FINAL REPORT OF THE SITKA LANDSLIDE WARNING WORKSHOP

Prepared for the City and Borough of Sitka

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By the Sitka Geo Task Force Workshop Group

SSSC Technical Memo 2018-01

Facilitated by
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Contents

Executive Summary: Sitka Landslide Warning System

At the request of the City and Borough of Sitka (CBS), the Sitka Sound Science Center (SSSC) convened a group of landslide experts in Sitka, Alaska, on September 13-15, 2017, to discuss the technical and scientific details associated with the possible development of a Landslide Warning System (LWS) for the community of Sitka. Scientists from the U.S. Geological Survey (USGS), U.S. Forest Service (USFS), U.S. Forest Service Pacific Northwest Research Station (USFS PNWRS), National Weather Service (NWS), National Park Service (NPS), State of Alaska Division of Geological & Geophysical Surveys (DGGS), Sitka Tribe of Alaska (STA), Shannon & Wilson (S&W), Rand Corp (RAND), and the University of Delaware Disaster Research Center (UDel DRC) gathered to discuss the current state of the physical science, review other LWS in place in the United States, and discuss aspects of the social science of LWS. Based on direction from the CBS, the group focused on the physical science of a system with an emphasis on life safety issues.

Landslides in Sitka are typically debris flows—rapid, high-impact events that can inundate and bury housing and other infrastructure. In Sitka, debris flows occur infrequently, but have resulted in loss of life and property destruction. This makes landslide prediction challenging, as there are limited historical examples specific to our geographic area from which to draw data. However, it was generally agreed that with the results completed from in-progress research, supplemented by a few targeted analyses, the team could provide, within a year timeline, valuable information to the NWS and CBS to support their decision-making process about community alerts. **Additionally, the working group strongly agrees that a donated weather station from DGGS would provide critical high-elevation information on rainfall and other important weather data, and urges the CBS and its partners to move forward to leverage this opportunity**. It was suggested that the CBS might reach out to the U.S. Coast Guard (USCG) for help with installation logistics.

The working group developed a prioritized list of the data or products needed to inform the physical science of a LWS (Table 1). The table includes a proposed implementation timeline and estimated costs. The workshop participants have developed the detailed steps needed to implement each project and more detailed cost for this final report to CBS. In most cases, workshop participants do not have the authority to authorize expenditure of funds from their agencies for these purposes. However, some of this work is proceeding based on internal agency priorities and through currently funded research projects.

Terms to define:

Landslide Hazard – the chance or probability that a landslide will occur in a particular location, including the areas of landslide initiation, transport and deposition.

Landslide Risk – the chance that any landslide hazard will cause harm to life or property.

Landslide Warning System - a system that forecasts an increased likelihood of a landslide occurring. In general, landslides in the Sitka area typically occur too rapidly to allow triggered sensors to broadcast an effective warning. Thus, LWS as presented in this report emphasizes forecasting the initiation of debris flows, rather than detecting their transport after initiation.

Lidar – a surveying technique, also known as known as Light Detection and Ranging, that uses pulsed laser light to measure distances. In recent years, lidar has become widely used in making high-resolution digital elevation models.

IfSAR – interferometric synthetic aperture radar, a remote-sensing technique for making digital elevation models using radar images.

The following products are underway or have been completed:

- Map of Kramer Avenue hazard areas (S&W, completed)
- Rainfall data: intensity and duration return periods (NWS, existing but based on sea level gages and modeling)
- Landslide inventory (USFS, mostly complete)
- Hazard map (DGGS, in progress)

Products that could be completed in the near-term that support increased awareness of potential landslides:

Recommending agencies or entities are listed in parentheses.

- Rainfall intensity and duration curves indicating landslide likelihood (recommended, NWS)
- Netmap shallow landslide/debris flow map that models initiation areas (recommended, USFS)
- Homeowner's Guide to Landslides (recommended, DGGS)
- Contractor's Guide to Landslides

Once the landslide inventory is updated and overlaid with: (1) modelled locations of landslide initiation and runout areas and (2) weather events, it may be possible to establish a threshold defining increased likelihood of landslides for Sitka hazard areas. The NWS could then alert the CBS Emergency Response Team (Chief Miller) to the increased hazard, or the likely approach to the threshold. This could be similar to NWS storm forecasting: outlook, watch, advisory, and warning. The CBS is responsible for policy and management of a warning system and the impacts: shelters, evacuation plan, etc. The memory of recent events is helpful in facilitating public awareness to the potential risks of landslides to city infrastructures, including schools, and impacts to the entire community regardless of where individuals live.

Longer term efforts to increase accuracy of threshold model

The team identified several priorities for collecting data to support enhanced modeling efforts for predictions. This could tighten the threshold relationship, reducing uncertainty. Some of these actions require funding.

- Siting and permitting of four weather stations (in addition to the initial donated weather station from DGGS)
- Hydrological and landslide modeling
- Collect anecdotal information from locals about historical landslide initiation and runout areas
- Installing stream gages and develop rainfall runoff curves for Starrigavan and Cascade Creek (NWS has procured stream gages for these two sites) to runoff response to rainfall
- Developing other sources of information: landslide mapping assistance from routine flights by Alaska Department of Fish & Game, Harris Air, U.S. Coast Guard (USCG), and citizen science reporting of landslides
- Soil moisture and pore pressure monitoring

Recommendations to CBS on the Social Science Track

- Meet with Joe Trainor, UDel DRC, national expert on social science of LWS
  - Focus on communication: early, often, and capturing uncertainty. Annual revisiting of procedures and risks (culture of information). How to reach everybody using multiple communication channels.
- Meet with Dennis Staley, USGS, and Jayme Laber, NWS, to hear an example of an existing LWS
  - Examples of NOAA and USGS system in southern California and in Washington State
  - Promote "whole community" response by focusing on city infrastructures, and not just people living in landslide risk areas.
- Query the community on their desire for an LWS (Juneau Avalanche Advisory as a similar model).
- Work with local emergency planning system to develop response: evacuation plans, shelters, etc.
- Add section at Contractor's Meeting/Building Officials – Landslide info?

- CBS Public Works Department obtain better enumeration of infrastructure and drainage networks—how does human action increase instability? Maintenance?

Workshop participants (Table 2) developed Table 1 as a guide to data and products. Working Group members volunteered to lead the continued discussion of these tasks (initials listed in bold). Details of these tasks follow.

Table 1. Data and Products informative to a Landslide Warning System

Task	Order/ priority	Data or Product	Time	Agency **Working group lead (see Table 2)**	Cost	Comments
1	In process	Updated landslide inventory with overlay events	2017	USFS (**J.F.** and D.L.)	In house	
2	In process	DGGS Hazard mapping (new lidar from NPS)	2018	DGGS/**R.D.** (USFS)	Paid for	Get boring logs and landslide inventory
3	In progress	Identify three possible sites for weather Station at Gavin or Harbor Mountain	2017	USFS: **A.P.** DGGS: **G.W.**	In house	In progress
4	1	NetMap (with Miller model) landslide initiation and runout modelling	2018	USFS: (**D.L.**, J.F., or A.J.)	$10K (contractor)	Lidar acquisition is a prerequisite
5	1	Gather local people with knowledge of previous landslides (contractors, city crew, journalist)	2018	SSSC (**L. B.**) RAND, USFS (A.J.) S&W (B.L.)	?	Landslide deposition locations
6	1	Create rainfall intensity and duration curves for existing information	2018	NWS (A.J.) USGS (**R.B.**) USFS (K.K.P., AJ)	In house	Add smaller slides to inventory slides (USFS)
7	1	Install weather station at higher elevation (existing equipment available)	2018	DGGS: **G.W.** USFS: permitting CBS: maintenance	Upgraded: $5K Installation: $20K Maint: $4K/yr	Permitting needed ASAP
8	1	Establish rainfall runoff (stream gage) rating curves for Indian River	2019	NPS (**B.C.**) USGS, NWS (A.J.), STA (J.H.)	USGS contracted by NPS	USGS has a published rating curve for Indian River
9	2	Install stream gages and developing rating curve - Starrigavan and Cascade Cr.	2017 (S) 2018 (CC)	NWS (**A.J.**) STA (J.H.) USFS (**K.K.P.**)	NWS installation and maintenance ($ TBD) STA personnel to help develop rating curve by taking flow measurements	Need to look into permits from USFS and city to install gages on bridges, before installing
10	2	APP to involve citizen science for reporting landslides: promotion	2018	DGGS (**G.W.**) SSSC CBS RAND	$5K-$10K	Modified for fishermen/ hikers/hunters (Mountain Hub, LEO)
11	2	Blue Lake height and connecting NWS	2018	CBS (**D. Tadic**) NWS		IT folks
12	2	A Homeowner's Guide to landslide	2018	DGGS (**G.W./R.D.**) CBS (M.Bosak)		
13	3	Targeted repeat laser scans of potential debris-flow source areas	11/17 – 5/18	DGGS/**G.W.**	Ad hoc if funds available	Repeat at 2-year intervals
14	3	Coupled hydrological/landslide model running in real time	In progress 2023	NWS (A.J.) DGGS (**R.W.**)	In house	Research effort Hydrological model sooner

15	3	Three additional weather stations		DGGS, NWS **CBS**	$50K x 3 = $150K	Do permitting now
16	3	Real Time SNOTEL – ask NRCS (could be higher priority if available)	2018	NPS (**B.C.**) NWS (A.J.), USFS DGGS (G.W.)	$35K install – maintenance TBD	Indian River Head waters, Permitting USFS
17	3	Soil moisture sensors and monitoring (radio network) (Research)	2019	USGS (**R.B.**) DGGS USFS/PNWRS (A.J., J.F.)	$117 K equipment. Labor, maintenance and monitoring extra	Source location in initiation zone (water table) three hollows
18	3	Improve Radar use from Biorka Flash flood monitoring program	2019	NWS (A.J.)	In house	
19	3	Detailed soil maps	2022	USFS (**J.F.**) DGGS	No funds identified	Prioritize catchment areas

TABLE 2. LANDSLIDE WARNING SYSTEM WORKSHOP PARTICIPANTS

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Detail on Working Group Recommendations

In Progress

1. Updated USFS Landslide Inventory

The Tongass National Forest landslide inventory can be used to validate modeling efforts. Currently, the landslide inventory is missing some of the small landslides in and around Sitka. Jacquie Foss planned to complete the landslide inventory for the Sitka Area including best-available date verification by mid-November 2017. All available imagery would be used. The landslides would be dated using newspaper reports and local knowledge. These data would then be shared with the group.

