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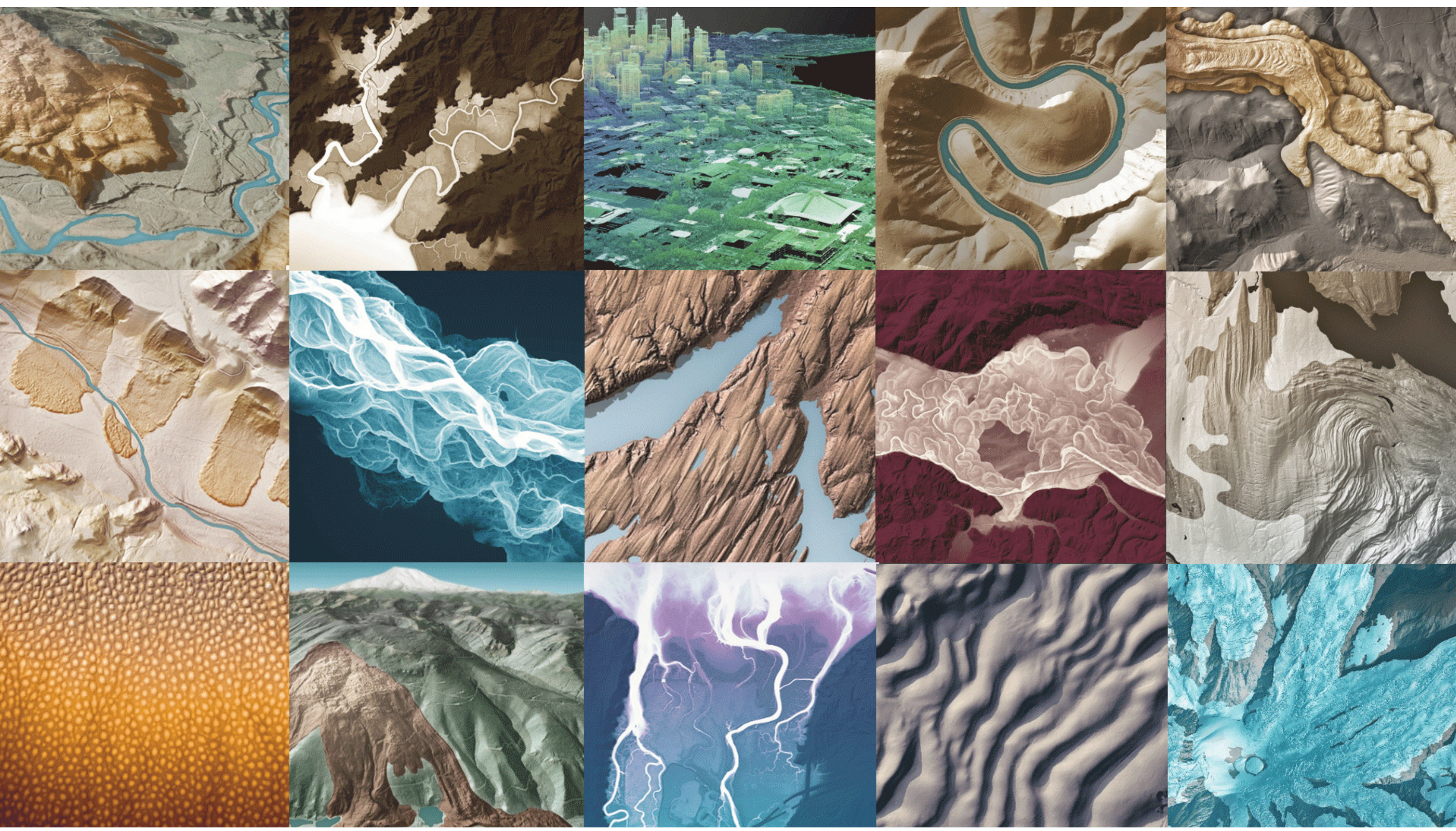
WASHINGTON STATE DEPT OF
NATURAL RESOURCES
WASHINGTON
GEOLOGICAL SURVEY

WASHINGTON STATE LIDAR PLAN

A Plan for Statewide Lidar Coverage in Washington

2020–2021



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A Plan for Statewide Lidar Coverage in Washington

2020–2021

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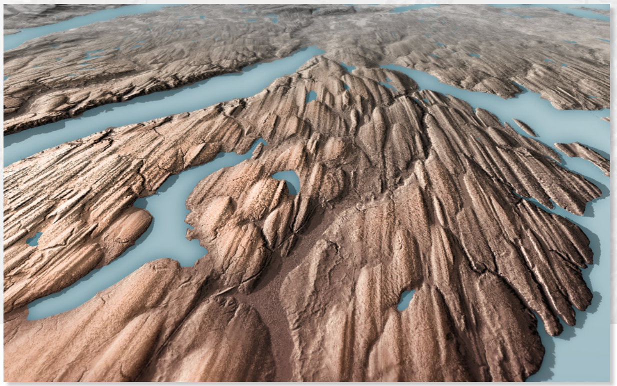

Learn more about the Washington Lidar Program on our website:

dnr.wa.gov/lidar

Explore Washington lidar data on our lidar portal:

