops (**Figure 1**) to illustrate the flow of information from the small groups [63]. Ideas generated from each group were clarified and summarized as part of a final discussion among the participants at the workshop and data were analyzed via the same method as the online survey data.


**Figure 1.** Graphic Facilitation Process during Beetle Café' workshop (Graphic facilitator Karina Mullin).

## 3. Results

The online elicitation surveys from Phase 1 of the study [13] and Beetle Café workshops informed us of knowledge levels, communication needs, challenges, and public outreach recommendations regarding the MPB effects on drinking water resources. The following highlights results in accordance with the four objectives of the study.

### 3.1. Elicitation Surveys

#### 3.1.1. Knowledge Levels

The first task (objective 1) was to identify respondents' current knowledge levels about the potential effects of MPB on drinking water. The majority of AWWA respondents reported limited knowledge of MPB impacts to drinking water with 53% identifying little to no knowledge about the science and research on the MPB effects to drinking water resources, while 36% had moderate and 12% had high levels of reported knowledge (**Table 1**). Forty-four percent of SCWC respondents identified having little to no knowledge about the science related to MPB and drinking water resources, while 30% reported moderate and 26% reported high levels of knowledge.

Concerns stated by respondents with little to no reported knowledge of MBP impacts for both samples included potential effects of wildfire on water quality through increased nutrients, soil erosion concerns, and forest management challenges [13]. For respondents with moderate to high levels of knowledge, the most common areas of prior knowledge were the potential effects on water quality, snowpack, and changes in streamflow volume and timing. Respondents with moderate to high knowledge levels indicated they read current published research and identified topics/knowledge of water quality (*i.e.*, total organic carbon, natural organic matter, nutrient enrichment, color, and heavy metals), potential increased risk of wildfire, and increased streamflow and associated erosion, turbidity, and sediment. Several of the respondents with higher levels of reported knowledge stated that they were involved in cooperative outreach, research, and activities to mitigate MPB effects on water resources [13].

#### 3.1.2. Research Communication

The next objective was to determine how communication of research on MPB effects on drinking water could be improved and potential solutions. Respondents from the AWWA and the SCWC surveys indicated different priorities for research communication (**Table 2** contents drawn from [13]). Though not related to specific types of research, most AWWA respondents requested improved dissemination and accessibility of research related to MPB effects on drinking water, including preliminary findings, research direction, and overall results. Their suggestions for improving the dissemination of research included setting up a centralized source for research findings to distribute non-academic summaries, and to publicize the location of such sources. Secondly, the AWWA respondents felt MPB-associated research did not need to be communicated more

**Table 1.** Reported knowledge levels by survey.

| Survey | Knowledge levels (%) | | |
|---|---|---|---|
| | None/Little | Moderate | High |
| 2013 AWWA (n = 93) | 53 | 36 | 12 |
| 2014 SCWC (n = 26) | 44 | 30 | 26 |

**Table 2.** Responses to survey questions by survey in ranked order.

| Topic | 2013 AWWA Survey (n = 96) | 2014 SCWC Survey (n = 26) |
|---|---|---|
| Research Communication Needs | Improve accessibility of information<br>No parts of MPB research on water resources need to be communicated more effectively.<br>MPB effects on drinking water quality | MPB effects on drinking water quality and quantity<br>Improve accessibility of information<br>Correlation between forest watershed health and drinking water resources |
| Identified Challenges | Addressing water quality effects of MPB<br>Increased fire danger and the resulting effects on water quality and quantity<br>Changes to water quantity as a result of MPB | Issues associated with increased water quantity<br>Addressing water quality effects of MPB<br>Understanding linkage between forest watershed health to hydrologic change and drinking water |
| Drinking Water Safety | Drinking water has not deteriorated or become unsafe<br>Unsure or do not know<br>Yes—Deteriorated water quality; degraded enough to cause treatment issues (increasing chemical usage and cost) but not health or safety issues | Drinking water has not deteriorated or become unsafe<br>Yes—Deteriorated water quality<br>Unsure or do not know |
| Public Outreach | The effects of MPB on drinking water quantity and quality<br>Connection between forest health and drinking water<br>General information on the MPB biology and status | The effects of MPB on drinking water quantity and quality<br>Methods to mitigate MPB effects to drinking water<br>General information on the MPB biology and status |

