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Community-Level, Participatory Co-Design for Landslide Warning with Implications for Climate Services

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Abstract: Inclusive, participatory governance is a key enabler of effective responses to natural hazard risks exacerbated by climate change. This paper describes a community-level co-design process among academic, state, and federal scientists and the community of Sitka, Alaska to develop a novel landslide warning system for this small coastal town. The decentralized system features an online dashboard which displays current and forecast risk levels to help residents make their own risk management decisions. The system and associated risk communications are informed by new geoscience, social, and information science generated during the course of the project. This case study focuses on our project team's activities and addresses questions including: what activities did the project team conduct, what did these activities intend to accomplish, and did these activities accomplish what they intended? The paper describes the co-design process, the associated changes in system design and research activities, and formal and informal evaluations of the system and process. Overall, the co-design process appears to have generated a warning system the Sitka community finds valuable, helped to align system design with local knowledge and community values, significantly modified the scientists' research agendas, and helped navigate sensitivities such as the effect of landslide exposure maps on property values. Other communities in SE Alaska are now adopting this engagement approach. The paper concludes with broader implications for the role of community-level, participatory co-design and risk governance for climate services.

Keywords: landslide warning; warning systems; participatory co-design; risk governance; community engagement; Southeast Alaska

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1. Introduction

Inclusive, participatory governance is a key enabler of effective responses to climate change [1] (Sect C5). Such participatory processes, which directly involve members of the public in making decisions in matters that affect them [2], can make decisions more effective by engaging multiple sources of knowledge, such as formal science and local and Indigenous knowledge; can better align decisions with community values; and enhance community ownership and acceptance. Participation is also a normative good consistent with principles of procedural justice [3] (Sect 1.4.1.1). Addressing climate change will often require significant changes in lifestyles and daily routines informed and enabled by new and evolving science and technology. Under such conditions, inclusive, participatory governance may be particularly important in helping to achieve equitable outcomes and to reduce tensions in this era of polarization, inequality, and distrust of elites and science.

This paper describes an exercise in community level, inclusive, participatory governance focused on the co-design and deployment of a landslide early warning system (LWS) for the small town of Sitka, Alaska. In the aftermath of the fatal Kramer Ave landslide in 2015, (see Figure 1) members of the Sitka community became concerned about landslide risk. They quickly realized that this risk had always been present and was likely to grow in the future as climate change increases the incidence of extreme rainfall events. Such realization generated anxiety among community members about personal safety and concern about the town's economic future [4].

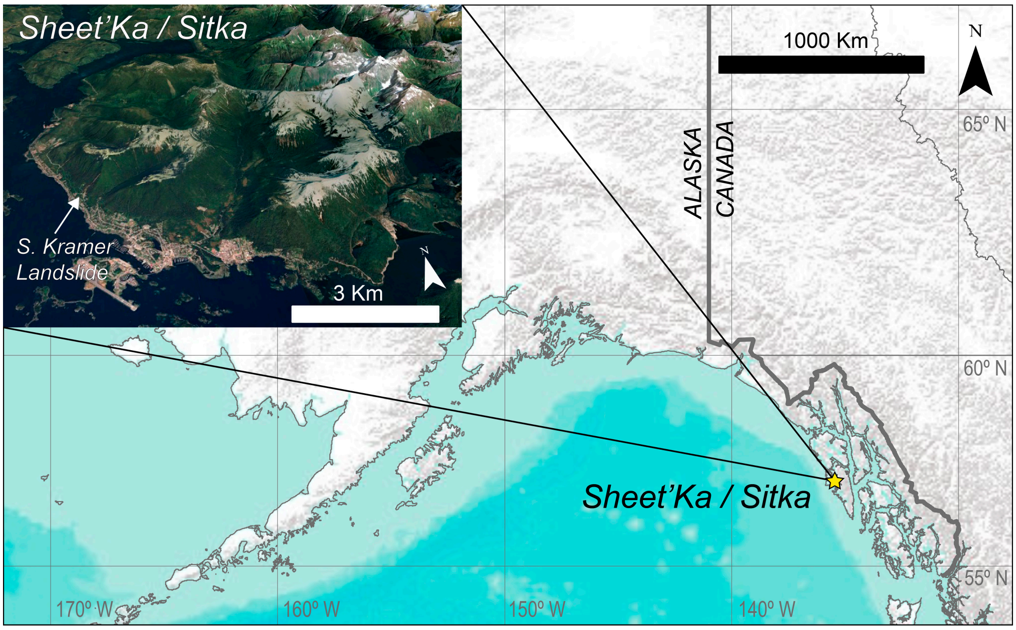


Figure 1. Map of the study area in Sitka, Alaska. Source: Service layer image credits: ESRI, USGS, NOAA. Inset map from Google Earth (2023), Maxar Technologies, Landsat/Copernicus, and Airbus (accessed on 6 February 2023).

With funding from the National Science Foundation, a team of community members and geoscience, information, and social scientists based at external institutions conducted a participatory co-design process which resulted in a novel, community-run, decentralized landslide warning system. Consistent with community values, the system employs a landslide risk dashboard that enables Sitkans to make their own evacuation decisions rather than rely on centralized evacuation warning. The warning system design and associated risk communications are informed by novel science and technology, including networks of low-cost sensors and social network analysis aimed at efficient and equitable dissemination of risk information throughout the community.

By co-design, we mean a creative, participatory process of fashioning solutions to public policy challenges in which community members and scientists collaborate as equals. In the context of early warning systems, such solutions can include information products, information services, and policies. The literature offers many versions of the co-design concept. The public administration literature adapts participatory processes of product design and design-thinking from the private sector and applies them to public sector solutions [5]. The sustainability literature often envisions co-design as a process in which academic and non-academic partners jointly develop research questions and research agendas as an initial phase in the co-production of knowledge [6].

Here we implement co-design as a participatory risk governance process embedded in a wide-ranging process of community engagement. The co-design, organized as a process of "deliberation with analysis" [7], engages multiple stakeholders; includes storytelling, serious games, and information provision by experts; facilitates deliberative dialogues; and follows an iterative process of framing and reframing [8].

This paper presents this effort to create a Sitka landslide warning system (LWS) as a case study of the type of community-level, participatory co-design process which may prove important to the effective provision of climate services in the United States and beyond. The case study focuses on our project team's activities and addresses questions including: what activities did the project team conduct, what did these activities intend to accomplish, and did these activities accomplish what they intended? To address these questions, the paper describes the co-design process, the associated changes in system design and research activities, and formal and informal evaluations of the system and the process.

Overall, the co-design process appears to have generated an LWS the Sitka community finds valuable. The system provides useful warning and reduces anxiety during periods of heavy rain. Community residents and officials report their satisfaction. The co-design process significantly influenced the design of the LWS consistent with local knowledge and community values, significantly modified the scientists' research agendas, and helped navigate sensitivities such as those related to the effect of landslide exposure maps on property values. Small towns across Southeast Alaska are now replicating this co-design and engagement approach to provide warning for climate-related risks.

Many U.S. communities face natural hazard risks exacerbated by climate change. This Sitka landslide early warning system and the co-design process that produced it have implications for U.S. climate services. The effort suggests that co-design processes previously used with expert stakeholders can be adapted for small town, lay audiences. The effort highlights the importance of strong local partners; active engagement by state and local agencies; an ability to engage with a broad range of information focused not only on the hazard but also exposure, vulnerability, and the responses to risk; the need for resources to support on-going operations of the system; and a cadre of personnel trained to facilitate the co-design process and supporting research. The Sitka system also provides insight into the contexts in which an individual-centered system is more appropriate than one based on centralized judgments regarding evacuation.

2. Context

Sitka, a town of 8700 residents, is located on Baranof Island, on the outer coast of Southeast Alaska. The Pacific Ocean borders one side of the town. Rising above the other side are the steep, forested mountains of the Tongass National Forest (see Figure 1), the largest temperate rainforest in the world. Accessible only by boat or plane, the community's road system is 14 miles.

The town of Sitka is located immediately below very steep post-glacial hillslopes on the western coast of Baranof Island. The landscape has extreme topographic relief. One local mountain rises from sea level to ~900 m in 2.2 km. The local geology and geomorphology is extremely spatially heterogeneous with a history of tectonic, volcanic, and glacial processes resulting in a complex topography and a patchwork of different soil types and bedrock [9]. The town and the surrounding area are exposed to persistent landslide hazards from multiple susceptible hillslopes [9–11]. On 18 August 2015, an extreme atmospheric river initiated over 40 landslides in and near Sitka, including the Kramer slide, a debris flow that resulted in three fatalities.

The Tlingit, the Indigenous people, have inhabited Sheet' Ka, the ancient name for the Sitka, area for more than ten thousand years. Today they comprise over 17% of the Sitka region's population [12]. Commercial fishing represents the largest economic sector, but the Southeast Alaska Regional Health Consortium, the region's hub hospital, is the biggest single employer. Every year during the summer, Sitka receives tens of thousands of visitors via its cruise ship dock, which helps fuel a large local tourism industry.