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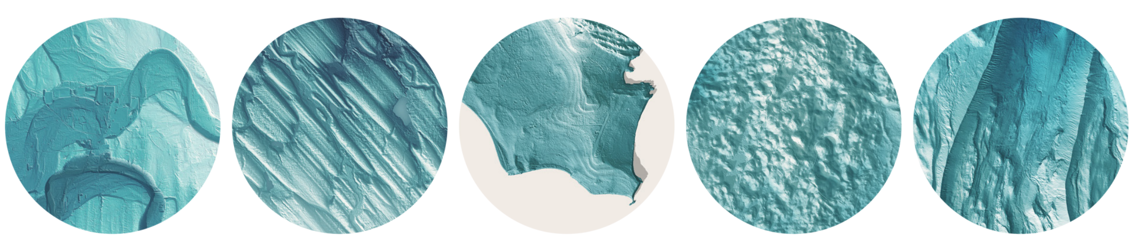


Introduction

The objective of this report is to provide an overview of lidar (light detection and ranging) in Washington State for potential users of lidar data, such as cities, counties, state agencies, federal agencies, and tribes. This report includes an overview of past data collection efforts, a list of stakeholders, a summary of the value of lidar data, and a strategy for completing statewide lidar coverage. The plan includes priority areas and estimated funding. This is the state's first formal statewide lidar plan, and it will be updated annually.

The State Lidar Program is managed by the Washington Department of Natural Resources (DNR) through their Washington Geological Survey (WGS). This plan is an interagency effort between WGS and the Washington Office of the Chief Information Officer (OCIO). Stakeholders from state agencies, counties, cities, tribes, and federal agencies also participated in the development of this plan.

The State Lidar Program was created in 2016 in response to the need for consistent, high-quality lidar data for hazards identification and to fulfill a mandate to publically distribute the data. Given that lidar data has a wide range of benefits and applications in addition to hazards identification, this State Lidar Plan has several aims: (1) to build upon the State Lidar Program mandate, (2) to support different application and business needs, (3) to standardize collection and quality control procedures, and (4) to incorporate new technologies for elevation data collection where appropriate. The ultimate goal of the program is to provide complete statewide coverage at a high resolution and to have a plan for refreshing the data moving forward. This document is also intended to encourage collaboration and coordination among the many potential stakeholders and funding partners.

Acknowledgment: *In 2018, the National States Geographic Information Committee (NSGIC) initiated a project for states to develop formalized statewide lidar plans. Washington was one of eight states selected to participate in this project, which was the catalyst for developing this plan. We appreciate their support.*

Past Efforts

Lidar collection started in Washington in 1996. The Puget Sound Lidar Consortium (PSLC) was established in order to continue collection efforts, with many local partners from Kitsap, Clallam, and Island Counties, the City of Seattle, and federal partners USGS and NASA. The goal of the PSLC was to create a lidar collection mechanism for Washington stakeholders and host a portal to share the lidar from more than 70 collection projects across the state. The PSLC set the stage for future lidar data collection and established technical specifications and guidance.

In 2015 the legislature passed RCW 43.92.025, mandating that DNR, through WGS, acquire and process lidar data. The program would focus on collecting new lidar or updating deficient data, and creating and maintaining an efficient, publicly available database of lidar data. The Lidar Program at WGS began in January of 2016 with two wide-area projects: a collaboration with the USGS over north and south Puget Sound, and with PSLC over portions of King County. Whereas initial work in Washington was primarily project-driven, resulting in inconsistent lidar coverage, WGS intends to work within the framework of this plan to fill in the gaps and systematically complete lidar coverage for the entire state. Currently, WGS is nearing completion of their third USGS collaborative project and will continue working toward statewide coverage.

Lidar collection started in Washington in 1996.

Statewide Lidar Management and Organization

Lidar management at the state level is the result of interagency efforts. WGS is the technical lead for lidar and the state lidar champion. OCIO assists in plan development. The agencies co-chair the lidar Planning and Coordination Team.

The Planning and Coordination Team is responsible for tasks such as identifying stakeholders, holding stakeholder meetings, obtaining stakeholder feedback, and updating the State Lidar Plan. For 2020–2021, the Planning and Coordination Team consists of:

More than half of the State of Washington has either current lidar coverage, or will be covered by ongoing lidar acquisitions.

- **Abigail Gleason**—Lidar Manager and State Champion, WGS
- **Casey Hanell**—State Geologist, Lidar Program Advisor, WGS
- **Joanne Markert**—State GIS Coordinator, OCIO

The State Lidar Plan is written and maintained by WGS and OCIO. The plan is edited and approved of by the Lidar Advisory Committee, a group of stakeholders that participates in planning and coordination meetings.

Identifying stakeholders to participate in the Lidar Advisory Committee meetings was critical to the development of this plan and will be key to its successful implementation. The role of the stakeholders is to participate in two meetings a year, assist with establishing priorities, identify funding options, provide feedback about the plan, and advocate for lidar in their agencies/regions.

The stakeholders in Appendix A either attended the stakeholder meetings in 2018 or expressed interest in participating in the future. These stakeholders comprise the Lidar Advisory Committee and represent a variety of state, local, federal, and tribal entities. Washington held its first Lidar Advisory Committee meeting in September 2018 and a follow-up conference call in October. More than 25 stakeholders participated in these meetings. The meetings were advertised using email forums, presentations, and direct requests to those who had expressed interest in the past. Hopefully future planning efforts will include even more stakeholders and participants.

Status of State Lidar Holdings

More than half of the State of Washington has either current lidar coverage, or will be covered by ongoing lidar acquisitions. The coverage extends over a 22-year time frame, with varying quality and utility. Given this, there are multiple ways to look at the coverage of lidar across the state: (1) by coverage, (2) by year collected, (3) by quality (high or low), and (4) by what remains to be collected with high-quality data (the “gap map”). The current public lidar extent is shown in Figures 1 to 4.