Note: Results drawn from Phase 1 online data (see [13]) were used for similarity/comparison with Phase 2 Bark Beetle Workshop data.

effectively, even though 53% of AWWA respondents had previously indicated limited knowledge levels. The third most common communication need identified by AWWA respondents was information on the effects of bark beetle infestation on drinking water quality. They specifically identified the need for research findings on MPB associated changes in potential disinfection byproducts (DBPs) precursors, total trihalomethanes (TTHM) formation potential, total organic carbon (TOC) and natural organic matter (NOM), nutrient enrichment, and the effects of pesticides used to combat MPB. Additional research communication requests from a smaller number of respondents included: the timeline for expected effects to occur following infestation, the effectiveness of water treatment mitigation approaches, and the correlation between mountain pine beetle and wildfire risk.

The primary request of SCWC survey respondents was improved communication of research on the MPB effects to both drinking water quality and quantity. Respondents did not separate these topics nor provide specific requests for the types of information they wanted. The second most common response from SCWC surveys was to improve the accessibility of research project information and findings. Respondents requested information on the research questions being looked at, the preliminary results, and study findings. They suggested improving accessibility of research by providing a compilation of research reports, sharing articles and project web links through a central listserv or website, and presenting information at professional and/or community group meetings.

The third topic identified by SCWC respondents was the communication of research on the relation between forest watershed health and the effects on drinking water quality and runoff. Specific requests included changes in spring snowmelt runoff timing and amounts, how forest management techniques (*i.e.*, harvesting beetle-killed trees) affect water quality and quantity, and the effects of stream temperature fluctuations on water resources. Other issues were identified by a few respondents, including requests for information on the MPB effects to streamflow and groundwater recharge, as well as recommended mitigation approaches to minimize MPB effects on forests and drinking water, the relation of MPB killed trees to wildfire occurrence, and the expected timeline for effects to persist after the beetle infestation.

#### 3.1.3. Identified Challenges

Of the topics most important (objective three), the greatest challenges noted thematically were water quality and quantity and understanding the linkage between watershed health in forests and drinking water (see **Table 2** from [13]). More specifically, the greatest challenge for the AWWA sample was treatment of potential water quality issues resulting from trees killed by MPB killed in forested watersheds. Increased turbidity, NOM, DBP, TOC, DOC, and changes in taste and odor of water were the specific concerns of the AWWA sample. Several also suggested the unknown duration of these effects was a considerable challenge while others were concerned about the increased treatment costs associated with these water quality changes and their ability to pass these costs on to consumers. Secondly were the challenges of increased wildfire danger in MPB-killed forest watersheds and related fire impacts to water quality and quantity. These concerns were common with little to moderate knowledge levels reported and less common amongst experts with higher levels of reported knowledge. Water quantity change was the third most identified challenge by the AWWA sample. Specifically identified concerns was water runoff (levels and timing of), and the direct and indirect effects on groundwater storage and water yield [13]. For the issues of water quality, several experts stressed their concerns of the potential of increased costs of water treatment associated "with water quantity, specifically sediment control" [13] among the transportation and treatment infrastructure. Further concerns indicated the uncertainty of the long-term impacts of bark beetle infestation as well as the challenge for effectively communicating this information to the water users and the public.