The Sitka community has two distinct forms of local government, the Sitka Tribe of Alaska (STA) and the City and Borough of Sitka (CBS). The latter has a city manager form of government, in which the elected CBS Assembly appoints the CBS Municipal Administrator, who is responsible for municipal operations including but not limited to the hiring and managing of department executive leadership, the oversight of Municipal property, public works, and budget [13]. The STA is the long-standing, federally recognized government for the more than 4000 Tribal Citizens who live in the CBS and traditional

Sheet'Ka area [14]. The STA provides programs including but not limited to addressing employment, natural and cultural resources protection, higher and vocational education, domestic violence prevention, and social services.

The CBS manages emergency services for the community. In support of this role, the city maintains a 19-member Local Emergency Planning Committee (LEPC), established by a State of Alaska statute and implemented through local resolution [15]. The LEPC is responsible for emergency planning to guide the community in preparing for, mitigating, and responding to disasters and emergencies. The committee further functions as a community convener determining the appropriateness of emergency response and the related use of public funds.

State and federal agencies, and their regional offices, also play an important role in Sitka's management of natural hazards. The National Weather Service (NWS) office in Juneau, AK provides forecasts for Sitka and maintains the weather station at the airport. The Alaska Division of Geological and Geophysical Surveys (DGGS) provides local geologic information, including collecting lidar data for the region and developing exposure maps of landslide runout zones. The U.S. Forest Service (USFS) maintains a Ranger District Office in Sitka and owns significant land in the Tongass National Forest area surrounding the town. Local USFS personnel also developed and maintain a landslide inventory for Baranof Island.

The project team, funded by the NSF Smart and Connected Cities Program, was led by the RAND Corporation, a non-profit, public policy research organization headquartered in California. RAND also led the social science and risk management project teams. The Sitka Sound Science Center (SSSC), a non-profit community science education and research organization located in Sitka, served as the project's main community partner. The STA served as the project's primary liaison with the Indigenous community. Other funded team members included the University of Oregon, which led the project's geosciences team, the University of Southern California, which led the project's information sciences team, and DGGS, which installed a weather station atop Harbor Mountain with project support. The web developer Azavea built the dashboard. Project partners included the regional NWS and USGS offices, researchers from USGS, local emergency services agencies, local schools, and the chamber of commerce.

As suggested by Figure 2, the Sitka LWS presents a challenge of polycentric governance [16], with many independent yet interdependent actors required to act in coordinated ways to create and operate it. Climate change adaptation increasingly faces this type of governance challenge [3] (Sect 1.4.2.2). In Sitka, the city and tribe have primary responsibility for the safety of Sitka residents and making it possible for Sitkans to respond effectively to any warning. Federal and state agencies are the primary sources of data on which the warning system depends. The system empowers Sitka residents to make their own decisions regarding landslide risk, so the system only functions if they use it appropriately. The warning system design also gives the SSSC significant responsibilities for maintaining the system and the community's awareness of it. Alongside these decision-making organizations, the project team functioned as a boundary organization [17] mediating among information relevant to landslide warning and the community actors whose decisions are integral to the warning system's function.

In this context, the project team faced a number of challenges. The team needed to engage a lay public and local officials with new and evolving science in a context of considerable anxiety about landslides, grief about previous loss of life, the potential effect of increasing the salience of landslides on life in the town, and distrust of outside experts. In addition, the project team also had balance among the related but different interests of the researchers and community. With its NSF funding, the research team had promised both to serve the community as well as to explore the utility of new and untested networks of low-cost moisture sensors to geoscience as well as novel applications of social networks and influence maximization to risk communications. While there was little contestation of values regarding landslides among Sitkans, some people were primarily concerned with personal safety and others worried that undue concern with landslides could harm property values and disrupt the community's daily life [4]. The project also needed to address a highly diverse community including blue collar workers in fishing and related industries, retirees, Indigenous people, Coast Guard personnel, and seasonal workers in retail, tourism, and related industries.

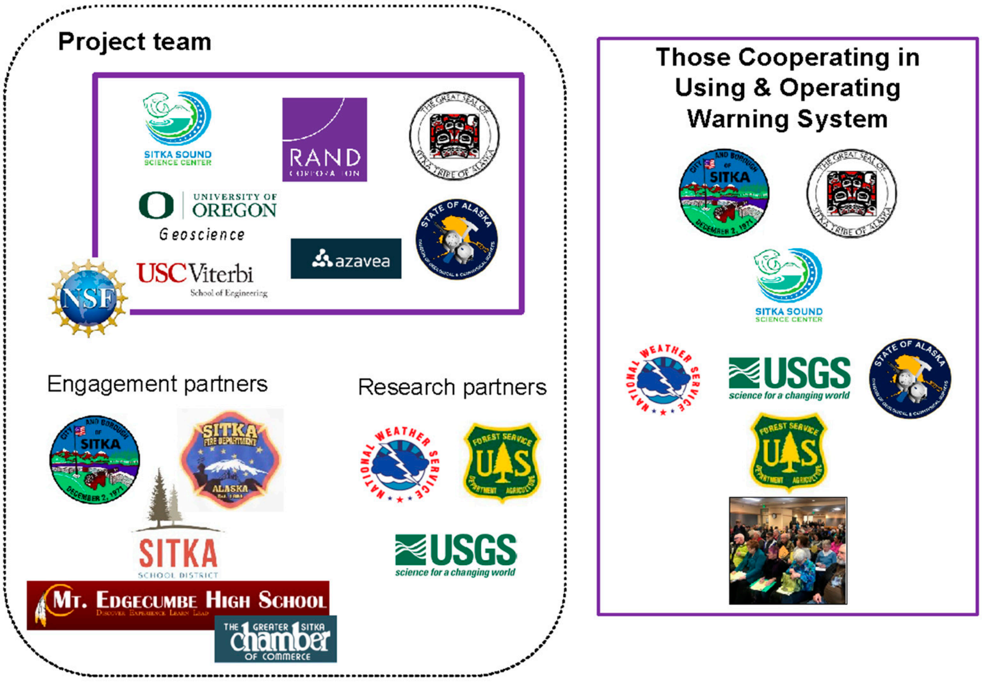


Figure 2. Organizations involved with Sitka landslide warning system. Source: authors.

3. Frameworks

Community engagement has played an increasingly important role in the theory and practice of disaster risk and environmental management in recent decades, as part of an overall turn towards including lay people in what had previously been seen as primarily technocratic decisions of experts [18–20]. Community engagement is a normative principle, seen as a key component of procedural justice, which examines who makes and participates in societal decisions [3] (Sect 1.4.1.1). Recognition, another component of justice, also requires engagement. Recognition entails acknowledgement, basic respect, and fair consideration of diverse cultures, values, perspectives, and worldviews. These principles are broadly recognized including, for instance, in Article 6 of the Framework Convention on Climate Change, which creates a binding commitment on parties to promote participation by civil society in climate-related decisions.

Principles of public consultation and participation have also become embedded in U.S. environmental policymaking. Public meetings and comment periods are required by law in many jurisdictions, and many U.S. and Alaska regulatory bodies have processes for public consultation and participation as part of the regulatory process. In Alaska specifically, public participation processes have been developed to address transportation policy and fisheries management. When well-executed, engagement makes disaster risk and environmental management more effective by enabling better integration of local knowledge, expertise, and values while also increasing the legitimacy and public support for the resulting risk management approaches.

This project conducted a community-level, participatory co-design process to fashion Sitka's landslide warning system. Several frameworks informed this process: *risk governance*, *warning systems* as defined by United Nations International Strategy for Disaster Risk Reduction (UNISDR) [21], and the concept of *co-design*.

Risk governance [22,23] provides a definition of risk along with a conceptual framework and normative principles for guiding multiple actors in identifying, assessing, managing, and communicating risks. Most broadly, risk is the effect of uncertainty on objectives [24]. In Sitka, landslide risk can be usefully estimated as the product of hazard, exposure, and vulnerability. Hazard is the potential occurrence of a landslide at a particular time and place, exposure is the presence of people or infrastructure in places that could be adversely affected by a landslide, and vulnerability is the propensity of a person or structure exposed to landslides to be adversely affected. It also proves vital to consider the psychological and social dimensions of risk. In Sitka, landsliding and warning systems interact with many features of daily life, including anxiety about personal safety, disruption of daily routines, personal independence, and choices of where to live.

Risk governance is not a method, but rather a set of principles that inform methodological choices in activities intended to understand, assess, and manage risk. Our co-design process aimed to embrace these principles which are: (1) *communication and inclusion*, in which information flows in multiple directions in an ongoing process of social learning that includes in a meaningful way all relevant parties; (2) *integration*, which recognizes the need to collect and synthesize all relevant knowledge and experience, including scientific, Indigenous, and local knowledge; and (3) *reflection*, which avoids reliance on potentially familiar but inappropriate understandings through a continuous process of revisiting assumptions and frames in light of new knowledge and interactions among the parties.