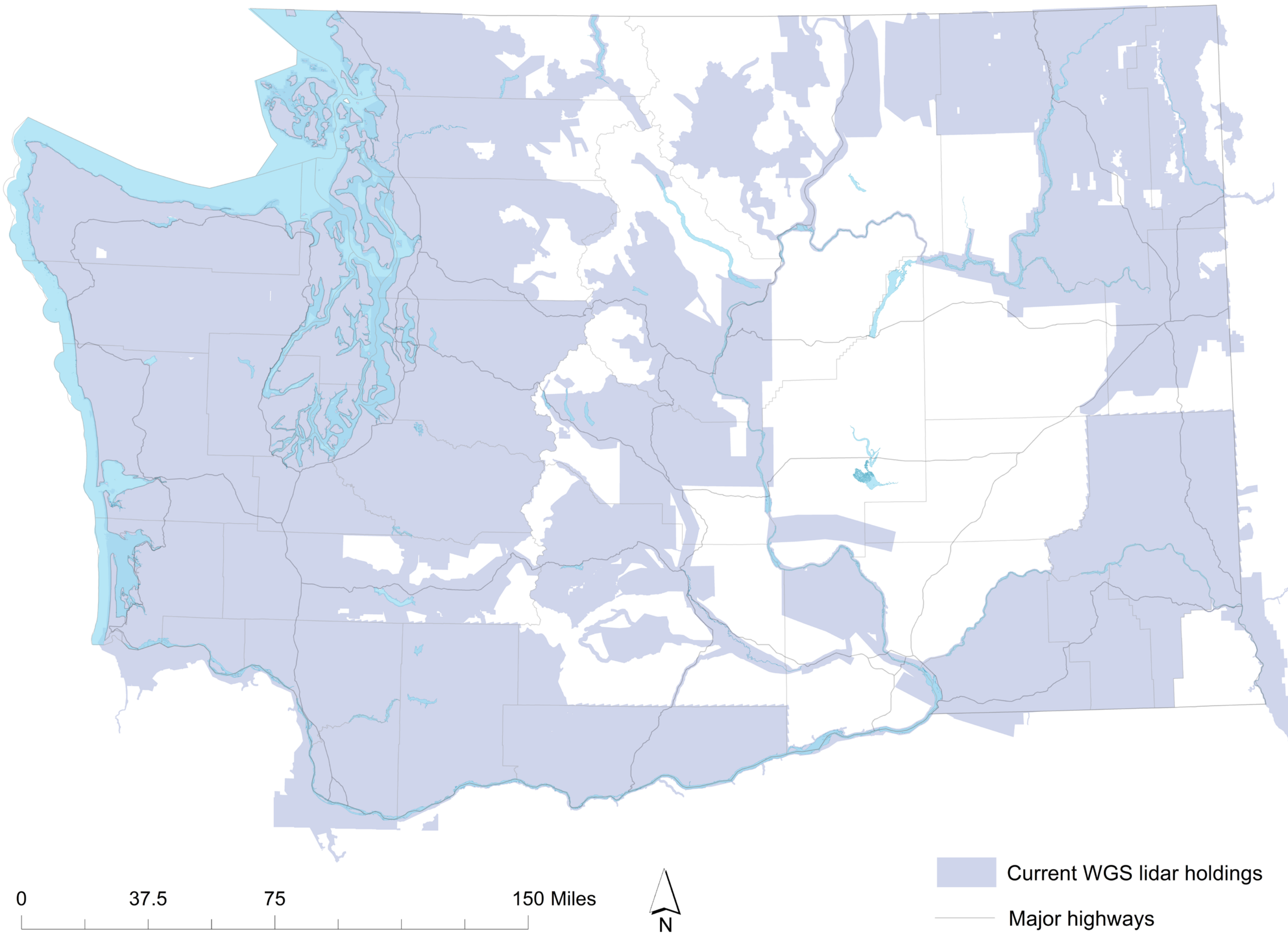


Figure 1. Extent of all current lidar holdings in Washington State.