2. DGGS Hazard Mapping (Lidar)

Over the last 2 years, DGGS has been working cooperatively with the NPS, USFS, Federal Emergency Management Agency (FEMA), the US Army Corps of Engineers (USACE) Cold Regions Research and Engineering Laboratory, and the CBS to develop more advanced and precise landslide hazard maps for populated areas along the road system in the CBS. This effort relies on a combination of precise elevation data, soil characterization, weather data (rainfall, wind, etc.), and geological data, as well as evaluative and predictive models developed in other areas (e.g. Washington State and Oregon). Hazard mapping is in an advanced state of development and will be shared when sufficient field data are collected—and model results verified—to maximize the reliability of the maps, given existing funding levels. This effort will be supplemented by fieldwork to be conducted in the spring and summer of 2018.

3. Identify Three Possible Sites for Weather Station at Gavan and/or Harbor Mountain

The working group recognized that there are significant differences between rainfall amounts at sea level and at high-elevation areas near Sitka, due largely to orographic effects (precipitation release on the windward side of mountains due to decreasing temperature with increasing elevation). Rainfall at higher elevation can be several times that observed at sea level. Without high-elevation weather stations, understanding the impact of rainfall on where and how landslides initiate will continue to be substantially constrained. A cluster of weather stations at high-elevation settings near Sitka would address this data gap, with three stations being the optimal balance of coverage and expense. At a minimum, a single weather station on a ridge over the Indian River flood gage (either Gavan Hill or Mount Verstovia) would enable rainfall response curves to be developed for the Indian River.

Priority 1 Tasks

4. NetMap Landslide Initiation and Runout Modelling.

TerrainWorks Inc., in collaboration with the Tongass National Forest, is proposing to apply an existing watershed analysis package (NetMap) to create a hazard potential map covering landslide initiation and debris flow inundation for the area surrounding the CBS. Mapping would extend to upslope areas of the adjacent Tongass National Forest. Landslide hazard mapping is needed for: (1) identifying high hazard areas (Fig. 1) for risk mitigation and (2) supporting land use zonation. High-resolution digital elevation data in the Sitka area (1-m lidar and incorporating 5-m IfSAR where needed) would be coupled to computer algorithms to provide the CBS with modern and defensible hazard mapping. Floodplain mapping would be included as one type of in-kind contribution. This project would support and extend the debris flow deposition zone modeling currently being conducted by the DGGS.

Sitka hazard mapping will require the following steps:

1. Update Tongass National Forest landslide and debris flow inventory near Sitka Borough (USFS in-kind contribution, see task 1). Data would be used to calibrate NetMap's landslide and debris flow model predictions to more accurately reflect hazard potential in and near Sitka.
2. Conduct field work to validate hillside physical conditions, compared with GIS predictions, covering initiation and runout of landslides and debris flows (USFS in-kind), to improve hazard map accuracy and defensibility.
3. Apply published landslide model (Miller and Burnett, 2007), calibrate (using #1) and predict potential landslide initiation sites and relative instability (see Figure 1a, 1b).
4. Develop a landslide debris transport (runout) model using numerical methods and based on landslide runout inventory (using #1).
5. Apply published channelized debris flow runout model (Miller and Burnett, 2008), calibrate (using #1) and predict potential hazard zones (see Figure 1a, 1b).
6. Create digital channel network and floodplain maps in the project area, including in Sitka (NetMap, in-kind).
7. Develop technical report covering the Sitka hazard mapping.

Deliverables would include (see Figure 1a, 1b, for example, and Figure 2 for the study area):

- Hazard maps showing initiation and debris runout areas of: (i) shallow landslides and (ii) channelized debris flows in terms of relative potential, as GIS shapefiles.
- Hazard maps in an online map viewer requiring no GIS hardware or software expertise.
- Written report detailing the science and technology underpinning Sitka hazard mapping. An educational webinar would be provided.

Estimate cost: $10,000 (Tasks 1-7).

In-kind contributions: USFS-Tongass National Forest, landslide inventory (value: $2,000); USFS, PNW - field validation (value: $3,000); TerrainWorks – channel network- floodplain mapping (value: $3,000); TerrainWorks-Online mapping tool, data load and access (value: $2,000). Total in-kind: $10,000.

Contact: Dr. Lee Benda (leebenda@terrainworks.com), 530-926-1066.

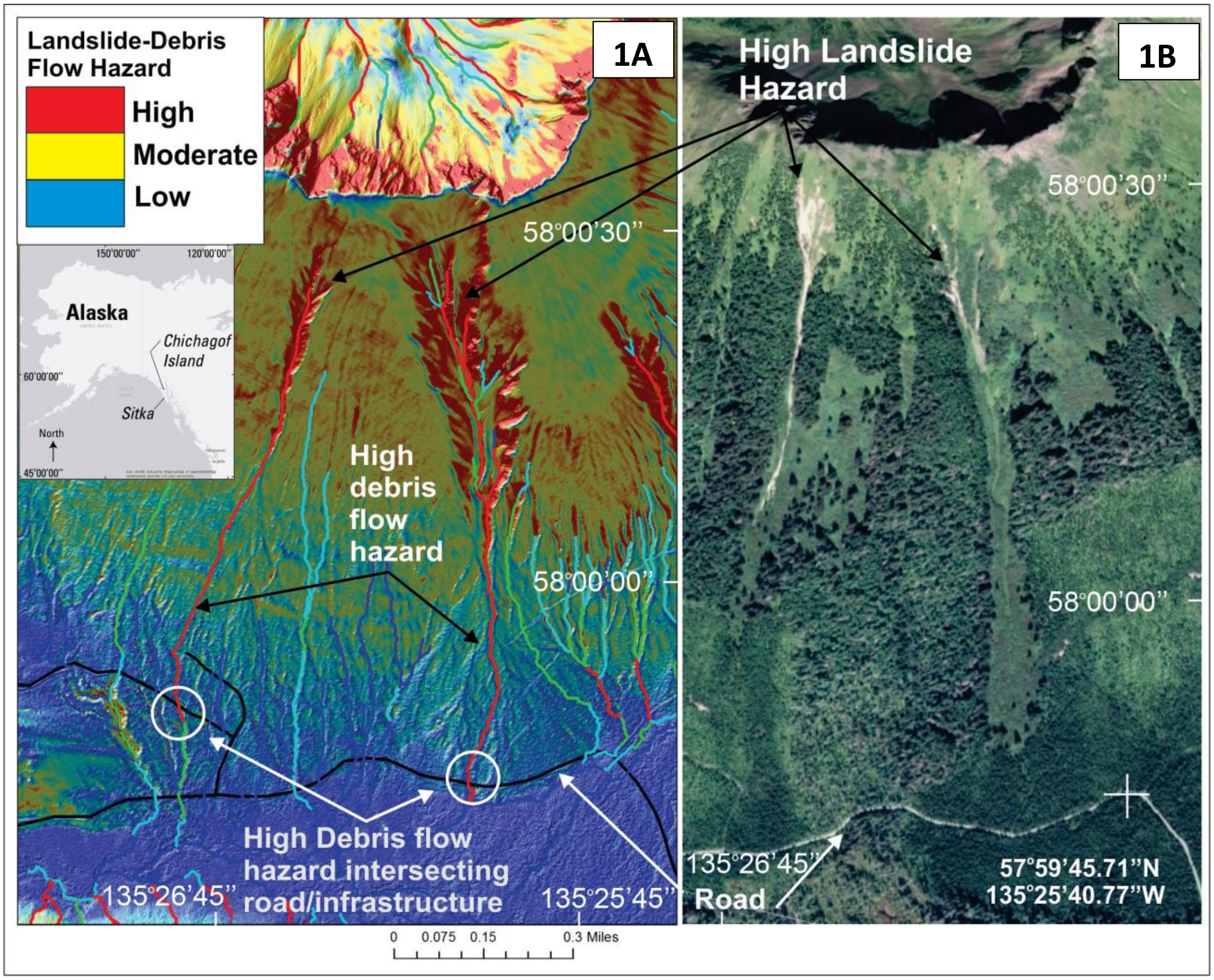

FIGURE 1. EXAMPLE OF HIGH-RESOLUTION LANDSLIDE AND DEBRIS-FLOW HAZARD MAPPING USING LIDAR FROM NORTH CHICHAGOF ISLAND, SOUTHEAST ALASKA (2016). THE SAME TECHNOLOGY WOULD BE APPLIED IN THE SITKA BOROUGH. A ILLUSTRATES PREDICTION OF LANDSLIDE (EXPECTED DENSITY OF LANDSLIDE INITIATION SITES) AND DEBRIS FLOW HAZARD (PROBABILITY OF DEBRIS FLOW RUNOUT) AND B IS A CORRESPONDING GOOGLE EARTH IMAGE OF RECENT LANDSLIDE AND DEBRIS FLOW AND SNOW AVALANCHE TRACKS. A ALSO SHOWS HIGH DEBRIS FLOW HAZARDS INTERSECTING ROAD/INFRASTRUCTURE. LANDSLIDE HAZARD (LOW-HIGH) COVER ALL HILLSIDE AREAS; DEBRIS FLOW HAZARDS FOLLOW HEADWATER STREAMS (AS COLORED LINES).