Risk governance is most appropriate when risks are systematic, characterized by deep uncertainty, and interpreted through multiple, legitimate points of view [23]. For Sitka's landslide warning, deep uncertainty and multiple points of view were most salient. In addition, risk governance is also most appropriate when, as is the case in Sitka, no single hierarchical organization can effectively control risk assessment and management, making it useful to consider governance as involving "the structures, processes, and actions through which government institutions, markets, businesses, civil society, tribes, and others interact to address societal goals" [3] (Sect 1.4.2.2).

A warning system, as defined by the UNISDR, represents the capabilities needed to generate and disseminate timely and meaningful information to enable people in Sitka to prepare and act appropriately to reduce the possibility of harm. UNISDR finds that an effective warning system has four components [21]: (1) risk knowledge, which in this case includes scientific understanding of Sitka's landslide risk and community understanding of that risk, the warning system, and response options; (2) monitoring, which includes collecting, processing, and disseminating timely and actionable information on landslides; (3) communications, which includes sharing throughout the community of risk knowledge and the warning information from monitoring; and (4) response capability, which is the ability to act on warnings in such a way as to reduce risk.

It also proved useful to consider Sitka's landslide warning as a *decision support system* [7] (p. 36) consisting of information products, services, and systems. Decision support products include the dashboard which displays levels of risk and the data used to predict those risk levels. Services include training workshops to help residents use the dashboard. Decision support systems are defined as "the individuals, organizations, communication networks, and supporting institutional structures that provide and use decision support products and services" [7] (p. 37).

The concept of *co-design* has many manifestations. As noted above, here we use the term to mean a creative, participatory process of fashioning solutions to public policy challenges in which community members and scientists collaborate as equals, consistent with other definitions in the literature [5,6]. We chose co-design as the appropriate form for the engagement because we aimed to help Sitkans reduce their landslide risk through the provision of timely warning. Creating and linking the four elements of effective warning—knowledge, monitoring, communication, and response—in decision support products, services, and systems to best meet community needs presented a non-trivial design challenge.

In addition to the co-design of the landslide warning system, this project also included knowledge co-production, in which researchers and non-academic partners jointly develop a research agenda that serves their interests and needs [6]. In this paper, we focus on the co-design of the system and only discuss co-production of the research as it directly relates or results from the co-design.

The co-design workshops were implemented as a process of *deliberation with analysis*, an iterative learning process in which stakeholders deliberate on their objectives, options, and problem framings; researchers then provide decision-relevant information; and then the parties to the decision revisit their objectives, options, and problem framing influenced by this new information [7]. Deliberation with analysis represents an "iterative interaction" form of engagement [25] intended for situations in which the problem formulations, understanding of system functioning, and the set of promising solutions emerge gradually through interactions among the involved parties [26–28]. In addition to quantitative decision support products and tools, such deliberative engagements also can include visioning, storytelling, and serious games [29]. Such engagements have proven successful in addressing complex and controversial challenges, in particular in water and coastal management with workshop participants consisting of skilled professionals, often working in large government, business, or advocacy organizations [30–34]. In contrast, this Sitka engagement focused on lay participants from a small town.

To supplement the co-design process, we embedded the exercise in a broader process of community engagement. The US EPA guide to public participation identifies five levels of engagement: inform, consult, involve, collaborate, and decide [35]. In this effort, the co-design process operated at the collaboration level. A wide range of other engagement activities, including town halls, small group meetings, citizen science, and media interviews, operated at the inform, consult, and involve levels. Actual decisions were taken by city government agencies, the Science Center, federal agencies, Tribal government, and individual citizens as informed by the engagement processes.

Communication is a key step in risk governance and a key component of a warning system. The risk communication literature highlights that effective risk communication should clearly convey to individuals how risks are proximate for them in time and space, identify actions people can take with the information, inform mental models of the processes creating and modulating risks, and recognize that different people understand risk in different ways [36]. The risk communication literature also emphasizes that individuals are more likely to act on risk information if they receive similar information repeatedly through different channels [37] and that effective risk communication builds on existing communication pathways and social relationships to disseminate information. These understandings informed many aspects of this landslide warning effort, including the design of the dashboard, the content of the co-design workshops, the multi-layered public engagement activities, our dissemination and outreach activities, and plans for how actual warnings are disseminated.

4. Warning System Architecture

As of August 2022, Sitka now has a decentralized LWS, organized around the four elements of knowledge, warning, communications, and response, as shown in Figure 3.

A risk dashboard lies at the heart of the system and provides the warning component of the LWS. The dashboard is accessible online via mobile device or a computer (https://sitkalandslide.org, accessed on 16 February 2023) and at any moment in time provides hourly projections of landslide risk in Sitka over the next 24 h and for each of the next three days, as shown in Figure 4. The main page displays risk in one of three categories—low, medium, and high—and provides a brief description of each. These descriptions employ both probabilistic language (e.g., likely, unlikely) as well as historical context (e.g., over the last twenty years, no rainfall-induced landslides have occurred in Sitka with rain similar to the current intensity) as also shown in Figure 4.

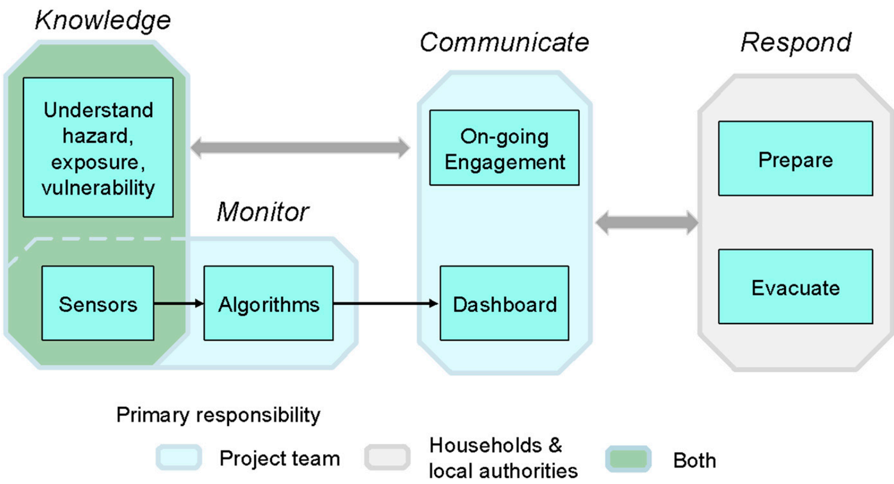
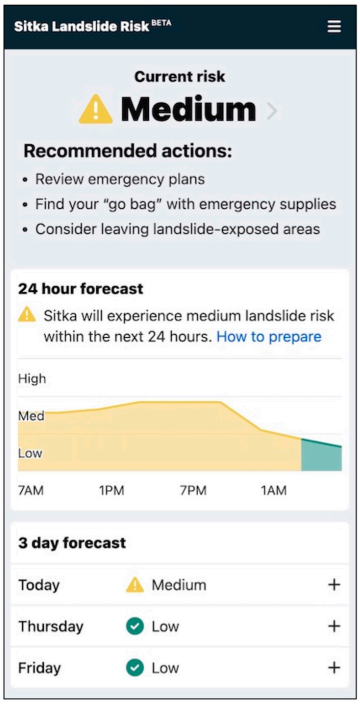


Figure 3. Elements of Sitka landslide warning system. Source: authors.



Risk Level	Description
High	Multiple landslides are very likely to occur in the Sitka area. There have been three storms in the last 20 years with similarly intense rainfall, and all three of them initiated multiple landslides
Medium	Landslides are possible. Isolated landslides have occurred in Sitka with similarly intense rainfall in the past.
Low	Landslides are unlikely based on historic observations in the last 20 years. Rainfall-induced landslides have not been documented for these rainfall conditions

Other resources available on Sitka Landslide site

Oral histories: Explore stories of landslides
Landslide 101: Find out more about landslide science
Areas at risk: Identify where you live relative to landslide exposure
How to prepare for a landslide: Learn how to prepare
Published work: Access articles by our research team
Report a landslide: Share new observations of landslides

Figure 4. Dashboard snapshot (left panel), text on risk levels (right panel), and other resources available on the Sitka landslide website. Source: authors, from https://sitkalandslide.org (accessed on 8 February 2023).

The intention is that community members will access the dashboard during periods of heavy rainfall or when such rainfall is expected in order to make informed decisions regarding whether they wish to alter their plans to reduce their landslide exposure. For instance, based on their risk aversion and the risk level reported by the dashboard, a family whose home is an area exposed to landslides might decide to sleep that night at a friend's house which has less exposure. NWS warnings, other public service announcements, or merely experiencing inclement weather might lead Sitkans to view the dashboard. The SSSC, supported by the project team, conducted a dissemination and outreach program (described below) to make the community aware of the landslide warning system and how to use it.