Many SCWC respondents identified issues associated with increased water quantity as their greatest concern. The primary issues these respondents identified with this were increased runoff, erosion, sediment mobilization, and organic debris. Changes to water quality were the second most identified concern of SCWC respondents, with less detail than the AWWA respondents regarding the types of water quality issues. Some respondents identified concern regarding erosion and changes in organic matter impacts to water quality. The third largest area of concern raised by SCWC respondents was the challenge of understanding the connection of forest watershed health to changes in hydrology and drinking water, with many emphasizing the concern of potential increased wildfire associated with MPB killed forests.

#### 3.1.4. Drinking Water Safety

For the question of whether drinking water quality had decreased or become unsafe because of bark beetle infestations, most respondents indicated no perceived changes to safety of water quality (**Table 2**) [13]. The remaining survey respondents were unsure if drinking water quality had changed. The AWWA and SCWC respondents who believed water quality had deteriorated indicated these issues were dealt with effectively via water treatment plants; therefore, did not present health or safety issues. Some respondents noted concern about potential increases in water treatment costs at water treatment plants because of increased TOC level reactions with chlorine and subsequent potential increases in TTHM [13]. Other respondents were either unsure or did not know if drinking water quality deteriorated or became unsafe to drink.

#### 3.1.5. Public Outreach

To address objective four, for both online survey groups [13] most felt MPB effects on drinking water were the greatest information to communicate to stakeholders to enhance awareness and understanding of potential effects of MPB on drinking water quality (see **Table 1**). More specifically information needs included potential taste and odor changes to water, clarifying short- versus long-term changes to drinking water quality, mitigation efforts being taken by drinking water providers to address these changes, as well as the increased costs to water users due to potential needs for additional treatment necessity to mediate MPB effects.

The second most identified topic to communicate to the public by AWWA survey respondents was the link between drinking water and forest health. This included the effects of drought and climate change, identifying if there is increased wildfire potential associated with MPB, as well as the effects of MPB associated forest management to drinking water. The second most identified topic by the SCWC respondents was to communicate to the public the methods used to mitigate the effects of MPB, including water treatment efforts to address drinking water quality issues, and the use of forest treatments to prevent and/or mitigate the MPB effects.

Across both survey groups the third most identified topic to communicate to the public was information about bark beetle disturbance generally, including its ecological characteristics (*i.e.*, it is an endemic species, its normal life cycle, preferred forest habitat, etc.) and the current status of the MPB outbreak.

## 3.2. Beetle Café Workshops

Twenty-five experts representing a variety of drinking water stakeholders participated in the Beetle Café workshops. From these in-depth discussions we gathered information on the primary issues and challenges, potential solutions, and recommended public outreach mechanisms related to MPB effects on drinking water resources. Knowledge levels ranged from low to high, with the majority having moderate amounts of knowledge regarding the potential MPB effects on drinking water quality.

### 3.2.1. Identified Challenges

Several challenges of the MPB effects on drinking water were identified through the two Beetle Café workshops (Table 3). The effects of MPB on drinking water quality were the highest priority challenge identified in both workshops. The AWWA workshop participants identified specific water quality challenges, including increased turbidity, TOC, DOC, DBPs, and heavy metals.

**Table 3.** Beetle Café Workshop Findings.

| | 2013 AWWA Workshop (n = 11) | 2014 SCWC Workshop (n = 14) |
|---|---|---|
| Issues and Challenges Identified | o Water quality<br>o Potential effects of wildfire (increased erosion from extreme runoff events)<br>o Management planning (mitigation costs and division of resources)<br>o Increased water runoff<br>o Changes in water supply<br>o Climate change | o Water quality<br>o Connection between forest management and water<br>o Linkage to landscape health<br>o Changes in soil biogeochemistry<br>o Overall ecosystem<br>o Dispelling myths<br>o Long-term effects |
| Solutions | o Public awareness<br>o Planning ahead<br>o Mitigation<br>o Goal setting | o Public education<br>o Coordinate information<br>o Accessibility of information<br>o Demonstration projects |
| Public Outreach | o General information on MPB<br>o How MPB affects the public<br>o Maintain consumer confidence<br>o Cost of doing nothing | o General information on MPB<br>o How MPB affects the public<br>o Link between forests and drinking water<br>o Mitigation efforts |