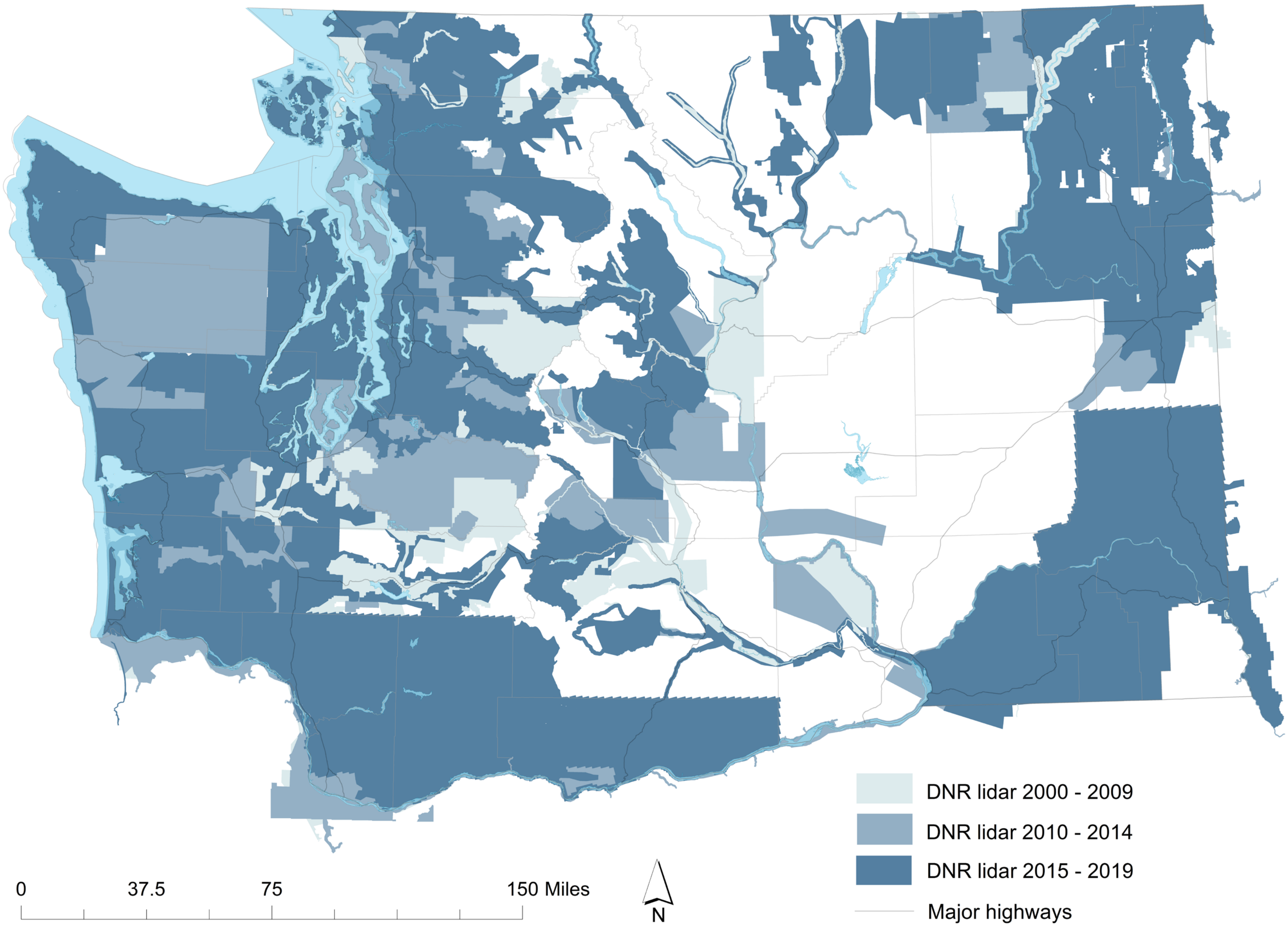


Figure 2. Lidar collection by year.

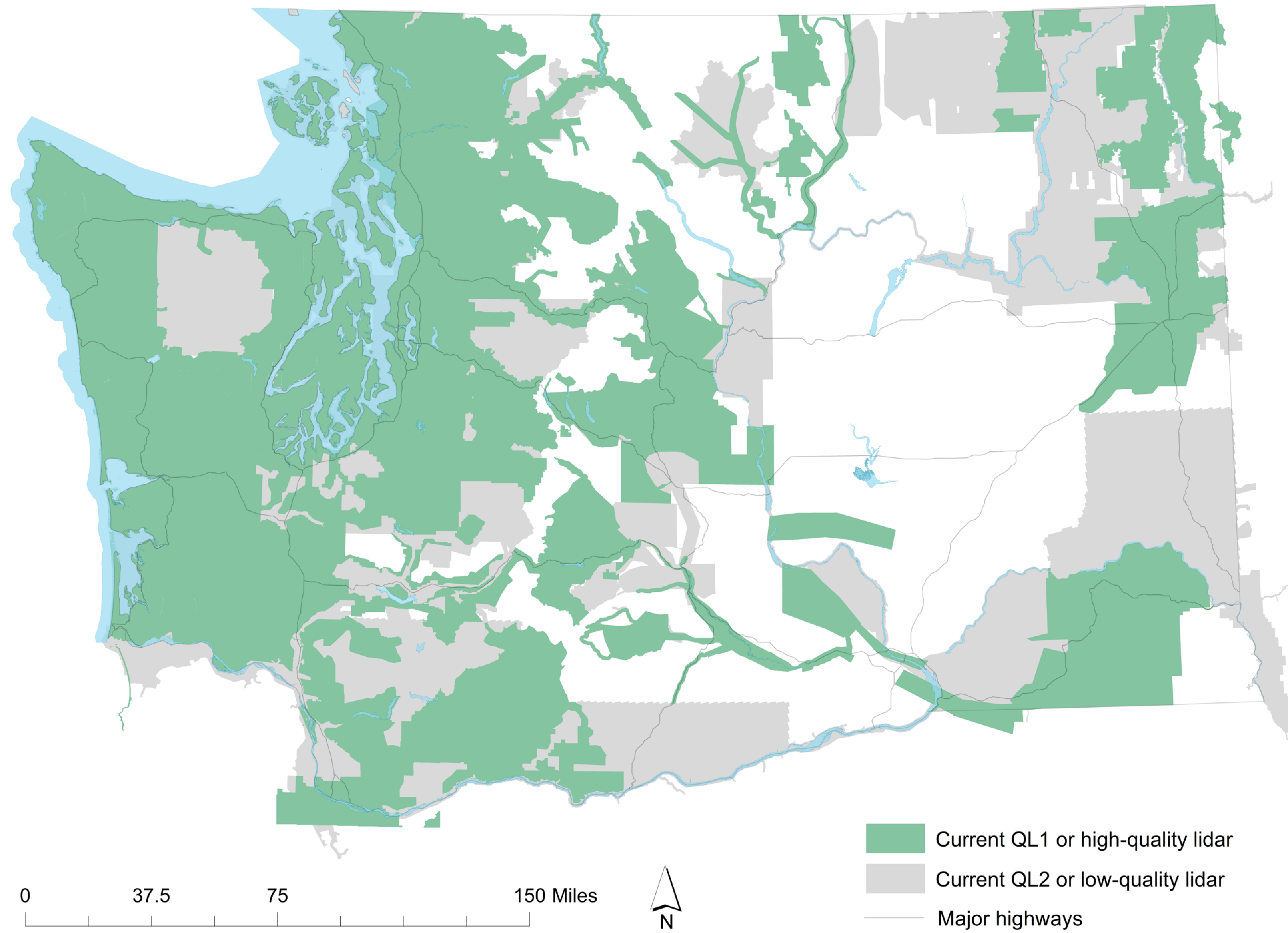


Figure 3. Lidar coverage can also be characterized based on quality level (QL), as defined by the USGS. QL1 is based on a minimum first return density of 8 pulses per square meter (ppsm) and a high vertical accuracy, whereas QL2 is distinguished by 2 ppsm and a lower vertical accuracy.