To enhance the community's risk knowledge, the dashboard also contains drill down menus which provide more detailed and contextual information. As listed in Figure 4, these include descriptions of how Indigenous peoples have thrived in this region amidst tumultuous geological forces including landslides, a primer on the science of landslides, maps showing which areas of Sitka are more or less exposed to landslides, information on how to prepare for landslides and respond to landslide warnings, a bibliography of relevant scientific literature, and links to an inventory of past landslides in and around Sitka, along with instructions for reporting new ones. Not shown in Figure 4, the drill down menus also provide more detail on the sensor data used by the dashboard for landslide predictions. In particular, the dashboard provides maps of landslide exposure from a debris flow model developed for the USFS by TerrainWorks [11] and links to other published works that document spatial patterns of landslide hazards [9].

Note that, formally, the dashboard reports a hazard level, not risk. Users can consult the exposure information provided by the dashboard's "Area at risk" drill down menu to begin to form a judgment about their level of risk. However, the project team decided to use the term risk on the dashboard as shown in Figure 4 for simplicity of communications with users.

The monitoring elements of the Sitka LWS rely primarily on sensors and forecasts from the local offices of the National Weather Service. The dashboard's risk estimates are calculated from the NWS's regional projections of three-hour rainfall intensity. The project's geoscientists developed the algorithm that converts estimates of rainfall intensity into the dashboard's landslide risk scale [38]. A network of sensors provides the data for the NWS rainfall predictions. These sensors include a rain gauge at the airport (sea level); a weather station atop Harbor Mountain (~2000 ft), one of the several peaks above the town; and a river gauge on the Kaasda Heen (also called Indian) River that flows through town.

The project team did not directly engage with identifying and planning response options that residents could implement based on the warning. Such responses might include relocating to a friend's house in a low landslide exposure area when landslide risks are high or not sending one's children to school on such high-risk days. The project's geoscience research concludes that medium and high-risk days are not likely to occur more than several times a year [38], suggesting that most residents may find that disruptions to daily life related to landslide warnings are relatively small. The project team worked with the Local Emergency Planning Committee to encourage them to include landslide preparedness in their portfolio of responsibilities and in their educational outreach to the community.

The LWS's development was supported by the project team's geoscience, social science, and information science research. The geoscience team informed the LWS's monitoring and risk knowledge elements. The team conducted a geomorphology survey to inform understanding of Sitka's landslide hazard, conducted an intercomparison of the four landslide runout models available for the Sitka area to inform exposure mapping [9], and developed landslide prediction algorithms [38]. In addition, the geoscience team deployed three moisture sensors in the hills above Sitka and ten tipping buckets as a citizen-science effort [39]. We had expected that these sensors would prove valuable to improving landslide prediction, but the predictions from rainfall intensity data alone appear to be surprisingly good. The moisture and tipping bucket sensors thus contributed primarily to improving risk knowledge. For instance, data from the tipping bucket rain gauges emphasize the spatial variability of rainfall intensity across Sitka's relatively small spatial area, thus supporting the decision to issue landslide risk warnings for the entire area and not specific hillsides. Data from the moisture sensors help confirm that drainage on the hillsides is sufficiently fast that instantaneous rainfall intensity alone, rather than instantaneous and cumulative rainfall intensity, is the best predictor of local landslide risk [38].

The social science and information science teams informed the LWS risk communications element. The social science team mapped Sitka's social networks using a survey in which respondents provided information on whom in the community they exchanged information on natural hazard risk [40]. Leveraging these data, the information science team developed an influence maximization algorithm that identified key influencers by weighting community members by geographical exposure to landslide hazards and considered demographic characteristics to ensure an equitable distribution of information [41]. This allowed us to identify key community connectors to receive training on the dashboard. The social network analysis also provided an empirical understanding of how information about risk flowed through the community and which groups might be most difficult to reach. In particular, the social network analysis revealed a pattern of landslide information sharing in which a highly connected community "core" was surrounded by several smaller groups apparently disconnected from this core.

The social science team also informed the risk knowledge associated with the LWS by gathering oral histories from the local indigenous community and contributed to the LWS response element by conducting, as described in Section 5, research on insurance response options.

The dashboard is operated and maintained by the SSSC. The software is designed to automatically update the risk projections twice per hour to reflect the most current rainfall forecasts. An important topic, unsettled at the project's end, involved funding for on-going maintenance, operations, and upgrades to the system. Initially the hope had been that the system would have been owned or adopted by either the city or by one of the federal agencies involved in the project. A new NSF-funded project awarded to the team (described below) provides some opportunities to maintain and continue operations of the Sitka dashboard. The SSSC is also writing grants for additional and longer-term funds to maintain the system.

5. Warning System Co-Design Process

Sitka's landslide warning system was developed through an intensive co-design process, embedded in a wide-ranging process of community engagement. The co-design focused on three in-person workshops, as shown in Figure 5, representing a collaborate level of engagement. Other engagement activities included on-going community outreach activities by SSSC staff, exploratory interviews with key stakeholders and representatives of different groups in Sitka conducted by the external social science team, surveys to support the social network analysis, as well as activities organized around three, week-long visits by the external project team to Sitka; and several extended stays in Sitka by individual external team members. Appendix A provides more comprehensive listing of workshops, engagements, and related activities.

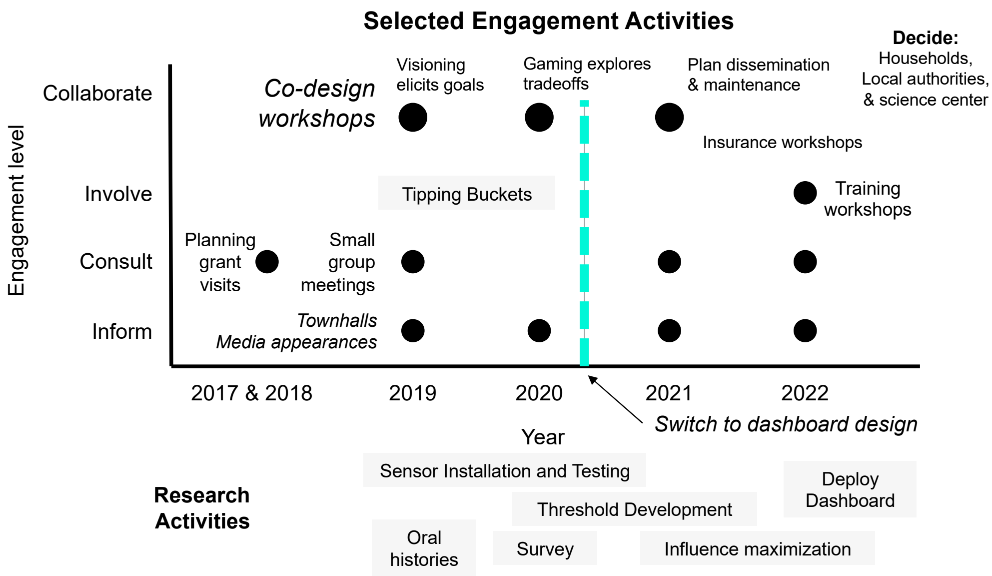


Figure 5. Selected engagement and research activities. Source: authors.

Landslides have been common in the Sitka area since the last ice age [9]. However, landslide risks were not on most Sitkans' minds until the 2015 slide killed three people and left the town confused and anxious. In response, the Sitka Sound Science Center convened a group of geoscience experts from academia and from federal and state agencies in what came to be called the Geotask force. The task force recommended that the town create a landslide warning system [42].

RAND had become involved in the later stages of the Geotask force and subsequently joined with the Science Center to write first a pilot grant and then a full grant to NSF to develop an LWS for Sitka. Recent USGS work in Washington State had demonstrated the utility of moisture sensors for improving landslide warning [43]. However, the USGS sensors were very expensive, on the order of $10,000 each. Our proposed project aimed to demonstrate the value of networks of low-cost, internet-enabled moisture sensors in the hills above Sitka. The project also aimed to improve risk communications with a novel social network analysis and influence maximization algorithms to better understand and to improve the flows of risk information through the community.

The full project began in the fall of 2018. A series of structured, day-long workshops in Sitka provided the core of the warning system co-design process. The external project team traveled to Sitka for a decision scoping workshop in May 2019, a design workshop in February 2020, and an update workshop in October 2021, as detailed in Appendix A. During that same October week in 2021, the project also held a separate workshop on landslide insurance options.