Other concerns differed between the two workshops. In the AWWA workshop the potential for increased fire risk resulting from the MPB epidemic was the second chief concern discussed, with participants identifying several challenges to drinking water provision that result from fire, including extreme runoff events and associated erosion. During the SCWC Beetle Café workshop, the second most discussed concern was the connection of forest management to drinking water quality. Participants were concerned there was a lack of understanding of how forest management activities (e.g., harvesting of beetle-killed trees) could affect drinking water resources. These participants recognized the overall linkage between forest and water resources and were concerned about the limited connection between forest management decisions and drinking water management.

The third major challenge identified at the AWWA Beetle Café workshop was the cost and time associated with management planning related to drinking water provision. Participants were concerned about the division of resources and management priorities among different jurisdictions regarding management of forest watersheds, as well as water infrastructure management. The third prominent challenge discussed at the SCWC Beetle Café workshop was the lack of information regarding the potential long-term effects of the bark beetle epidemic to drinking water resources and forested watersheds. Participants raised concerns about misinformation regarding the effects of the MPB and how these myths have or could potentially influence management decisions.

#### 3.2.2. Solutions

Potential solutions to these concerns were identified during the Beetle Café workshops. Increased public awareness through education and improved communication was the most identified solution at both workshops. The SCWC workshop participants emphasized the use of demonstration projects as an important educational opportunity for both forest and water management mitigation efforts. The second primary solution identified from both workshops was to improve planning efforts across jurisdictions. To address this the AWWA Beetle Café participants recommended coordinating goal setting and management efforts between different entities associated with the forested watersheds and drinking water systems affected by the MPB. Participants at the SCWC Beetle Café workshop suggested the coordination of both scientific and on-the-ground information through databases and information clearinghouses to address the challenges of the MPB epidemic.

#### 3.2.3. Key Messages to Communicate to the Public

The workshops concluded with a discussion of the key messages that should be communicated to the public regarding potential MPB effects on drinking water quality (Objective 4). Participants from both Beetle Café workshops believed general information about the MPB needed to be communicated to the public. Another common message was to share information about how the MPB was affecting or could affect the public through changes in drinking water quality and quantity. AWWA workshop participants discussed how consumer confidence should be maintained through proper messaging, including the communication of the effects to drinking water and consumers if no mitigation occurred. SCWC workshop participants emphasized the importance of communicating information about the linkage of forest health and water resources, and mitigation efforts used to address the MPB effects on the forest and by drinking water providers.

## 4. Discussion and Knowledge Exchange Recommendations

Answering calls for research assessing how human perspectives respond to bark beetle outbreaks and evaluations of how stakeholders respond to changing resource conditions [4] [5], this study sought to identify effective means of communication of MPB effects to drinking water quality and quantity among scientists and drinking water stakeholders in the northern Colorado and southern Wyoming region. Effective communication between researchers (our team of scientists) and drinking water stakeholders provides an opportunity for knowledge exchange to occur. A growing facet of literature [4] [17] [20] indicates successful knowledge exchange is a critical component for adaptation to climate-induced ecological disturbances affecting social-ecological systems [3], such as the MPB epidemic. Our intent was to establish baseline information to identify how well this population is prepared to respond to climate-induced disturbances, such as the MPB, and identify mechanisms for improved communication, learning, and knowledge exchange. This empirical analysis of stakeholder knowledge levels, communication needs, and concerns provides the groundwork to understand knowledge exchange associated with the MPB ecological disturbance and identify strategies to improve communication and adaptive capacity in response to ecological disturbances. Methodologically, the combined elicitation and Beetle Café workshop approaches [59] [64] [65] provided a depth of information less attainable through other approaches. In our attempt to identify baseline knowledge levels and research communication needs necessary to understand and further examine knowledge exchange and its contribution to adaptive capacity in climatic shifting conditions, findings identify communication opportunities to address uncertainty, or at least to begin to address it.