Figure 4. Current gaps in high-quality (QL1 or equivalent) lidar coverage

Applications, Benefits, and Value for Washington State

Lidar data has a wide range of uses and applications in Washington State. Of these, characterizing bare earth terrain may have the biggest impact. The dense vegetation of western Washington made traditional mapping techniques from aerial imagery nearly useless and prone to significant error. With lidar, geologic features such as fault scarps and landslides have been mapped for the first time. In 1996, when the Toe Jam Hill fault was mapped, the underlying terrain revealed by the lidar data was startling (Fig. 5).

With lidar, geologic features such as fault scarps and landslides have been mapped for the first time.

For landslides, the comparison between traditional mapping techniques and lidar is no less significant, and the benefit for the state is tangible: landslides are common across Washington and impact the population regularly. Lidar data not only reveal the locations of landslides for inventory mapping, but provide detailed information on their features and characteristics (Fig. 6).

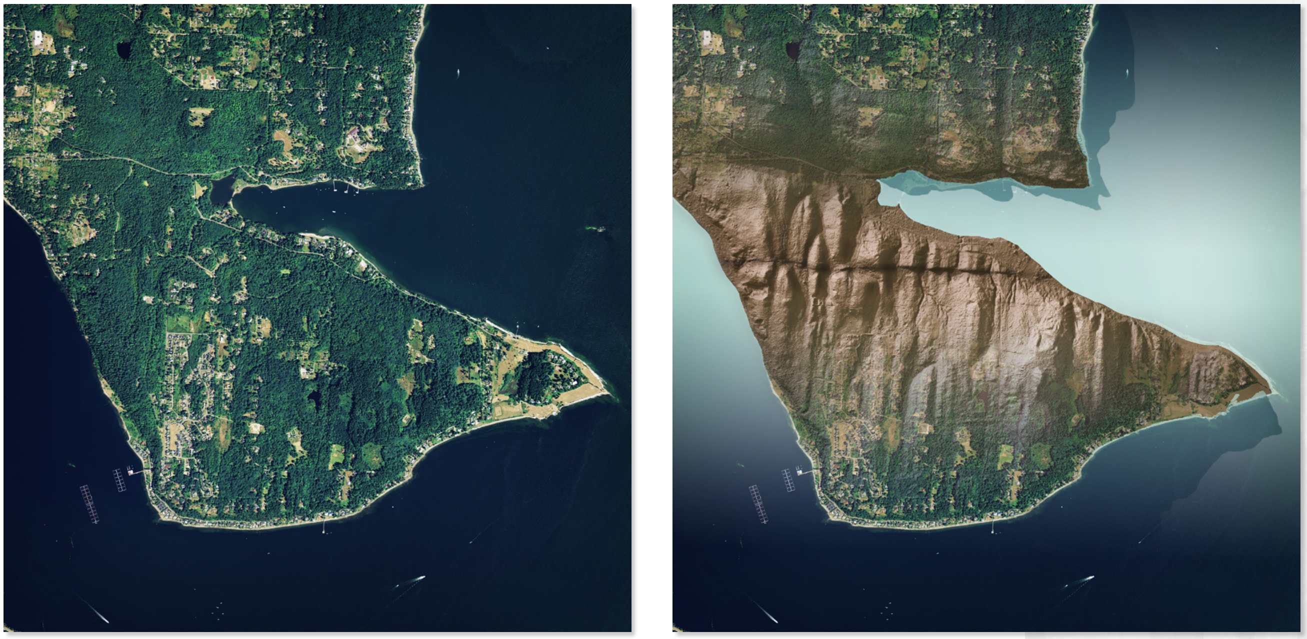


Figure 5. Bainbridge Island. Aerial imagery over the island (left). The lidar imagery (right) reveals the fault scarp underneath the vegetation.