The May 2019 decision scoping workshop introduced the community to the project, and then used a backcasting exercise [44] focused on visioning and storytelling on the theme of a future Sitka with effective and well-regarded landslide warning. This exercise helped community members to articulate and research team members to understand goals for the warning system as well as potential actions to pursue those goals. Participants in the day-long workshop included about a dozen Sitkans, including community leaders and city officials responsible for emergency response. The workshop confirmed the project team's understanding that community goals for the warning system included reducing loss of life and the anxiety felt during intense rainfall events. However, the workshop also raised additional goals including offering opportunities for participation and access for everyone in the community, building and maintaining trust, clear and consistent communications, an orderly process of evacuation if and when needed, low cost, and minimal impacts on property markets.

Informed by the workshop and ongoing geoscience research, the project team developed an initial design for landslide warning based on a centralized, siren-based system similar to Sitka's existing Tsunami warning system. In the February 2020 design workshop, participants reviewed and suggested revisions to this initial plan. The workshop used serious games to help participants appreciate the challenges in balancing between failed and false warnings and to understand the potential role social network analysis could play in efficiently and effectively disseminating landslide risk information throughout the community.

The results of this workshop contributed to the warning system redesign shown in Figure 3, featuring the online, landslide risk dashboard enabling individuals to make their own evacuation decisions. The design workshop also informed changes to our geo- and social science research, as discussed in Section 7. The pandemic curtailed travel shortly after this design workshop, so for the next year and a half, subsequent discussions with the community were conducted in smaller, online groups. At the final design review and launch plans workshop in October 2021, the project team presented the emerging dashboard-based warning system and discussed with the community plans for disseminating and maintaining the system.

Concurrently to the co-design workshops, the project team engaged in a wide range of community engagement activities designed to increase knowledge and awareness in the community about the project, landslides, and the risks they generate. The project team participated in town halls organized by the Science Center, which were held parallel to each of the design workshops and provided a public forum for citizens to learn about the project and ask questions of the team. As one important purpose, these events aimed to engage a much larger number of Sitkans than could participate in the co-design workshops. The project team also provided regular updates to the city assembly and the tribal council through presentations at the regular meetings of those legislative bodies. The team also met several times a year with other parts of the city government including the LEPC, the Planning and Zoning Commission, and the School Board. The team also promoted a presence in local media. Team scientists were interviewed on the public radio station and sat in on the AM radio station's "problem corner" to answer audience questions. The project was profiled multiple times in the daily newspaper.

In addition, the team worked to forge more individual connections with community members. The Science Center's Scientists in the Schools program organized opportunities for the team scientists from external institutions to visit Sitka elementary and high school classrooms. Over the course of the project, external team members also spent one-month mini sabbaticals in Sitka, engaging in a breadth of community activities meant to help scientists learn about the community and help community members learn about the science. On their visits to Sitka, project team members participated in science cafes, met people at the local brewery and introduced themselves at tribal and city government meetings. They participated in trivia nights and shared in potlucks, community hikes, and boat rides, all with the intention of setting up a two way "getting to know each other" relationship so that scientists did not seem separate from the community but rather integrated into it.

To help implement the dashboard design, the project team conducted a range of dissemination activities and hired Azavea, a professional software developer, to build the dashboard. In the fall of 2021 Azavea met with the project team to understand our design concepts and then conducted interviews with eight individuals chosen to be broadly representative of the community to better understand their view of important design features. Based on this input, Azavea generated wireframe examples of dashboard designs and contents to facilitate discussions with the project team. These discussions helped finalize the dashboard content, including the names of the risk levels and the language connecting them to historical events. After several iterations, Azavea programmed the current dashboard including the data pipelines that feed the prediction algorithms and the information available in the drill down menus.

During the design process and as the dashboard neared completion, the project team launched its dissemination activities, intended to provide all members of the Sitka community with the knowledge and capacity to use the dashboard. The team employed multiple channels of communications including formal dissemination workshops informed by the social network and influence maximization analysis. The team also made presentations to various community groups, including boards and commissions for the city and tribal governments, as well as the Chamber of Commerce and the Rotary Club.

The SSSC and STA hosted the structured rollout workshops, which aimed to teach a select group of residents about the dashboard. The social network analysis and influence maximization research described in Section 4 helped to inform the invitation lists. We could only provide intensive training on the use of the dashboard to a small number of individuals (roughly forty total over four workshops), so we aimed to focus on inviting those individuals who could most efficiently and equitably disseminate information to the community. Most of the invitees (roughly 80 percent) were chosen by our community partners, based on their personal knowledge of their fellow residents. However, we supplemented the invitation lists for each workshop with two or three high-influence community connectors identified by the social network analysis. Using information on all the attendees at previous workshops and the invitees for the planned workshop, the influence maximization algorithms would suggest additional invitees who would provide the most effective and equitable dissemination of information, weighting community members by geographical exposure to landslide hazards and their demographic groups.

During the course of the co-design process and community engagement, it became clear that many Sitkans were concerned about the availability of landslide insurance and the effects of landslide risk information on local property values. In the aftermath of the Kramer slide, and the hazard mapping efforts it spawned, some homeowners had trouble insuring their homes and obtaining mortgages due to a lack of landslide coverage. The topic of landslide exposure maps had also become controversial, complicating the project team's decisions regarding what exposure information to provide on the dashboard. It became clear that the project team needed to address the landslide insurance issue to maintain the trust of the community.

The project team thus conducted an additional engagement to share information and identify potential options for landslide insurance. We conducted a nine-month effort from April 2021 to November 2021 consisting of twenty-four key informant interviews, a facilitated half-day workshop in Sitka on October. 4 described in Appendix A, and a post-workshop survey for participants [45,46]. The insurance workshop included a facilitated discussion regarding exposure maps, which led to the decision to include on the dashboard a map with sufficient resolution so that users could judge risk in their immediate neighborhood, but without sufficient resolution to identify specific properties.

6. What Changed during the Co-Design Process

Co-design aims to collaboratively fashion solutions to policy challenges. So, one measure of the process is the extent to which it shifts the design of Sitka's LWS to better align with scientific understanding and community goals. Here we document how the LWS design changed significantly during the project; how the team's geoscience, social science, and information science research evolved; and how the co-design process itself changed. In the next section we present evidence that the co-design process aligned with community goals was responsible for these changes.

The Sitka Fire Department has operated a tsunami warning system for over forty years. The system employs sirens to disseminate a city-wide alert when the fire chief determines, based on information warnings from the National Tsunami Warning Center, that an evacuation of low-lying areas in the city is warranted. At the start of the project, we envisioned that landslide warning would operate similarly [4]. The fire chief would make evacuation decisions, a siren would communicate the warning to residents, and a neighborhood buddy system would ensure everyone had heard and responded to the sirens. The co-design process shifted the LWS to one that empowers residents to make their own evacuation decisions using risk information provided by the online dashboard. In addition, the team's initial plans for the buddy system were supplanted by a more voluntary model, partially because community members during the co-design workshops indicated that they would not feel comfortable holding formal official responsibility for notifying others in their communities of imminent landslide risk.

Consistent with a co-production process, interactions with the community also shifted the research agendas of the project's research teams. The team's geoscientists adjusted their approach to what constituted a successful landslide prediction based on the community's criteria. At the start of the project, the geoscientists would have regarded a prediction as successful if a landslide subsequently occurred anywhere near Sitka, even if it didn't affect property within the city. For community members, however, successful prediction required much more spatial specificity, differentiating landslides that endangered people and property from those that did not [4].

Spatial hazards analysis in Sitka can identify susceptible hillslopes within Sitka and on nearby slopes [10,11,47], but current prediction tools do not allow practitioners to identify which of several susceptible hillslopes will experience failure during a particular storm. In response to community definitions of successful landslide warning, the project team's geoscientists fundamentally shifted the structure of the statistical models they used to predict landslides. Most LWSs around the world make predictions based on large landslide inventories (tens to thousands of landslide-inducing storms) across larger areas—mountain ranges, states, or even countries [48,49]. Instead, the geoscience team implemented novel statistical applications to train and evaluate probabilistic models with an extremely limited landslide inventory (5 storms) from only those hillslopes adjacent to (<2 km) the Sitka road network [38].

Community input also informed warning threshold selection. The team originally envisioned a single alert level for a siren-based system, but varying levels of risk tolerance documented in the workshop series demonstrated the need for two warning levels, one which minimized the probability of missed alarms and one which minimized the probability of false alarms. For example, the team chose a lower threshold for the "moderate" risk level at an estimated landslide probability of 1%, using a combination of traditional statistical metrics (Precision Recall) and a heuristic approach to select a conservative threshold with this very low probability of missed alarms [38].

The teams' social scientists also adjusted their research designs in response to community feedback. Initially, the social science team had intended to map existing patterns of communication and social relationships in the community and then use this information to help create the buddy system. However, Sitkans were skeptical of an outside research group mapping and analyzing their social networks. The project team thus adjusted to use the social network analysis primarily to inform our local partners, the SSSC and STA, as they created invitation lists for our dissemination workshops. In addition, the social science team had initially intended to gather oral histories from indigenous community members to improve our understanding of how members of the Sitka Tribe viewed landslide risk and to inform our risk communications. However, the Tribe was uncomfortable with the research team sharing the oral histories, so we agreed to just summarize their themes on a page on the dashboard.