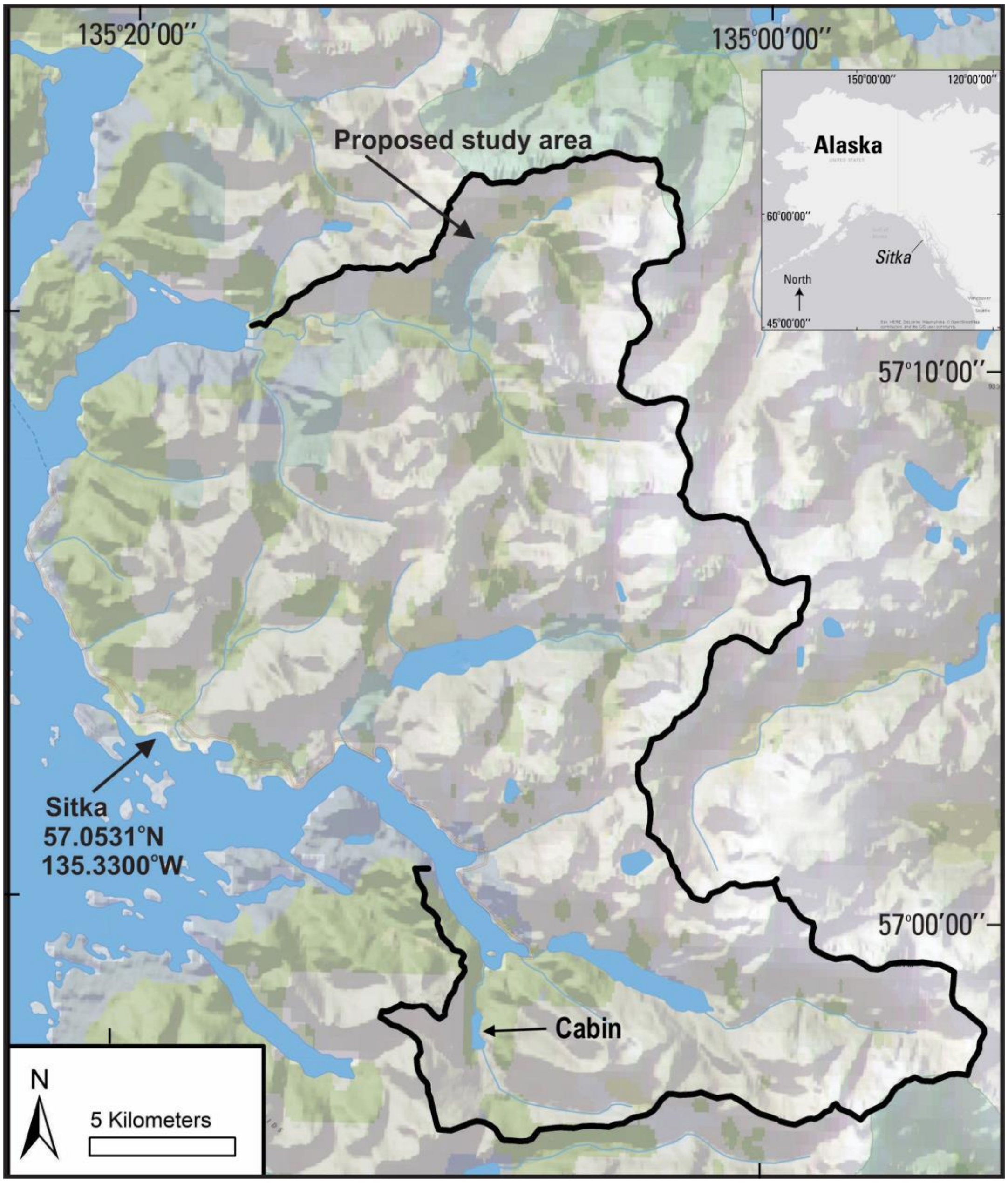

FIGURE 2. STUDY AREA. NOTE STUDY AREA EXTENDS NORTH OF SITKA, INCLUDING THE PROPOSED ROAD EXTENSION, AND EXTENDS SOUTH, TO INCLUDE AREA WITH A FOREST SERVICE CABIN

5. Gather Local Knowledge

Local knowledge is critical for developing effective and sustainable landslide prediction, warning, and mitigation systems (Alcántara-Ayala, 2004; Anderson et al., 2011). This is especially true in rural and remote areas, as opportunities for observing landslides and precursor conditions are limited by minimal existing infrastructure and small or distributed populations. Local citizens can provide critical information regarding past landslide events; for example, contractors or city construction crews have examined soil cross-sections containing landslide debris while building and excavating, and those fishing, hunting, and hiking in remote areas have seen landslides that may not be currently documented. In addition, Sitka citizens also have their own strategies for determining landslide risk based on geophysical and meteorological factors and responding to perceived risk. Citizens communicate with their neighbors and community about such risks and about their own observations and observations they have heard from others. Gathering this local knowledge may help illustrate a richer picture of the existing and predicted hazards in the region.

The group recommends gathering knowledge and insights from private contractors, city work crews, aviators, fishermen/women, outdoorsmen/women, and other Sitka citizens, focused on the following topics: (1) observations of landslides or landslide debris in the Sitka area; (2) personal and professional perspectives on determining and responding to landslide risk (including communication with others in the community); and (3) perspectives on the optimal design characteristics for a LWS that is sustainable and meets the needs of the community over the long term.

6. Rainfall Intensity-Duration and Hydrological Thresholds for Landslide Occurrence

Rainfall intensity-duration thresholds are an important tool for forecasting landslides and debris flows (NOAA-USGS Debris Flow Task Force, 2005; Guzzetti et al., 2008). The idea behind these thresholds is based on observations that it must rain hard enough (intensity) and long enough (duration) to cause landslides. A threshold is usually defined as a curve separating combinations of rainfall intensity and duration for which landslides are either likely or unlikely in a specific geographic area. For example, Figure 3 shows landslide threshold curves for a number of areas including Seattle, Washington (Baum and Godt, 2010).

To define a threshold, scientists use historical data on the exact times when landslides occurred and the amount of rainfall (as measured at rain gages) leading up to the landslides. By plotting the rainfall intensities and durations for historical landslides from at least three different storms, as well as intensities and durations that did not produce landslides, a threshold can be defined representing the minimum rainfall intensities that have produced landslides at different durations (Wieczorek et al., 2000; Godt et al., 2006). Intensity-duration thresholds have various sources of uncertainty; additional data gathered as more landslides occur can help constrain the uncertainty. Techniques have been developed recently to define thresholds objectively, thus providing repeatable and scientifically sound approaches for defining thresholds (Jakob et al., 2012; Staley et al., 2013).

Developing a rainfall intensity-duration threshold for the Sitka area will require collaboration between the NWS, the USFS, and USGS. Time-series precipitation data and rainfall intensity-duration return periods for gages operated by the NWS and its partners are the first ingredient for developing the threshold. These data are currently available for a few gages near sea level in and near Sitka. The USFS has a landslide inventory for the Sitka area that is mostly complete. When the inventory is completed, it should be checked to ensure accuracy of landslide locations and dates (see "Updated USFS Landslide Inventory"). After the landslide inventory is ready to use, USGS and NWS scientists could analyze the inventory and rainfall data to define a preliminary threshold that can be used by the NWS in its Flash Flood Monitoring and Prediction (FFMP) system to forecast landslide occurrence (NOAA-USGS Debris Flow Task Force, 2005). Depending on how many historical landslide-producing storms can be identified, testing and validation of the threshold might need to await future landslides. To the degree possible with available data, objective techniques would be applied to optimize the thresholds to balance the avoidance of false alarms against avoidance of missed alarms.

Observations by USFS employees indicate that the stream gage at Indian River might be an additional indicator of watershed conditions that can result in debris flows. Hydrological (streamflow) thresholds are complementary to precipitation thresholds in landslide warning, but cannot be substituted for them (Reichenbach et al., 1998). These readings are available at 15-minute intervals and provide an indication of response of the watershed to current and recent precipitation. In addition to the precipitation intensity-duration threshold, investigating the use of stage (water height) or discharge readings as a second indicator of landslide potential is a possibility. We are aware of one study where this has been done but it led to only minor improvements (Ciavoletta et al., 2016). This analysis would consist of comparing times of historical landslides near Sitka to the discharge and rate of change of discharge at the Indian River gage for the period of record, October 1998 through September 2017. A USGS Open-File Report would describe the methods and results of the rainfall- and stream-flow-threshold analyses.