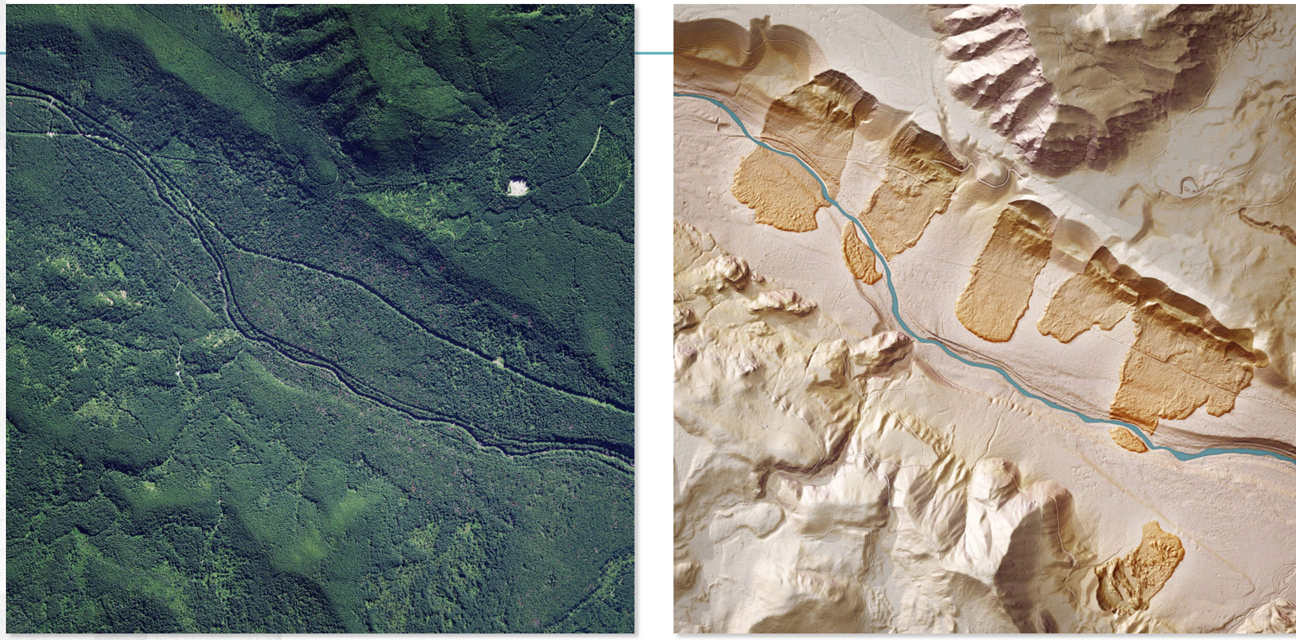


Figure 6. Comparison of imagery and lidar data over Cedar River, King County. Lidar data reveal several landslide features beneath the vegetation.

Consistently, we found that in order to support the work stakeholders wished to conduct, quality level 1 (QL1) data with a minimum aggregate density of 8 pulses per square meter is required.

This information can help people understand the history of a landslide event, identify the type of landslide, and determine the susceptibility of a particular area to similar events in the future.

Lidar is very useful in low relief and urban areas. In eastern Washington, highly accurate lidar data have a wide range of applications, including precise flood mapping, planning for rural communities and urban growth, water resource management, modeling sheet and rill erosion, defining topographic changes for hydraulic analysis and wetlands restoration, planning for rural communities, and habitat restoration. Change detection between multiple lidar surveys is also eye-opening—with the high resolution of lidar data, dynamic changes in river channel migration (Fig. 7), urban development, and slope stability over relatively short periods of time are quite apparent. As the population of Washington grows, changes in the environment become more important to track and understand.

In the fall of 2018, stakeholders were asked about their applications for lidar. The applications are summarized in Figure 8. Consistently, we found that in order to support the work stakeholders wished to conduct, quality level 1 (QL1) data with a minimum aggregate density of 8 pulses per square meter (ppsm) is required. Without this level of density, the bare earth under even moderate vegetation cannot be accurately characterized. For other applications, such as urban development and resource planning, a QL1 lidar dataset is needed as a baseline for future work, and ultimately QL1 data provides the opportunity to serve a much wider range of applications.

Lidar plays an important role in serving the state, including addressing key items in the governor's priority issues (https://www.governor.wa.gov/issues/issues):

- **Safe Communities: Emergency Preparedness**—Washington is taking steps to protect lives and help communities in the aftermath of a potential large-scale natural disaster. Lidar data and analyses identify and delineate areas with landslide, earthquake, tsunami, flooding, and wildfire risks. Lidar has also been used to evaluate zoning designations based on hazard identification. Examples include reviewing other features near the SR-530 landslide disaster and calculating tsunami inundation in the Port Angeles area (Fig. 9).