Finally, the co-design process itself changed during the project. Initially, we had expected community members to deliberate on an appropriate threshold that the fire chief could use to issue a centralized warning. We expected these deliberations would be informed by a decision support tool the project team would build showing the tradeoff between lives at risk and disruptions from false warnings as a function of the warning threshold. However, as our understanding of the underlying geoscience and the LWS design evolved, we switched to a gaming format to sensitize community members to the false vs. failed warning tradeoffs inherent in landslide warning. We also added the insurance research stream in response to community feedback, as described in Section 5.

7. Did the Co-Design Process Succeed?

To what extent did the participatory co-design process accomplish its intended purposes? The project aimed to provide Sitka with an LWS that aligns with community goals while conducting research to improve understanding of new sensor technologies and of social networks and influence maximization.

For reasons described below, the project team could not formally evaluate Sitka's new LWS and the associated co-design process. We were, however, able to conduct a more formal evaluation of the insurance research and the extent to which the co-design process contributed to beneficial changes in LWS design and associated research activities. Here, we first report on our informal evaluation of goal alignment and then report on the more formal evaluation of the co-design process.

To consider goal alignment of the system and process, we documented in detail the co-design process, the goals articulated during that process, the changes that occurred during the process, and the resulting warning system. We then gathered available evidence on the extent to which the system and process align with the goals.

In the first co-design workshop, participants articulated the following goals for Sitka's LWS: (1) the system should help reduce loss of life from landslides, (2) reduce the anxiety felt during intense rainfall events, (3) offer opportunities for participation and access for everyone in the community, (4) build and maintain trust, (5) provide clear and consistent communications, (6) have low cost, (7) support an orderly process of evacuation, and

(8) have minimal impacts on property markets. Appendix A provides more detail on each goal.

The project team was unable to formally evaluate the extent to which the co-design process and resulting LWS aligns with these goals. In part, the warning system became operational in August 2022 only a month before the end of the project, making it difficult to measure community attitudes towards the deployed system. We have not evaluated the community response to the LWS in periods of heavy rain because, as of this writing, there has not yet been any landslide warnings, heavy rain events, or landslides since the dashboard became operational. In addition, other research groups as well as city, state, and federal agencies were reporting and acting on landslide risk concurrently with our project, making it difficult to isolate the impact of our efforts on residents' attitudes. Finally, the pandemic intervened, so that the community we surveyed at the start of the project was different from that at project's end. For instance, the co-design effort settled on a dashboard-based system in mid-February 2020 at a time when many community members were likely unfamiliar with the dashboard concept. When the landslide dashboard launched in August 2022, many community members had two years of experience gleaning information from ubiquitous COVID-related dashboards.

We did, however, gather evidence to suggest the co-design process and the warning system it produced were successful. First, the landslide prediction algorithms appear accurate and thus able to provide useful warning. During the winter of 2021, our geoscience team was able to use the then-current algorithms to disseminate to local officials' accurate warnings of intense landslide-producing storms.

The project team, in particular our community-based members, solicited extensive feedback during the final year of the project and its aftermath. This feedback suggests that the community is pleased with the results of this effort. Local officials and residents spoke favorably of the system. Since its launch, the dashboard has had about 6500 unique users, with about 25% of them from Alaska. The City Assembly and the Tribal Council both informally stated that they were extremely pleased and grateful for the work of the team and that they perceived the outputs of the research to be useful and valuable. This included positive feedback from the city's Fire Department, who had initially been skeptical of the practical value of the project but became impressed by how well the system seems to work and became comfortable with their role in the dashboard-centered system design.

Additional evidence is provided by the reactions of neighboring communities. Towards the end of the Sitka project grant, the project team received another NSF award to support co-design efforts for multi-hazard warning systems in six other communities in Southeast Alaska. This new project is called K̲UTI, both an acronym for the English phrase *Knowledge and Understanding, Technology and Institutions* and the Tlingit word for weather. In recruiting new partners for K̲UTI it became clear that many communities in the region were familiar with the work in Sitka, were eager to engage with our project team, and cited the reputation of the Sitka effort as one of their reasons.

A formal evaluation of the project's insurance-related activities proved possible. These activities occurred over a short time span, and no other group conducted similar work. After the insurance workshop, the project team fielded a web-based survey for workshop participants. The results suggested that almost all the participants found that the workshop improved their understanding of the challenges of securing landslide insurance, intended to share what they learned with others, and wanted to see landslide insurance become more available. However, less than a third of participants reported that the workshop increased their optimism that such insurance would become available [45,46].

Overall, this mostly informal evidence all suggests that the LWS and co-design process does align with the first five community goals. Regarding the other three goals: landslide risk has affected property values, but the project did help the community grapple with that challenge; orderly evacuation remains untested; and costs are discussed in the next section.

We did formally evaluate the extent to which the design process conformed to theories and best practices for stakeholder engagement in early warning system development [50].

As one component, this evaluation explored the ways in which the team's perceptions of the problem evolved over time and aimed to identify key moments that led to the changes in system design and research plans described in Section 6. These shifts were evaluated through analysis of nine interviews conducted with core project team members; notes taken during monthly team meetings, the three design workshops, as well as during public presentations to the city's political and administrative leaders and smaller discussions with representatives of Sitka's Police and Fire departments, Coast Guard, school district, mayor's office, city engineer and planning offices. The team also examined 41 local news articles and stories about the project, minutes from city council meetings where landslide risk was discussed before and during the project, and the Sitka Geoscience Taskforce report, which preceded the current co-design effort. By coding for key themes in these documents, we could track how the team's and community perceptions changed over time [50].

This evaluation suggested that research team members perceived a moderately clear breakpoint in the first year of the project, when it became clear that a top-down centralized system would not meet the needs of community stakeholders, specifically that warnings would not be accurate enough in the short term to enable emergency responders to feel comfortable issuing evacuation warnings. The interviews conducted in 2019 and early 2020 suggest that this realization was an important factor in shifting from a centralized, siren-based system to one that was decentralized and dashboard-based. Interviews with the team's geoscientists also confirmed that community interactions had been important in expanding their concept of what constituted a successful landslide prediction to include the community's criteria.

8. Lessons Learned and Implications for Climate Services

This paper describes a community-level, participatory process of co-design and community engagement that resulted in a landslide warning system for the small town of Sitka, Alaska. As a decision support system, the Sitka LWS includes information products and services and engages supporting networks and institutions. It includes the four warning system components: knowledge, monitoring, communications, and response. Intended as a risk governance exemplar, the co-design and community engagement aimed to embrace communication and inclusion, integrate multiple sources of knowledge, and promote reflection which revisits and reframes initial assumptions. Processes of deliberation with analysis, previously used in larger jurisdictions with expert participants, worked well in a small town. The co-design process helped to redirect the project's research; shift the design from a centralized, siren-based system to a decentralized, dashboard-based one; align the institutions and organizations needed to implement and operate the system going forward; and result in an LWS that the community recognizes as serving their needs.

To what extent does this Sitka LWS and its co-design process represent a model for U.S. climate services that could be scaled nationwide? This question has at least two parts. The first asks the extent to which its decentralized, dashboard-centered design might offer a model for U.S. disaster response and management. The second asks what it would entail for the participatory risk governance employed in Sitka to become the norm for U.S. climate services.

To the first question, the Sitka experience suggests that the appropriateness of individualized evacuation decision- making is highly context-dependent, and that US disaster response and management would require an extensive community co-design process to make location-specific judgments regarding its use. The appropriateness of individualized evacuation depends strongly, in Sitka at least, on the accuracy of warnings generated, potential spillover effects of evacuation decisions on first responders and others, the community's views of risk, and how best to ensure equity. In Sitka, each of these criteria favor the decentralized system.

The algorithms in the Sitka warning system seem unexpectedly accurate in predicting when landslides will occur in and around the town. However, the predictions lack any geographic specificity, due in part to the significant variability in rainfall intensity across the town, significant variation in soil composition even among nearby hillsides [9], and the current reliance on measuring rainfall intensity at a single location. The inability to predict whether landslides would occur within as opposed to nearby Sitka was interpreted by the community as a high false alarm rate and thus a reason for a decentralized system [4].

In Sitka, the spillover effects from evacuation lean in the direction of individual decisions. The town lacks sufficient space for everyone who would need shelter if evacuations were mandatory. Not evacuating, or choosing to evacuate at the last minute, does not put first responders at risk since last-minute evacuees generally do not need to travel far to safety. If community dissemination of the individualized warning system works as intended, there is little reason for first responders to enter an exposure zone until a landslide has occurred. This situation can be contrasted to that of a flood or wildfire in many communities, in which first responders might take on risks to save people still in the flood or fire zone and the geography is such that people fleeing at the last minute can block roads needed by the first responders for their own effectiveness and safety.