Continued collection of rainfall, stream-flow, and landslide occurrence data will allow for future improvement of the preliminary thresholds to be developed from currently available data. Proposed addition of high altitude precipitation gages (see "7. High-Elevation Weather Stations") along with addition of stream gages at both Starrigavin and Cascade Creeks (see "9. Install stream gages and develop rating curve for Starrigavan and Cascade Creek Watersheds (USFS)") would eventually (after several years) provide additional rainfall-runoff-landslide relationships in different sized/shaped watersheds—thus strengthening the relationships and understanding between rainfall, streamflow, and landslide initiation. Storm characteristics that can be combined with precipitation thresholds might also help improve accuracy of landslide forecasts (Jakob et al., 2006).

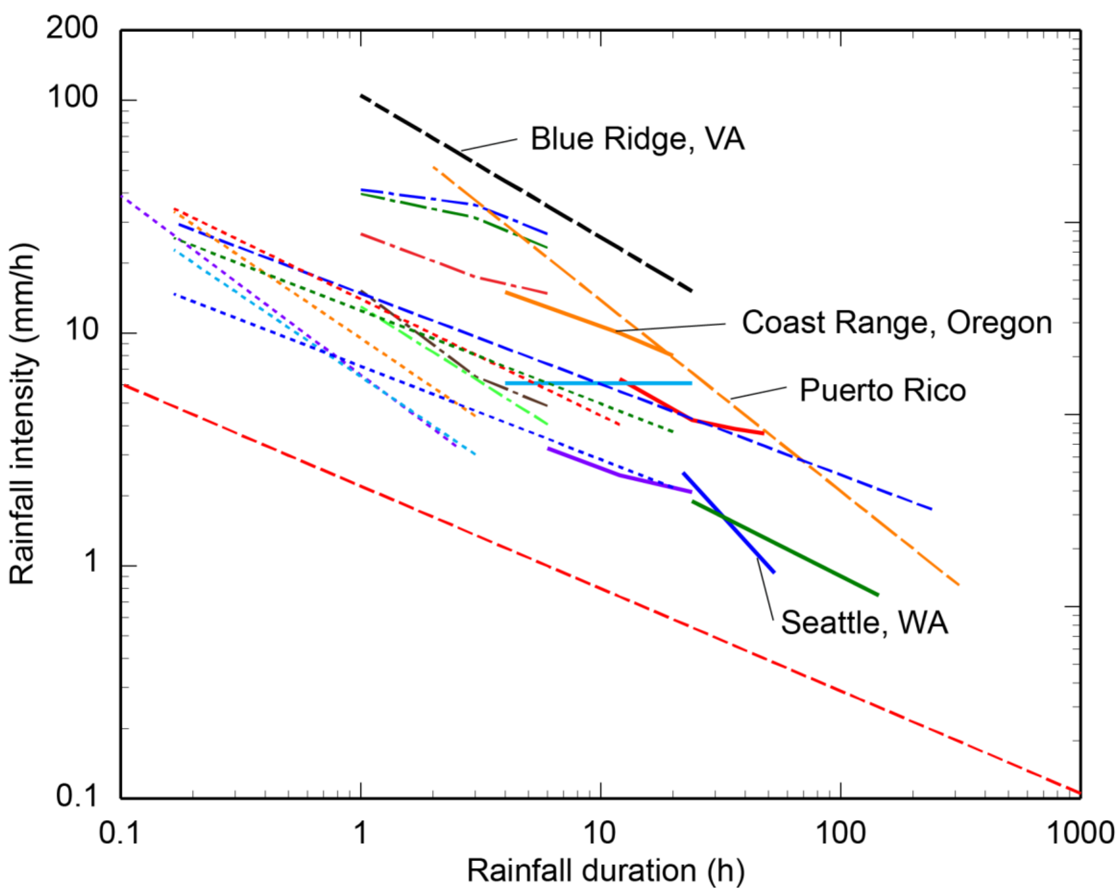

FIGURE 3. RAINFALL INTENSITY AND DURATION THRESHOLDS FROM VARIOUS LOCATIONS, WITH SPECIFIC AREAS IN THE U.S. LABELED, MODIFIED FROM BAUM AND GODT (2010). THE VARIABILITY IN THE THRESHOLDS RESULTS FROM DIFFERENCES IN CLIMATE, VEGETATION, TOPOGRAPHY AND GEOLOGY.

7. High-Elevation Weather Stations

Scientists rely on weather information from weather stations to improve understanding of weather, climate and earth surface processes, and to develop predictive models of geologic hazards (Fig. 4). Weather data in Alaska are often acquired near communities, most of which are located at low elevations and do not represent high-mountain conditions. There is pressing need for improved understanding of the atmospheric processes occurring at high-elevation settings in the mountains surrounding Sitka.

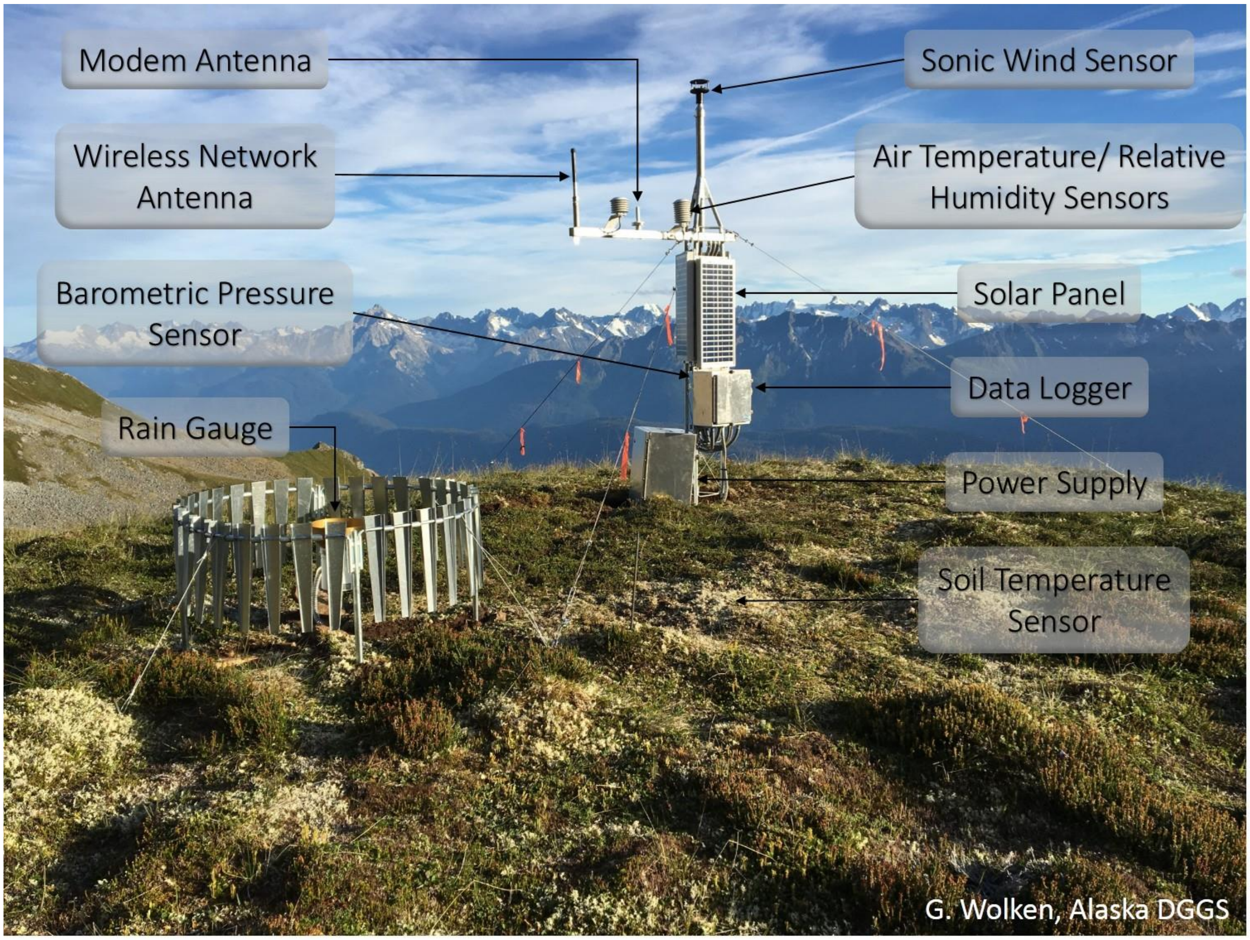

FIGURE 4. ***EXAMPLE OF PROPOSED HIGH-ELEVATION WEATHER STATION***

Data from Sitka high-elevation weather stations would be used to inform a number of research and public service efforts connected to the Sitka LWS. Strategically placed stations would allow scientists to monitor precipitation events, understand the magnitude of increase in precipitation with increasing altitude, and how it varies spatially, in order to assess potential thresholds related to debris flow initiation and downstream flooding hazards (Fig. 5). The weather stations would also provide critical calibration and validation data for NWS precipitation products (e.g. radar-derived precipitation amount estimations), and would help to improve weather forecasts and aviation safety by providing real-time information from data-sparse regions directly to forecasters.