### 4.1. Knowledge Levels and Research Communication Needs

Knowledge levels were relatively low with approximately half of the survey respondents reporting little to no knowledge of the effects of MPB to drinking water quality and quantity. With low reported knowledge levels these findings indicate limited knowledge exchange among scientists and drinking water stakeholders. Knowledge of climate-induced change due to MPB impacts and the associated vulnerabilities takes many forms and is inherently uncertain. Knowledge exchange is much more than just providing facts but involves an exchange of information. This exchange of information among our team of scientists, science in general, and local drinking water managers involves numerous factors that influence how people respond and react to the information and communicating the effects of the MPB disturbance to drinking water resources is not easy. Limitations to the exchange of information are attributed to differences in communication venues, networks, and information sources.

Research communication needs identified by respondents supported the finding of limited knowledge exchange. One important difference between populations is that a majority of the AWWA respondents, consisting primarily of drinking water providers, did not believe research communication with scientists needed to be improved. In sight of the low levels of knowledge reported by the respondents, this finding indicates a general lack of awareness of the research conducted and its relevance to effective drinking water management, confirming the need for improved communication between scientists and stakeholders.

The most common theme across survey respondents and Beetle Café participants was the need for increased accessibility and dissemination of scientific research findings. They were interested in learning about current research efforts, methods, preliminary findings, and results. Specific information requests from a variety of drinking water stakeholders (*i.e.*, drinking water providers, consultants, community watershed group representatives, local government, and agency representatives) focused on the MPB effects to drinking water quality and quantity. The prominence of this request for increased accessibility and dissemination of research findings supports a recent analysis of stakeholder needs regarding climate-related information where stakeholders requested access to research information, improved communication and data coordination, and improved outreach to the public [18].

One solution for improving communication is through increased multidisciplinary efforts among scientists and stakeholders [36] [66]. Similarly, the use of citizen-science initiatives and participation in existing community-based programs are an effective mechanism to share scientific information with stakeholders and provide public input to scientific processes [67]. Intermediary or boundary organizations have played an important role in natural resources through knowledge transfer with scientists, practitioners, policymakers, and other stakeholders that should be considered [23] [38] [68]. The common need for improved accessibility of research findings we found across stakeholders identifies an opportunity for improving knowledge exchange through intermediary organizations. For example, the local watershed groups and other outreach organizations may serve as intermediaries for information exchange between scientists and stakeholders [69]. These entities may play a crucial role in improving adaptive capacity of drinking water systems by enabling knowledge exchange between scientists, stakeholders, and the public.

## 4.2. Stakeholder Challenges

Challenges associated with the effects of MPB to drinking water resources identified from the surveys and workshops reveal stakeholder concerns. Again, the effects of MPB to drinking water quality and quantity were commonly identified by both populations. The potential for increased wildfire risk in MPB affected forests and the associated impacts to drinking water quality and runoff was also identified in both populations, raised by those with lower reported knowledge levels. Although a limited connection between MPB and wildfire has been established scientifically [24] [45] [70] [71] [72] [73], the prevalence of this concern is tied to recent wildfires (2012) and flooding (2013) which had severe impacts to drinking water within the region. Understanding the primary challenges and concerns of stakeholders provides useful information for scientists to account for when disseminating research findings and developing future research objectives [69]. Understanding stakeholder challenges and concerns increases our ability to connect scientific knowledge of climate disturbance impacts with local needs, to inform scientific endeavors with local knowledge, and thereby improve adaptive capacity [16] [17] [23].