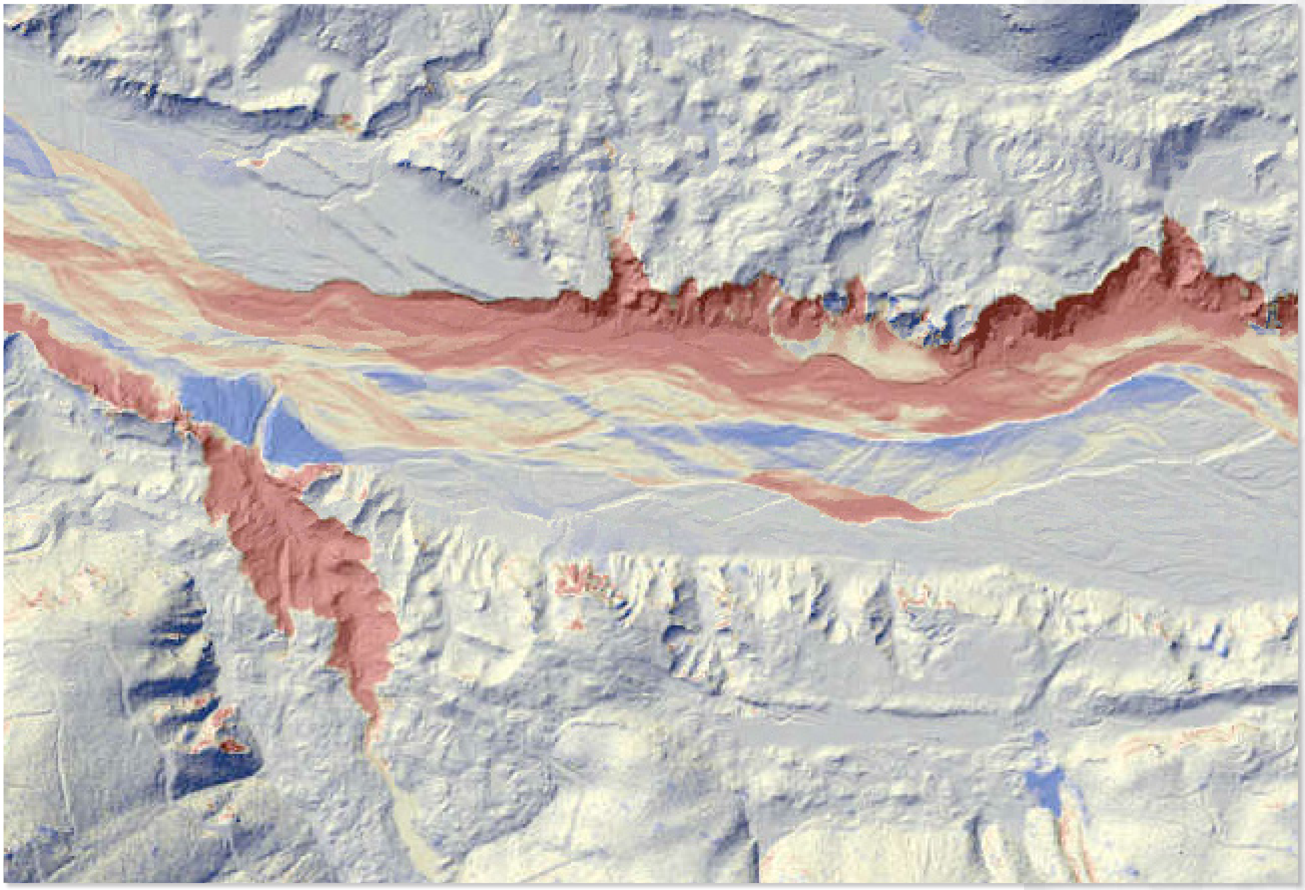


Figure 7. Change detection map of the Toutle River, from 2007–2012. Red shades denote removed material, where erosion or landslides have occurred, whereas blue shades show deposited material.

- **Energy and Environment: Protecting Puget Sound**—Lidar data and analyses can be used to characterize salmon-bearing rivers and streams as well as identify key areas for recovery options. Additionally, lidar data is an essential input for flood plain mapping. Bathymetric lidar data has also been used to map places such as the Nisqually Delta (Fig. 10) and the Cowlitz River, helping to gain greater insight into Washington's complex riparian environments and river systems.
- **Economy: Clean Energy**—Washington is leading the nation's transition to a clean energy economy. Lidar data identify building heights and footprints and help calculate solar exposure. Another example is using lidar in planning new energy projects, such as geothermal exploration (Fig. 11) or wind farms.

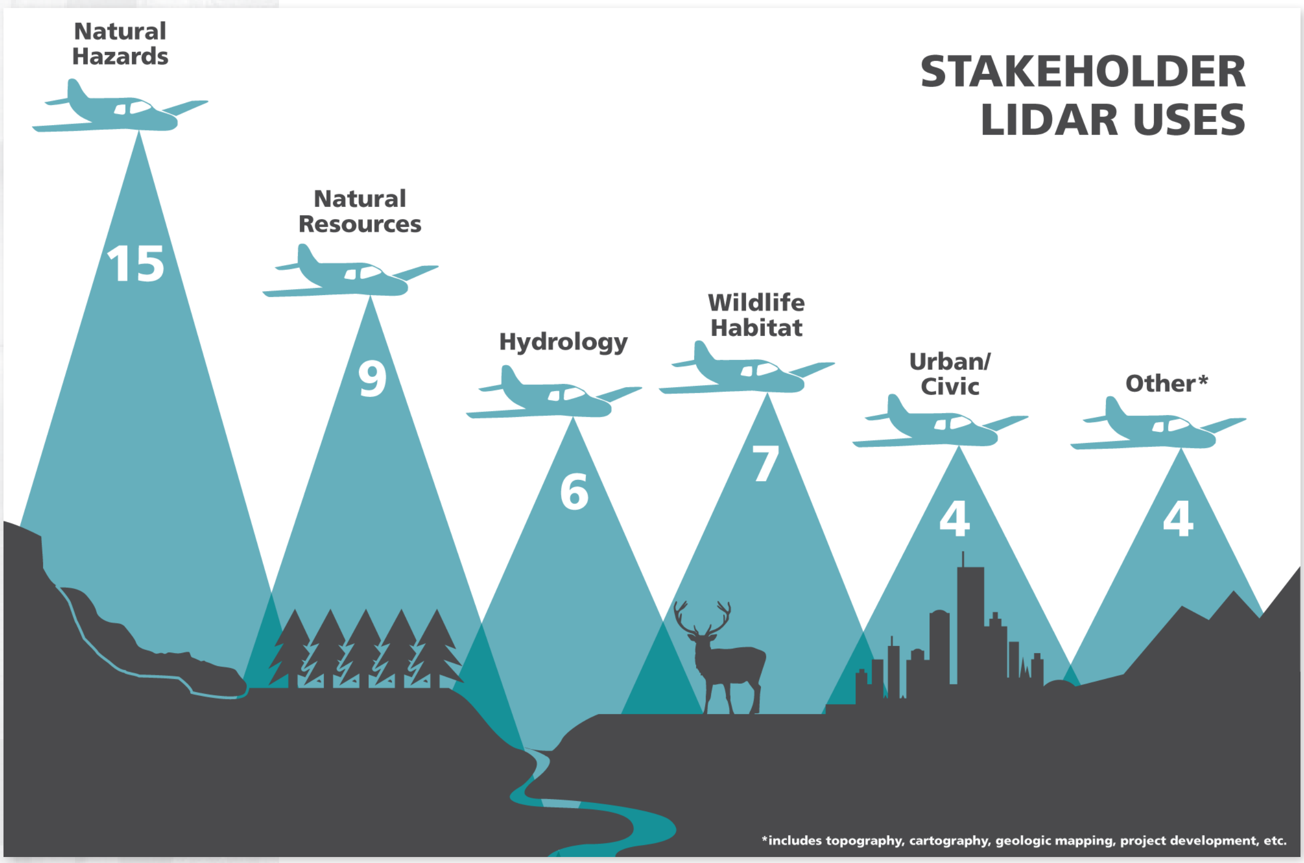


Figure 8. Applications and uses of lidar data in Washington State, categorized by number of stakeholder responses listing the application as a top priority.