The workshop discussions and community engagement emphasized that many Alaskans have a strong sense of independence, so they prefer to make their own decisions about risk. Equitable access to warnings and responses in Sitka seems best handled through the social networks highlighted in this project, which appear at least as effective as would be a siren or other centralized warning.

Overall, while a decentralized landslide warning system seems appropriate for Sitka, any judgments about warning accuracy, potential spillover effects, community views of risk, and equity are context dependent and most usefully explored in a co-design process.

The Sitka experience with community level, participatory co-design also suggests what would be required to conduct nationwide such participatory governance at a local scale. These requirements include: (1) a strong local partner, (2) active engagement by state and federal agencies, (3) support for and skill with multidisciplinary research, (4) resources for ongoing operations and maintenance, and (5) trained personnel to conduct co-design processes and the supporting research.

This project's local partner, the Sitka Sound Science Center, anchored the warning system and its development with the community. While much of the research and project management was conducted by the team's external partners—RAND, University of Oregon, and University of Southern California—in the eyes of the community, the main focus of any credit and blame for the project's perceived successes and failures resided with SSSC. The Science Center enabled the co-design process and its embedding in widespread community engagement; hosted all the project's community meetings, provided voice for all the project's communications with the community; organized the project's citizen science, served as home base for external team members visiting the community; arranged the project's town halls, science in the schools, and other outreach activities; and brokered most of the project team's interactions with community groups. The STA also provided a vital connection to the community's Indigenous population, including representatives for the project's deliberative processes and liaising with the local tribal government.

Replicating this Sitka model nationwide would require a national effort to create and support more local organizations with the capabilities of SSSC.

This project was also fortunate to have specific individuals from the regional offices of the USFS and NWS who were personally committed and excited by community engagement. Some of these individuals lived in and were widely regarded as members of the Sitka community. These individuals acted as trusted members of the community, as active members of the research project team, and as liaisons to the Federal agencies which provide crucial information and expertise to the local Sitka warning system. Individual members of the Alaska state government played similar roles.

Replicating this Sitka model nationwide would require moving beyond these committed individuals to a strong institutional commitment to community engagement from the relevant federal and state agencies.

The project team supporting the Sitka warning system effort was broadly multidisciplinary, involving geoscience, social sciences, information sciences, and risk management research. The project's geo-science research was central, but the project also gathered local and Indigenous knowledge and conducted research on social science, risk governance, and policy analysis regarding options for landslide insurance. This information all also proved critical to the design, deployment, and dissemination of all four components of a decentralized warning system and to effectively engaging the community in its design.

However, the community and project team both presented barriers to this multidisciplinary research. Coordinating the multiple strands of research was an ongoing project management challenge, in particular as the research directions evolved through the course of the co-design process. Community members also lacked an initial appreciation for multidisciplinarity. They had a strong initial appreciation of the value of geoscience for reducing the risk from landslides and were often eager to engage with the team's geoscientists. Most community members, however, initially had less appreciation and some suspicion of the role of social sciences and policy analysis. The project's workshops and other community interactions thus needed to build such appreciation and trust.

Replicating the Sitka model would require ongoing and enhanced support of such multidisciplinary research and training in how to conduct it most effectively.

While ample federal funding was available to design and deploy the Sitka warning system, funds for maintaining it have been more difficult to come by. Our project team has estimated the staff time and financial resources that the SSSC would require to maintain Sitka's warning system on an ongoing basis. As detailed in Appendix B, such operations would cost about $65,000 per year. This includes a junior SSSC member working about one-third of their time organizing maintenance of the sensors and their data feeds, upgrading algorithms, community education and outreach programs, and maintaining contact with relevant city, tribal, state, and federal agencies. This also includes annual equipment costs of about $25,000 for website maintenance, telecommunications contracts for the sensors, and materials and depreciation on the sensors.

Finally, for this Sitka model to be scaled up nationwide, many of the project team's tasks, including some of the research and co-design facilitation, would need to be operationalized by trained staff working in government, NGOs, or related operational organizations, rather than by PhD's working in research institutions.

Replicating the Sitka model nationwide would require stable funding for maintaining such systems and a nationwide effort to train and support individuals and their institutions who could specialize in the work of helping communities to co-design them.

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Appendix A. Co-Design Workshops and Community Engagement Activities

The Sitka landslide co-design process was one component of a larger process of community engagement. The co-design process was organized around three in-person workshops in Sitka, Alaska, a decision scoping workshop in May 2019, a design workshop in February 2020, and a review and launch plans workshop in October 2021. Table A1 shows these workshops in bold type with other key events and engagement activities shown in regular typeface.

Table A1. Community engagement and co-design activities.

Date	Activity
2015	• Kramer slide
2016	• Geoscience task force
2017	• Planning grant visit (Dec)
2018	• Geoscience task force report • Submit proposal to NSF (Feb) • Project start (Sept)
2019	• **Decision scoping workshop (May)** • Scientist in residency (Fall)
2020	• **Design workshop (Feb)** • Landslide runout model workshop (Aug–virtual)
2021	• Scientist in residency (Spring) • Scientists in the schools (Aug-Sept) • Dashboard developer design workshops (Sept–Nov) • **Design review and launch plans workshop (Oct)** • Insurance workshop (Oct) • Scientists in the schools (Dec)
2022	• Town hall (Jan–virtual) • Scientists in the schools (Feb) • Presentations and work sessions with Sitka tribal council and Sitka city assembly (Spring–summer) • Dashboard dissemination workshops (May–July) • Dashboard launch (August)

Bold indicates a co-design workshop.

The May 2019 decision framing workshop agenda was organized around a backcasting exercise, a planning method that starts by defining a desirable future and then works backwards to identify policies and programs that will connect that future to the present situation. Workshop participants were asked to imagine that it is the year 2025 and Sitka has the nation's best landslide warning system. Participants crafted stories describing how Sitka had arrived at this happy situation, with a focus on describing key actions taken in the years 2019–2021.

This exercise generated a common understanding of goals for the warning system, including reducing potential loss of life, reducing anxiety about landslides, inclusion of all community members in the benefits of the warning system and opportunities to participate in its design and operations, an ability to inspire trust in the system, effective monitoring and communications, effective response to warnings, sustainable operations and costs, and an ability to protect property. The exercise also generated an understanding of actions the community would consider pursuing to achieve these goals, including developing appropriate knowledge, setting appropriate warning thresholds, effective communication, effective response actions, operations, and insurance pools and structural measures to protect property. The project team crafted initial versions of these lists based on the workshop discussions, and then shared them back with participants for revision and refinement. The final versions are shown in Tables A2 and A3.

Informed by the decision scoping workshop results and their ongoing geoscience research, the project team subsequently generated an initial design of the landslide warning system, as shown in Figure A1. This design envisioned a system in which the Sitka Fire Department would activate a siren when local conditions indicated landslides were sufficiently likely. The February 2020 design workshop presented participants with this initial design, engaged participants on scientific concepts and issues central to design choices, and provided an opportunity for review and comment on the initial LWS design.

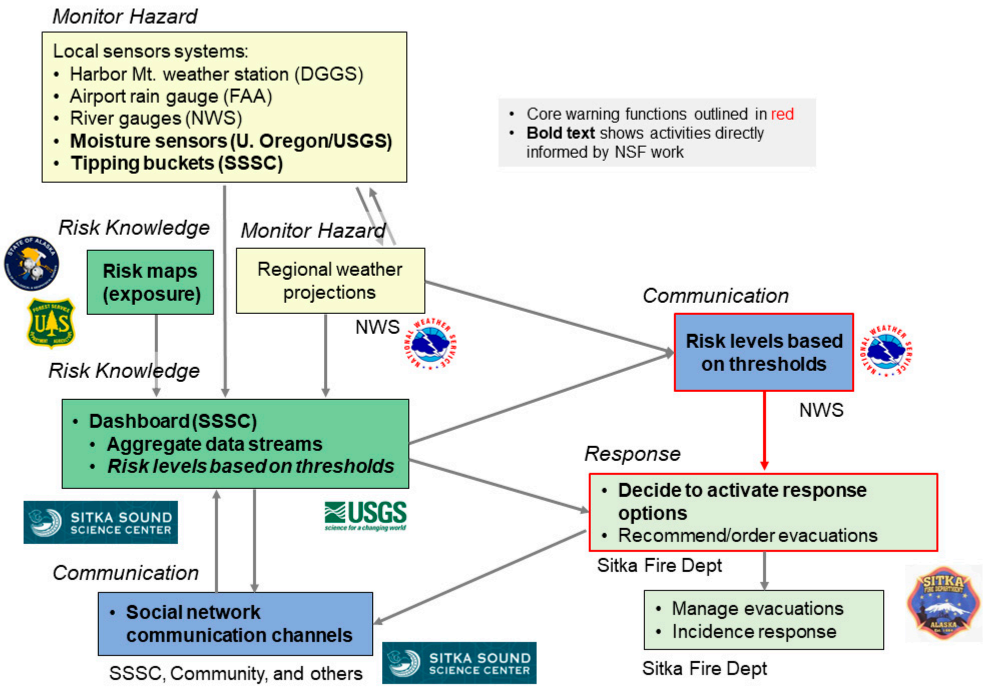

Figure A1. Warning system design used at start of second co-design workshop. Source: authors.