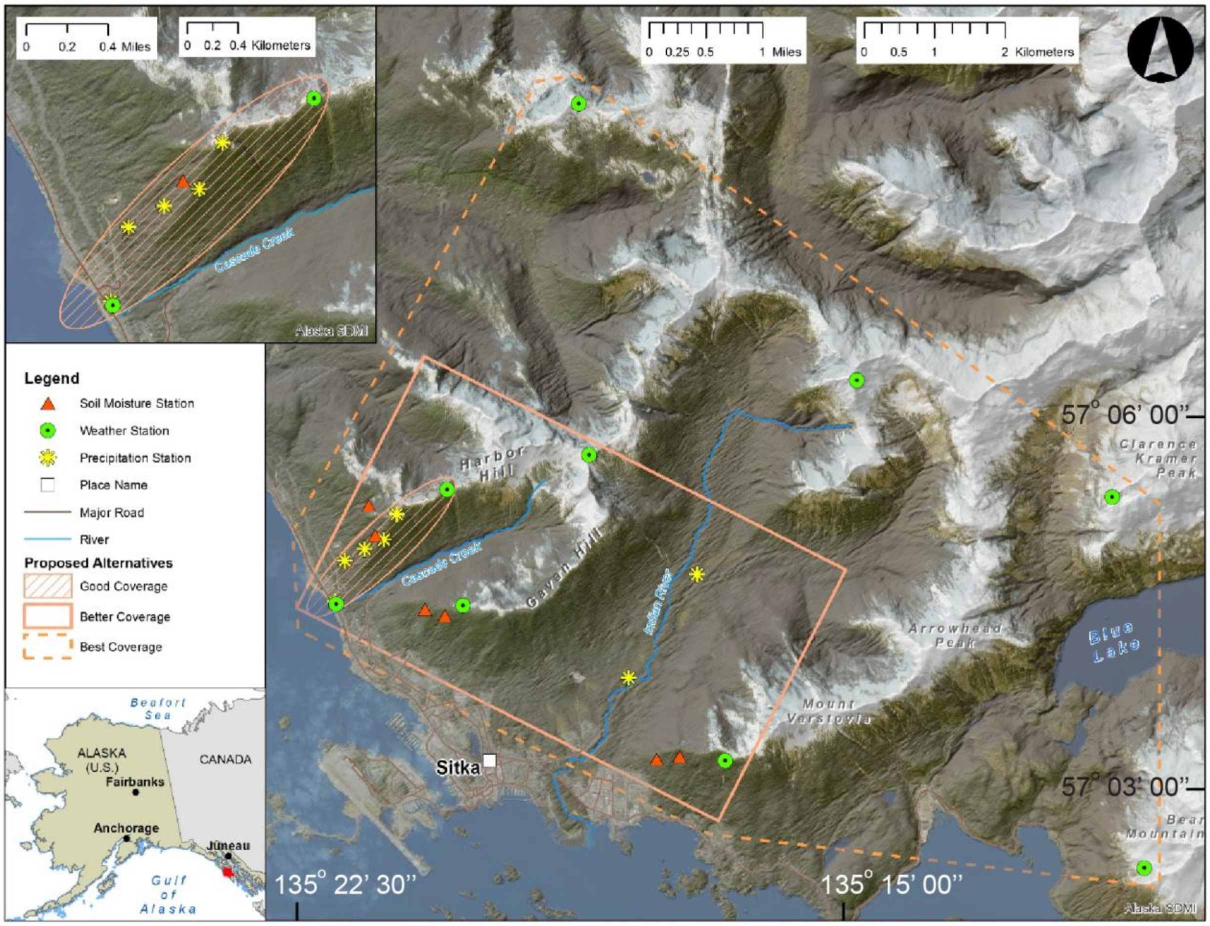

FIGURE 5. . MAP OF PROPOSED INSTRUMENTATION FOR IMPROVED UNDERSTANDING OF HYDROMETEOROLOGICAL VARIABLES ASSOCIATED WITH SITKA LWS. THE MAP INCLUDES SYMBOLOGY FOR FULL WEATHER STATIONS (FIG. 4), PRECIPITATION STATIONS, AND SOIL MOISTURE STATIONS. PROPOSED OBSERVATION ALTERNATIVES ARE RANKED FROM GOOD COVERAGE TO BEST COVERAGE, WHICH CORRESPONDS TO BASIC TO IDEAL SCIENTIFIC DATA AVAILABILITY.

Three nested arrays of possible instrumentation coverage would improve understanding of hydro-meteorological variables relevant to the Sitka landslide warning system (Fig. 5). In Figure 5, Good Coverage corresponds to the most basic station array located on Harbor Mountain, which would comprise a main high-elevation weather station, temporary multi-elevation precipitation stations, soil moisture station, and a telemetry receiving station with basic meteorological sensors. The DGGS has offered to provide the high-elevation weather and telemetry receiving stations designated for this coverage area, and it is currently available for use. Better Coverage provides a station distribution that is aimed at providing improved understanding of the spatial distribution of meteorological variables along the mountain front north-northeast of the populated areas of Sitka. This coverage array includes the Good Coverage area in addition to weather and soil moisture station installations (see “17. Soil Moisture and Pore Pressure Monitoring”) on Gavan Hill, Mount Verstovia, and in the lower Indian River watershed. The Best Coverage option adds expansion of the weather station network included in Good and Better coverage options, and is designed to provide enhanced understanding of the weather system dynamics responsible for intense precipitation events and improve area forecasting. These locations can be used for any of the proposed stations (tasks 3, 7, 15, and 16, Table 1), e.g., the SNOTEL station could be placed in the headwaters of the Indian River.

8. Indian River Discharge Rating Curve

The CBS, the NPS, and the USGS have maintained a stream gage on Indian River since 2007. The gage has provided stage data during that time. The USGS completed and circulated a rating curve for Indian River in early October 2017. The CBS, NPS, and USGS plan to continue to work together to maintain and update this rating curve so that freshwater discharge from Indian River can be continuously calculated from stage data in combination with discharge data from SSSC infrastructure. Discharge amounts are critical for calculating basin-wide rainfall response curves going forward, as well as for estimating historical, basin-wide rainfall amounts leading to documented landslides.

Priority 2 Tasks

9. Install Stream Gages and Develop Rating Curve for Starrigavan and Cascade Creek Watersheds (USFS)

Discharge rates, which may be useful as an indicator for landslide potential, are variable and dependent upon rainfall, watershed shape, vegetation, soils, and other watershed characteristics as well as stream gage location. Indian River, adjacent to the City of Sitka, is currently monitored for discharge using stream gage (height) and a discharge rating curve has been established (task 8). The installation of additional stream gage equipment at Starrigavan and Cascade Creek watersheds would provide a range of discharge rates in the Sitka area and might improve the accuracy of landslide prediction over a period of years. Specifically, after the gages are installed and operating, new observations of landslide occurrence can be analyzed for correlation with stage or discharge measurements to improve future landslide predictions (Ciavoletta et al., 2016).

Starrigavan Creek and Cascade Creek are located in the northern and central areas of the Sitka road system. These watersheds are smaller in size and different in character than the Indian River Watershed. Varying soil depths, narrower valley bottoms and varying amounts of volcanic ash may result in different rates of runoff between Starrigavan, Cascade, and Indian River Watersheds.

The NWS has procured two stream gages for installation at Starrigavan and Cascade Creeks. Partnerships between the NWS, the STA, the USFS, or other local entities could be used to field validate the gage data, take flow measurements and collaborate with the NWS to develop stream-discharge relationship curves.

The timeframe for stream gage installation and stream discharge analysis is estimated to total about 15 days during the first year. It is estimated that about 3 days' time is required for the NWS to install the stream gages in collaboration with a local representative. Annual stream flow measurements would then occur by the local collaborator with an estimated 5-10 days needed for both sites to have sufficient flow data to develop a rating curve. Once a rating curve has been developed, about three to four visits per site would be needed per year to keep the rating curve relevant from stream bed changes. The NWS would use the flow measurements to derive the rating curve; this is estimated to take about 5 days. These additional Sitka area rating curves would provide a range of stream discharge rates across Sitka, and is expected to decrease threshold uncertainty values, and improve landslide prediction for the Sitka area.

10. Software Application to Facilitate Collection of Community Landslide Observations

An important aspect of a LWS is the development of thresholds that can be used to identify the conditions under which landslides could occur. In order to improve our understanding of these threshold conditions, it is helpful to develop a landslide incidence database by identifying where and when landslides occur, so they can be linked to specific hydro-meteorological conditions. One way to record landslide incidence in the Sitka area is through community engagement and crowdsourcing data collection. In this scenario, members of the community (citizen scientists) would use an existing multi-platform mobile (iPhone and Android) and web-based (internet browser) crowdsourcing application (app) that would allow citizen scientists to record, submit, and instantly share geo-located landslide observations with project scientists, CBS officials, and the public. As an example, DGGS is involved in a similar citizen science project (communitysnowobs.org) where community observers use an established crowdsourcing app as an efficient method for delivering real-time snow science data for automatic ingestion into project databases. Mountain Hub (mountainhub.com) and Local Environmental Observer (LEO) Network (leonetwork.org) are crowdsourcing apps that could be used or adapted for Sitka-area community landslide observations.