### 4.3. Stakeholder Recommendations

Solutions outlined by survey respondents and workshop participants provide additional insight into potential mechanisms to improve communication among scientists, stakeholders, and the public. Survey respondents recommended improving the accessibility of research findings through increased use of non-academic research summaries, sharing results through centralized information sources, and exchanging information through professional associations and community meetings. Beetle Café workshop participants provided additional recommendations for improving research accessibility, including demonstration projects, cross-jurisdictional planning processes, and coordination of scientific and on-the-ground data through databases and information clearinghouses. Topics to communicate with the public, include a focus on the linkage between forest health and drinking water, how the MPB epidemic can affect the public, methods for mitigating MPB's effects on forests and drinking water, and an overview of the biology and ecology of the MPB insect and its impact to forests and drinking water.

Among the communication achievements of the project was the development of key messages for placed-based science education and public educational programs about the effects of mountain pine beetle infestation on water quality and natural resources. This was accomplished via an NBC News Learn "Sustainability: Water - Dead Trees & Dirty Water in the Rockies" video [see https://www.youtube.com/watch?v = IOtBBJuKg5U] and through a university honors seminar conducted collaboratively between COM and CSU entitled "Naked Trees, Killer Beetles, and Dirty Water" [74] (see https://warnercnr.colostate.edu/announcements/naked-trees-killer-beetles-dirty-water/) for 61 plus undergraduate students at Colorado State University over seven years culminating in outreach videos, educational outreach at Outdoor School with 6th grade kids in Jefferson County Colorado and 9th grade biology classes at Rocky Mountain High School in Fort Collins Colorado. This class continues at Colorado State University once a year. A final K-12 Train the Teacher's Workshop [75] focused on creation of curriculum resources for the classroom developed collaboratively among university students, K-12 teachers and the research project scientists at COM and CSU. The Integrated Ground Water Modeling Institute at COM continued science communication efforts of this project in the Denver metropolitan area until the lab was moved to Princeton University as part the High Meadows Environmental Institute https://igwmc.princeton.edu/people/university-affiliation/hmei/.

The project developed new approaches to study landscape level bark beetle disturbances and social perspectives on high severity outbreaks in collaboration with the NSF funded Research Collaborative Network (Mountain Social Ecological Observatory Network (MtnSEON)) see https://webpages.uidaho.edu/mtnseon/ [4] [5]. This led to further understanding of factors that influence adaptive capacity for increasing resilience to bark beetles [5] [16] using mountain pine beetle (*Dendroctonus ponderosae*) in the western U.S. as a model as well as identification of priority research questions [4] on insect forest disturbances through socio-environmental collaboration.

Further, a theoretical framework was developed by a research workshop group in 2016 funded internally at CSU to provide land managers and policymakers a potential tool for identifying limitations for adaptive capacity in social ecological systems (SES) in hopes of addressing future bark beetle infestation events [16]. This effort was intended to motivate future research in the assessment of adaptive capacity and to foster collaboration among scientists and land manager efforts to manage for bark beetle impacts.

## 5. Conclusions

In sum, improved accessibility of study findings via non-academic research summaries, centralized information sources for state level governmental agencies, and professional association and community meetings is recommended. Examples include demonstration projects, cross-jurisdictional planning processes, and coordination of scientific and on-the-ground data through databases and information clearinghouses. Communication topics for outreach include the link between forest health and drinking water safety, mitigating MPB's effects on forests and drinking water, and ecological aspects of MPB insects in their impact on forest health and drinking water resources.

Communicating the role of bark beetle disturbances in natural resources is an important aspect of educating governance agencies, water user groups, and the general public [5] [16]. Results allude to further study needs among other populations (*i.e.*, forest ecologists and natural resource managers). Additional research will build on these results to determine knowledge outreach needs, and stakeholder and public concerns, as well as optimal outlets for science communication outreach. This information will continue to inform the hydrological and biogeochemical research being conducted, as well as aid in development of outreach and educational materials for sharing the biophysical and social science findings of this project [74].

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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