The design workshop was organized around two key project research areas: geoscience aimed at improved landslide predictions and social network analysis aimed at improving the efficiency and equity of landslide communications. The geoscience discussions provided an overview of progress to date with developing and testing the new moisture sensors. The social network discussions provided an overview of how better understanding such networks could improve risk communications in Sitka. Each segment included a "serious game" designed to illuminate and seek feedback on important design choices and tradeoffs for the LWS.

The geoscience research suggested the extent to which any improved landslide prediction would remain imperfect, thus highlighting a design tradeoff between failed and false warnings. The latter could increase community anxiety and disrupt daily life. The former could increase loss of life. In addition, there exist decisions as to the spatial resolution of the warning, that is, the extent to which warnings are generated for particular areas or provided more generally. For instance, workshop discussions revealed that the geoscientist and Sitka residents viewed differently the spatial scale of successful warning. The geoscientists would regard a warning to be accurate if a landslide occurred within many miles of Sitka. Many community members would regard a warning as failed if a landslide occurred outside the city bounds.

To address these issues with a serious game, participants were each given a plot with data showing maximum precipitation intensity for storms in Southeast Alaska that did and did not initiate landslides. Participants were asked to draw lines through the data representing a precipitation-duration threshold that might be used to generate warning. The answers were diverse. Some participants chose low thresholds that would generate no failed warnings, some chose high thresholds that would generate no false warnings, and some those thresholds in between.

Participants were then divided into groups based on where they drew their threshold and asked to choose a card which would reveal either a failed, false, or accurate warning. Each group chose from a card deck with probabilities corresponding to their chosen thresholds. Participants revealed their choices and were asked to describe how they felt about the results and how they would explain them to others. For instance, participants in the group with low thresholds would need to role play an official explaining a false alarm that had needlessly disrupted life in the community. Participants in the group with high thresholds would need to explain a failed warning that resulted in injuries in the community.

Social network analysis can improve the flow of appropriate warning and risk knowledge to all who need it; help ensure that all Sitkans receive useful, understandable, and actionable information; and improve message redundancy in which the same information reaches an individual through multiple channels. However, social network data collection and analysis raises issues of privacy, equity, and trust. To engage with these tradeoffs, we demonstrated a social network analysis with participants. We used a survey to collect data on who in the room participants would most trust for advice when clothes shopping. We used the resulting network map to animate a discussion of how social network analysis might improve the efficiency and equity of communications regarding Sitka's landslide warning system.

Table A2. Measures of success for landslide warning system discussed in visioning workshop.

<table>
<tr><th colspan="2">Measures (M)</th></tr>
<tr><td>Overall</td><td>Monitoring and Communications</td></tr>
<tr><td>· Limit loss of life
· Low Stress</td><td>· Consistent with/doesn't conflict with other warning systems
· Provides situation awareness in a timely and trusted manner
· Gives measured levels of risk
· Few false alarms/avoid alarm fatigue
· Timely</td></tr>
<tr><td>Inclusion</td><td>Respond</td></tr>
<tr><td>· Clear lines of participation
· Opportunities for volunteering
· Accessible to entire population</td><td>· Orderly evacuation process
· Timely</td></tr>
<tr><td>Trust</td><td>Operations and cost</td></tr>
<tr><td rowspan="3">· Familiar
· Easily understood/explainable/simple
· Compassionate/kind to people at most risk
· Inspires public confidence
· Sets reasonable expectations, but not create fear
· Community buy-in
· Good science
· Trusted science, even when it changes
· Acknowledge its own limitations</td><td>· Not cost much/cost effective/affordable
· Maintainable
· Reliable/System redundancy
· Clear lines of responsibility
· Sustainability
· Capable of continual improvement</td></tr>
<tr><td>Protect property</td></tr>
<tr><td>· No excessive liability</td></tr>
</table>

On 4 October 2022, during the same visit as the final LWS co-design workshop, the project team also convened a landslide insurance workshop. This workshop aimed to

improve community understanding of landslide insurance issues and to gauge interest in various alternatives to the status quo. The eighteen workshop participants included insurance professionals, homeowners, real estate professionals, and banking professionals as well as State of Alaska officials responsible for natural hazards insurance. Prior to the workshop, the project team identified and estimated the potential economic implications of four alternative options for providing landslide insurance in Sitka.: (1) the State of Alaska requires private insurers to provide landslide insurance, (2) the State of Alaska or the Federal government share risk with private insurers by reimbursing private insurers if claims exceed a specified level, (3) the State or Federal governments directly offer landslide insurance, and (4) a landslide insurance pool in which homeowners from multiple SE Alaska communities join together to pool risks. At the workshop, the project team presented these options, described analogues elsewhere in the United States, and facilitated a discussion among participants of pros and cons. The team also facilitated a discussion which led to the decision to provide exposure maps on the dashboard, with sufficient resolution so that users could judge risk in their immediate neighborhood but without sufficient resolution to identify specific properties.

Table A3. Levers discussed in visioning workshop with which one or more actors in Sitka could engage to pursue goals for landslide warning system.

Policy Levers (L)	
Knowledge	Response
· Lots of education · Hazard maps · Media Management · What *citizen* science	· Evacuations plans/places to go · Training: community, first responders, mental health (even at command centers) · Table-top scenarios/drills · Post-event care/trauma · Are evacuations mandatory? · Ways to deal with volunteers, especially when they aren't helpful · Contingency plans for events outside expectations
Monitoring	Operations
· Where the thresholds are set	· Trust fund · Source and amount of funding · Clear lines of responsibility for action/communications · Who runs app/website · Who is in charge of training
Communication	Protect property
· Dissemination channels for warning - Use paper system - Flashing lights (to avoid areas) - Street signs/warning markers · Attributes of warning - Focused warning - Timed warnings - How far our warning occurs? 48 h? 6 h, etc. · App or website with real time data · Good ways to get accurate information out to people that don't impede incident command · Ways to recover from alarm fatigue	· Insurance pools · Physical mitigation/diversion of flows

Appendix B. Cost Estimates for Maintaining the Sitka System

What would it take to operate and maintain the Sitka landslide warning system as an ongoing operation? Based on our experience to date, our project team made the following estimates of the resources required.

- STAFF TIME: The operations and maintenance would require Sitka Sound Science Center staff person ~1/3 time to:

- Organize maintenance of local environmental monitoring instruments (about a month of time per year)
  - Harbor Mountain Weather System
  - 10 Tipping Buckets (community hosted)
  - 3 Soil Moisture Sensors (ONSET)
  - FAA/NWS Airport Weather Station—This facility is run by the Federal Aviation Administration (FAA) and National Weather Service (NWS), so SSSC isn't responsible for its maintenance, but close contact should be maintained with the Sitka Flight Service operators as it feeds the webpage
- Implement any upgrades to data feeds from NWS and other sensors and implement any upgrades to dashboard prediction algorithms as more data becomes available.
- Produce annual summaries of instrumental data and dashboard predictions
- Annual lesson in high school class—they host one of the tipping buckets
- Maintain community contacts
  - USFS, Fire Chief, STA Safety Officer, etc.
  - Prepare for and attend:
    - Local Emergency Planning Commission (monthly, summer off)
    - Sitka Tribe of Alaska—Natural Resource Committee (attend annually)
    - City and Borough of Sitka Assembly (attend annually with update)
    - Planning Commission, if commission becomes interested in applying landslide hazard to city planning, zoning etc.
    - Southeast Environmental Conference (annually)
- Respond to questions
- Be point of contact for geoscience-related issues in Sitka (e.g., work with Volcano Center)
- Create physical materials like rack cards, maps, posters
- Storm Reports—during and after extreme rainfall events, compile and send to community contact list
- Annually send updates to USFS with updates for the Landslide Inventory based on storm, community reports
- Upgrade and update site; sitkalandslide.org and SSSC Landslide Research page
- Oversee contracts associated with telecoms and dashboard

- Materials for maintaining the system would require:
  - Website: $20,000 per year for website mainatinance service contract
  - Tipping buckets: $100/year for batteries for tipping buckets
  - $3500 telecommunication contracts for tipping buckets
  - Moisture sensors:
    - $100/year data connection fee
    - $300/year repair and replacement ($3000 sensor amortized over 10 years)
  - $1000/year IT support
  - $350/year office consumables

  TOTAL COSTS

- Labor ~ $25,000/year
- Materials: $25,250
- Indirect: $13,100
- Total: $63,350

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