11. Blue Lake Information Provided to National Weather Service

Information about the rate of rainfall runoff from hillsides into area streams is important for a LWS. These added data can give a hydrologist some qualitative information on soil saturation. There is an opportunity to obtain this type of information from the Blue Lake Dam project, east of Sitka (Fig. 5), if the dam operators are collecting pool height elevation. Another source of information that could increase the understanding of the amount of runoff is the amount of precipitation at the dam itself. A precipitation gage on the dam would provide an additional measurement of precipitation at intermediate elevation within the "Best" coverage area shown on Fig. 5. The potential of having power at the top of the dam would give a great opportunity for a working year-round precipitation gage if one is installed there. The line power would allow a heater unit to be installed on the precipitation gage and melt any snow in the winter time. Having real-time precipitation and lake level data may show a correlation between rainfall and the rate of rise on the lake that can be used to infer relative soil saturation. This information may be input into the warning system to reduce uncertainty of thresholds.

The NWS has the capability to receive and analyze pool elevation data along with rainfall information, similar to receiving meteorological and hydrological data from other dam operators across the region. Once the pool height elevation is received by the NWS, it can be plotted on the NWS Advanced Hydrologic Prediction Service (AHPS) for constant monitoring. The pool height along with the precipitation data would be analyzed by meteorologists and hydrologists to give a better situational awareness of the event. Also, these data would assist research identifying thresholds that might trigger debris flows.

Having the CBS and Federal Energy Regulatory Commission (FERC) share as much data as possible with the NWS would assist in this work.

12. Homeowner's Guide to Landslides

An information circular or pamphlet for homeowners and businesses would provide useful information about landslides. The Homeowner's Guide to Landslides would provide general information about landslides and suggestions about how to recognize landslide activity on or near their property, reduce property damage, and respond in the event of a landslide. An example of such a guide for residents of Washington and Oregon is available online at http://file.dnr.wa.gov/publications/ger_homeowners_guide_landslides.pdf.

Priority 3 Tasks

13. Targeted Repeat Laser Scans

Some landslides show ground surface indications of slope instability prior to their release. Targeted, repeat laser scanning (lidar) of suspicious landslide source areas would provide precise topographic data for quantitative assessment of changes in topography associated with slope movement. DGGS has the expertise and capacity to conduct repeat ground-based or airborne laser scanning of landslide source areas. Initial scans planned for November 2017 and May 2018 will create a baseline and identify potential and incipient landslide areas for further observation on two-year intervals thereafter.

14. Coupled Hydrological/Landslide Model Running in Real Time

Although linking geology, soils, vegetation, hydrology (rainfall, rainfall response, stage/discharge), and landslides presents significant challenges, the workgroup recognizes that having a model that can take these input variables and model the probability of landslides in "real time" would be an improvement over the predictive power of each variable individually, or in smaller groupings. Therefore, the workgroup recommends that the long-term goal of any scientific work be to advance towards having a coupled, multivariate model running in real time to both improve landslide prediction, and to serve as a back-reference when any future landslide may occur. Despite considerable research on such models in recent decades, scientific, computational, and numerical challenges remain as obstacles to using such models in real-time, operational forecasting of landslide activity. We are not aware of any coupled hydrological and landslide prediction models currently being run in operational mode (Schmidt et al., 2008; Canli et al., 2017).

15. Three Additional Weather Stations

Additional weather stations at elevation will increase the robustness and precision of landslide prediction. If additional resources are available, a total of six (6) weather stations at elevation along the CBS road system would provide enough weather data for landslide models to cover all CBS infrastructure and occupied properties on the road system. Possible locations are indicated within the "Better" and "Best" coverage areas delineated in Fig. 5.

16. Snow monitoring station

A Natural Resources Conservation Service (NRCS) Snow telemetry (SNOTEL) site in the Sitka area would be very beneficial to be incorporated into a LWS within the Indian River basin. This type of site would give a better understanding of upper basin (high elevation) precipitation, temperatures, and wind, and in the winter time, how much snow is on the ground and snow water equivalent (SWE) contained in the snow pack. There is a USGS stream gage along the Indian River and to tie the upper headwaters precipitation along with snowmelt would help in identifying threats of landslides in the surrounding area and potential flooding along the Indian River. Installation and operation of a SNOTEL station at one of the suggested weather station points around the rim of the Indian River basin (Fig. 5) would supplement the Priority 1 high-elevation station(s) (see "7. High Elevation Weather Stations"). Below are the steps that will be needed to install a NRCS SNOTEL site in the Indian River Basin.

1. Sponsorship costs and agreements
2. Locating the site
3. Permitting the site

1. For sponsorship of a site, the cost is generally $24-30K for installation depending on requested sensors, and annual operation and maintenance (O&M) of the site is $3100 per year. On top of this, NRCS generally asks the sponsors to provide local access to the site (helicopters charters, if needed). NRCS generally requests a five-year commitment. The paperwork is generally broken into two agreements: an installation agreement and then a 1-year annual maintenance agreement with four optional year extensions. This price includes: an all-season storage precipitation gage, snow pillow for snow water content measurements, snow depth, air temperature, and the necessary infrastructure to store and transmit the data hourly. Additional sensors which can be added are a tipping-bucket precipitation gage (liquid precipitation only), relative humidity, solar radiation, wind speed and direction, soil moisture and temperature, and barometric pressure. Annual O&M expenses include data transmission, hosting the data and posting on our webpages, quality control of the daily data, routine upkeep and replacement of the sensors, and verifying the sensor readings.
2. Site location is based on several factors including: representation of desired snow regime (elevation, aspect, vegetation, windage, etc.), safety and viability (not in an avalanche path or where the snow will experience creep), and access. Generally, the best sites have a minimal slope and a canopy opening of 90-120°. It's usually a considerable benefit to be able to see the site in both the snow-on and snow-off seasons before making final location decisions. Concerning access, it looks like a helicopter would be needed for installation. If there is a local useable trail, storing 4 years of fluids at the site and hiking in for routine maintenance might keep the overall cost down.
3. Generally, NRCS handles all the permitting and fees, unless a site is requested by the agency which manages the land, in which case NRCS lets them handle it internally. Depending on which agency manages the area of interest, permitting usually takes 3-6 months.

17. Soil Moisture and Pore Pressure Monitoring

Recent and ongoing research indicates that additional information about hillslope and watershed conditions before and during a storm can give further insight to support landslide forecasts (Godt et al., 2009, 2012; Mirus et al., 2017a, 2017b). For example, subsurface moisture levels and water pressures are more accurate indicators of landslide susceptibility than antecedent precipitation (precipitation accumulating in the weeks or months preceding a landslide) or stream discharge. Warning thresholds based on precipitation alone are known to misclassify some landslide-producing storms due to low antecedent precipitation, sometimes in combination with snowmelt or low rainfall intensity (Chleborad et al., 2008; Jakob et al., 2012; Scheevel et al., 2017). Whereas rainfall thresholds can only be established with analysis of historical landslide events, the subsurface monitoring can provide useful information on susceptibility and hillslope wetness, as well as relations between rainfall events and hillslope responses.

To address some of the expected uncertainties in the rainfall intensity-duration threshold to be developed for Sitka, potential landslide source areas can be equipped with subsurface monitoring equipment to track soil moisture at different depths and locations and to observe water pressures or perched water tables in the small hollows where debris flows initiate. The USGS Landslide Hazards Program has experience in this kind of monitoring at other locations (Godt et al., 2009; Collins et al., 2012; Smith et al., 2014; Smith et al., 2017a, 2017b) and with additional funding could deploy instrument arrays in three potential source areas. The state-of-the-art system would be designed for reduced maintenance to provide data needed to characterize landslide susceptibility and would provide opportunities to advance the science of forecasting of rainfall-induced landslides and debris flows in southeastern Alaska. In addition, the system would have built-in redundancy to minimize outages. The work would involve collaboration with the USFS and others to identify and permit candidate sites and to complete the installation. Pending field reconnaissance, a possible site might be potential debris flow source areas on Gavan Hill upslope from Keet Gooshi Heen Elementary School. Other possible sites are on the west flank of Harbor Mountain, which has the advantage of access from road NF-7576. These and other possible sites are indicated in Figure 5.

Establishing subsurface monitoring will require several steps:

- Imagery analysis and field reconnaissance to select representative sites for monitoring,
- Permitting,
- Equipment acquisition, configuration, and staging,
- Site investigation to establish the exact locations and depths for sensors,
- Installation of sensors and data collection equipment, and
- Operation and ongoing maintenance of equipment.

The steps leading up to installation will require many months. To allow adequate time for permit review and weather constraints, the sites should be selected the summer or early fall before anticipated installation. Installation would occur in spring or summer after the sites are clear of snow. After the sensors and other equipment have been installed and are operating, two or more years of observations will be required to establish an adequate record for interpreting hydrologic response of the potential source areas.

Site investigation would focus on characterizing the materials in the potential source areas that can influence the movement of water and formation of landslides. Soil pits would be dug to observe and sample deposits at locations of soil sensors. A combination of mechanical soil depth probing and geophysical exploration could be used to extend results beyond the test pits. Representative specimens of the various soil layers would be collected for laboratory testing to characterize soil strength and soil-water retention characteristics.

Each potential debris-flow source area (hollow) would have about five nests of two water-content sensors and one piezometer. Three nests would be along the axis of the hollow, and two off to the side. Tensiometers would be collocated with water content sensors at selected locations during the first summer and early fall to collect additional data about soil-water retention characteristics. To simplify annual maintenance and to avoid damage by winter frost, tensiometers would be withdrawn before the onset of freezing temperatures and would not be a permanent part of the installation. Use of tensiometers, given their high level of accuracy in the 0-10 kPa suction range, would aid future interpretation of water content in terms of landslide potential. Piezometers placed near the top of bedrock would indicate the rise and fall of shallow perched groundwater that could destabilize surficial deposits and induce landslides.

Sensors would be selected and positioned to show the lateral extent of saturated soil and any perched water table(s) that might form in the potential source areas. Recognition that the potential debris-flow source areas are in small hollows or depressions with variable soil depth calls for establishing arrays of sensors in a minimum of three hollows to effectively sample soil moisture, pore pressure, and (or) water level at points along the axis and side slopes of each depression to show the vertical and lateral extent of saturated soil in the depression as it varies through time in response to snowmelt and rainfall. In addition, air and soil temperature sensors would be deployed to aid recognition of freezing conditions that might lead to confusion in interpreting moisture readings. Depending on results of reconnaissance and site investigation, other kinds of sensors could be added to detect deformation or movement at preexisting cracks or below bedrock outcrops. All sensors would be connected to a central data collection and control unit (data logger) equipped for remote communication using IP modem or other technology appropriate for the location. To reduce the need for long cable runs, each sensor nest would use wireless technology to communicate with its corresponding main data logger. Locations of these sites would be coordinated with sites of mid-slope precipitation stations (Fig. 5).

Estimated costs for equipment are $39K per site, totaling $117K for the three sites. Substantial additional costs would be incurred to prepare and install the equipment including labor, materials, shipping, travel costs, and administrative overhead. Annual maintenance costs include costs for data transmission and processing, web hosting, battery replacement, occasional replacement of sensors, labor, travel costs to visit the site annually, and administrative overhead. Maintenance costs might be reduced by identifying a local partner that can participate in the site maintenance.

18. Improve Radar Use from Biorka (Flash Flood Monitoring Program)

The NWS utilizes the WSR-88D weather radar on Biorka Island in operations. The radar can provide valuable information on rainfall amounts (QPE: quantitative precipitation estimates) along with rain rates for the Sitka area. The radar coverage area map (Fig. 6) shows data for a large area that also includes high elevation areas around Sitka. This spatial distribution of QPE puts Sitka in a great place to take advantage of rain amounts from a widespread area.

The NWS is investigating how to improve the performance of the radar's QPE algorithms. There are a few ways that the QPE performance of the radar can be improved; one is to correlate rainfall amounts from rain gages to QPE amounts from the radar to obtain a bias. More precipitation gages within the radar coverage leads to a better value for a bias. Another way to improve the QPE output is to study the algorithms the radar uses in generating QPE and refine them to Southeast Alaska specific conditions.

The NWS's Flash Flood Monitoring & Prediction (FFMP) system is a computer program that provides continuous monitoring of rainfall rates and QPE. The QPE values and rainfall rates are then compared against flash flood guidance (FFG) for high-resolution stream basins. QPE amounts from the radar are vital for FFMP to work well.

This program provides NWS forecasters good situational awareness and can alert staff when precipitation amounts/intensity are favorable for flood/debris flow situation to develop on a given stream or catchment. This information ensures staff is aware of hydrologic threats during a rapidly evolving meteorological situation. The FFMP program in tandem with other data sets described in this report could give NWS forecasters better in situ data resulting in improved decision-support service to Sitka emergency managers when there are increased risks for flash floods along with debris flows.

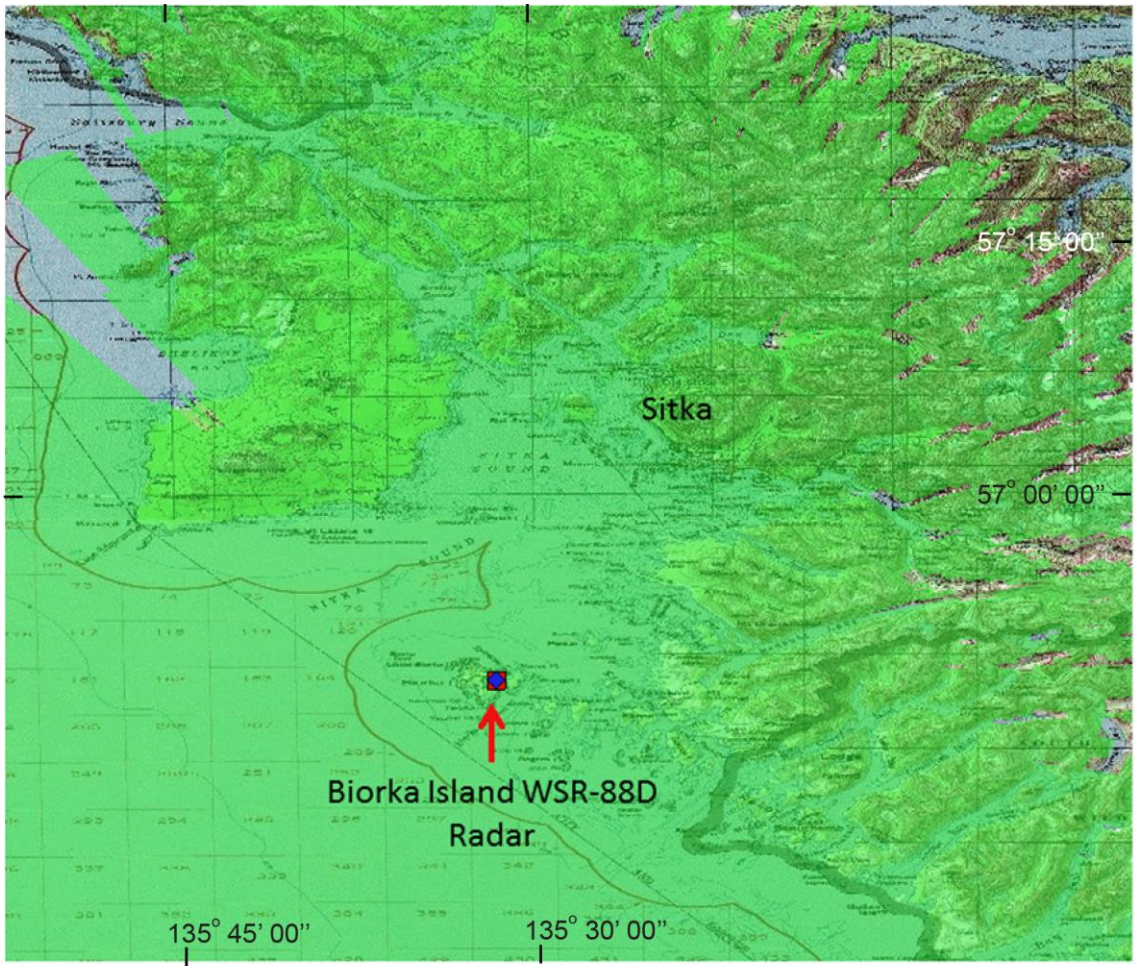

FIGURE 6. BIORKA RADAR STATION COVERAGE AREA, GREEN OVERLAY INDICATES AREAS VISIBLE TO RADAR.

19. Detailed Soil Maps:

There is a significant amount of lab and engineering data from around Sitka. Much of these data can be useful in understanding the depositional history of the area of interest around the community of Sitka. Jacquie Foss intends to pull together the data to share with the group. The short list includes:

- Engineering reports and bore logs from Harbor Mountain road
- Engineering soils reports for the Sitka area
- Laboratory data for Sitka soils
- All Scientific papers related to the soil properties for Sitka soils.

Discussion

Development and operation of any LWS is a dynamic process requiring active participation of technical experts, stakeholders, and the public to achieve the desired loss reduction. The science and technical components of the LWS are designed to assess the "when?" and "where?" of landslide hazard as a basis for issuing alerts and warnings. Based on hazard information contained in an alert, a stakeholder can take action to reduce risk and ultimately reduce losses. Two-way communication between scientists and stakeholders can help refine the system over time. Key areas of communication include scientific and technical details (scientists and engineers), desired or planned risk-reduction actions (stakeholders), and lessons learned (all).

This report describes the working group's initial assessment of the technical and scientific details of an early warning system for the CBS. The tasks and products outlined and prioritized in the previous sections describe the components needed initially to develop a basic operational system for assessing and forecasting debris-flow hazard as well as components needed to fully develop the system and improve its accuracy over time. Figure 7 shows the components of a basic system, developed by completion of in-progress and priority one tasks (1 – 8, Table 1) described previously. For the basic system, the process of assessing landslide hazard relies on three input types (Fig. 7): (1) rainfall from a small network of existing weather stations and the proposed high-altitude weather station (tasks 3 and 7), (2) streamflow at Indian River (task 8), and (3) new or recently completed landslide hazard maps (tasks 2, 4, and 5). Each input type supports a separate decision tool for either ***when*** (rainfall and streamflow thresholds, tasks 1 and 6) or ***where*** (high-hazard areas, tasks 2 and 4) aspects of debris-flow hazard. Creation of specific rules for interpreting conditions relative to the thresholds and determining the outcomes (null, alert, or warning) of threshold exceedance for high-hazard areas will be an outcome of defining the thresholds and study of the completed hazard maps.

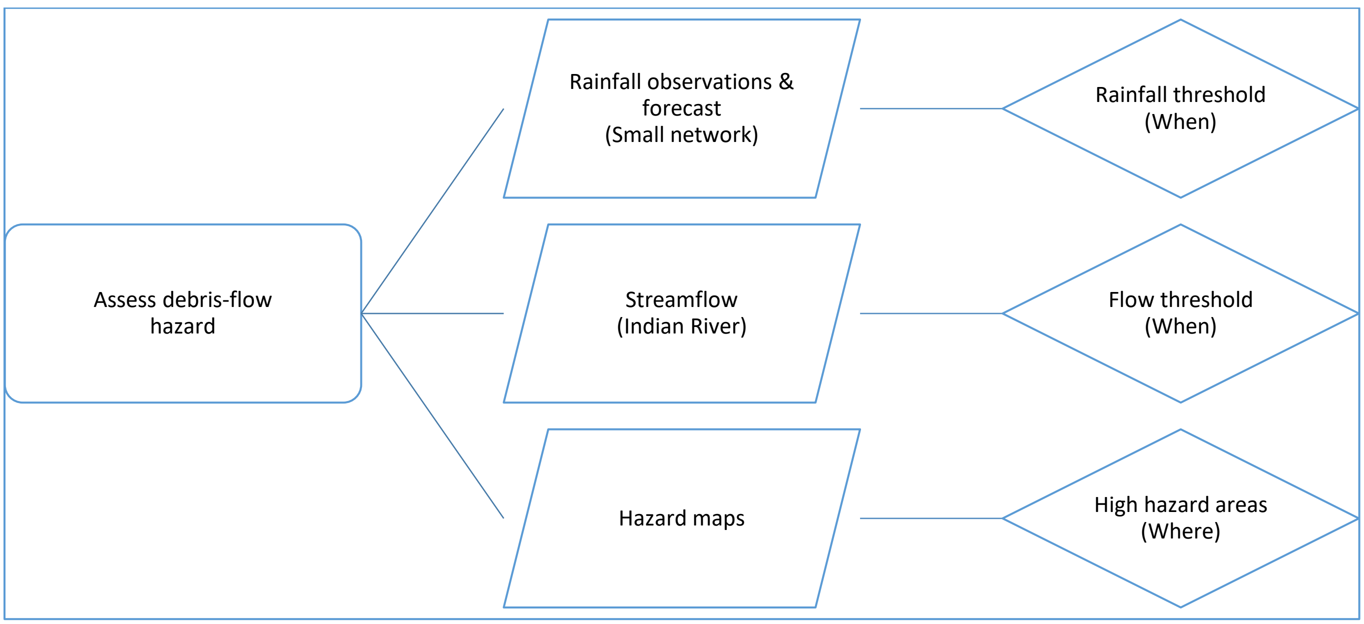

FIGURE 7. COMPONENTS OF A BASIC OPERATIONAL SYSTEM FOR ASSESSING AND FORECASTING DEBRIS FLOW HAZARD FOR SITKA. THE PROCESS, ASSESSING LANDSLIDE HAZARD (LEFT COLUMN), RELIES ON THREE INPUT TYPES (CENTER COLUMN). EACH INPUT TYPE SUPPORTS A SEPARATE DECISION TOOL (RIGHT COLUMN). INTEGRATION OF OUTPUTS FROM THE DECISION TOOLS DETERMINES CONDITIONS FOR ISSUING DEBRIS-FLOW WARNINGS TO INFORM STAKEHOLDER ACTION.

Fig. 8 shows components of a fully developed system as envisioned by the working group. Further development results from completion of priority 2 and priority 3 tasks and includes expansion of the precipitation (tasks 11, 15, 16, and 18) and streamflow (tasks 9 and 11) data collection networks found in the basic system along with the addition of new data streams for soil moisture (task 17), and ground deformation (task 13). Suggested addition of a numerical model (task 14) is intended to provide three-dimensional insight to subsurface quantities, such as soil moisture and pore pressure, that can be measured only at selected points with field instrumentation. Deformation monitoring bolsters the hazard map by identifying areas that might be progressing toward failure, thus helping to pinpoint likely source areas of future debris flows. Detailed soil mapping (task 19) would benefit both the numerical modeling (task 14) and refinement of the debris-flow hazard maps (tasks 2 and 4). Addition of a process for checking the accuracy of landslide forecasts ensures that the system will remain robust by making it possible to adjust and improve decision criteria, such as thresholds and hazard maps, over time. This process will rely on efforts to collect reports of landslides as described in tasks 5 and 10. Efforts to inform and educate the public about landslides (task 12) will help members of the public know how to reduce their own exposure to landslide hazard and how to respond to landslide warnings. Coordination of the proposed tasks will help ensure adequate coverage and redundancy of instrumentation while avoiding any unneeded duplication. Final configuration of the fully developed system will vary from that depicted in Fig. 8, depending on agency priorities, funding, scientific advances, and specific needs voiced by the CBS and its residents as well as other stakeholders.

Disclaimer

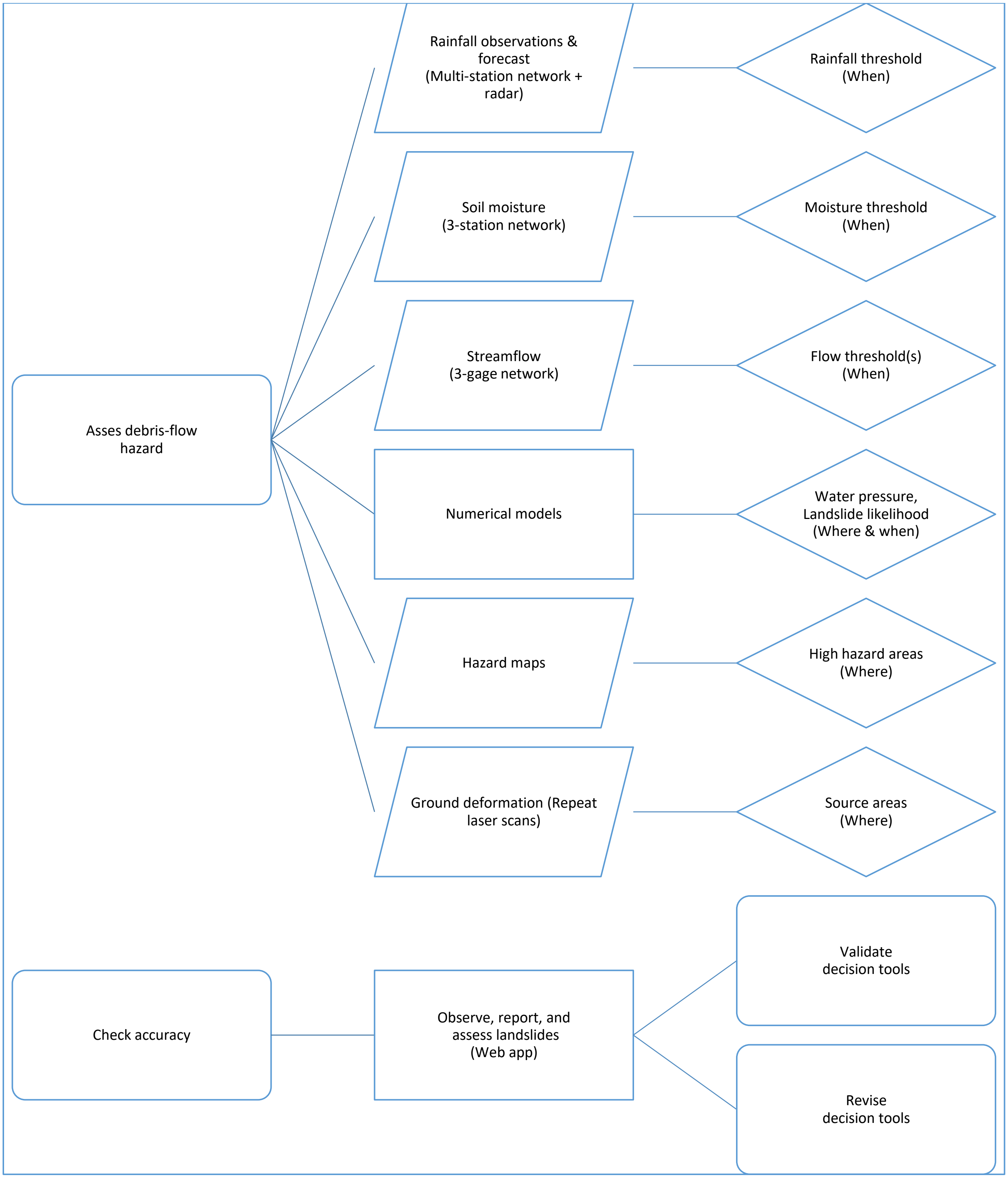

FIGURE 8. COMPONENTS OF A FULLY DEVELOPED SYSTEM FOR ASSESSING AND FORECASTING DEBRIS FLOW HAZARD FOR SITKA. THE MAIN PROCESS, ASSESSING LANDSLIDE HAZARD (LEFT COLUMN), RELIES ON FIVE INPUT TYPES PLUS AN EXTERNAL PROCESS, NUMERICAL MODELING, (CENTER COLUMN). EACH INPUT TYPE SUPPORTS A SEPARATE DECISION TOOL (RIGHT COLUMN). A SECONDARY PROCESS, CHECKING ACCURACY (LEFT COLUMN), RELIES ON A SINGLE PROCESS (CENTER COLUMN), WITH TWO POSSIBLE OUTCOMES (RIGHT COLUMN).

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