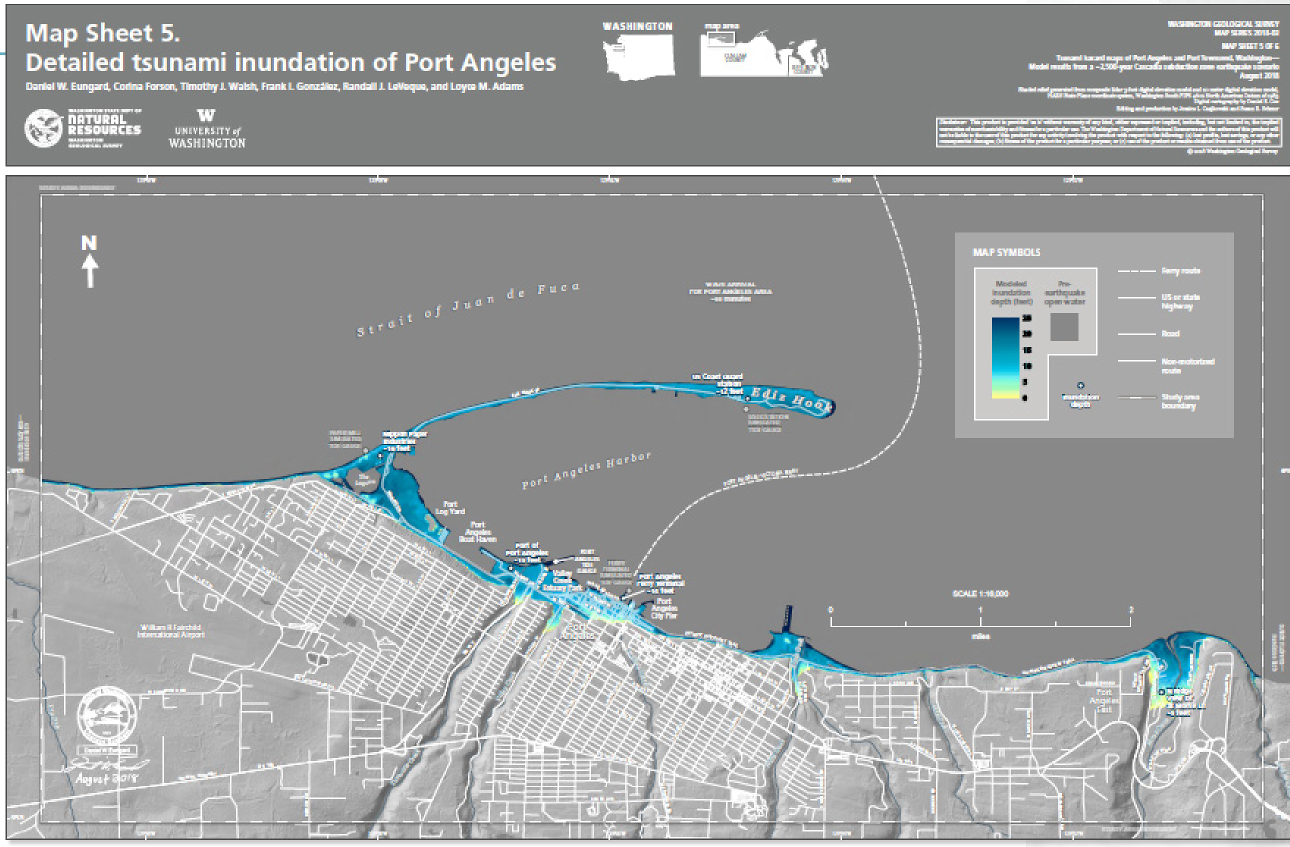


Figure 9. Detailed tsunami inundation map of Port Angeles. This map incorporates lidar data in the generation of the inundation model as well as in the basemap it is displayed upon.

- **Transportation: Target Zero**—Washington has a goal to reduce highway deaths to zero by 2030 as part of the Target Zero Strategic Plan. Mobile lidar is already being used in Washington for bridge and infrastructure inspections, to ensure safety on our roads. Complete lidar data across the State will help characterize the terrain the roads traverse and identify what potential hazards and changes are present (Fig. 12).

For WGS alone, it is estimated that more than 2,000 hours of field verification are saved by using lidar data as a starting point.

Value

It can be incredibly difficult to estimate the dollar value or return on investment (ROI) on collecting lidar data for Washington State. There are a few examples of ROIs for lidar data in Washington. For landslide mapping, lidar data reduces the amount of field verification time needed. For WGS alone, it is estimated that more than 2,000 hours of field verification per year are saved by using lidar data as a starting point. As a conservative estimate, more than 300 hours may be saved by using lidar in planning and monitoring activities

Figure 10. Lidar topography and bathymetry of the Nisqually Delta. Lidar reveals complex estuarine topography relevant to salmon and environmental factors.

Figure 11. Geothermal drilling near Mount St. Helens. Lidar was an input for the original modeling work, and was also used for drill site planning.

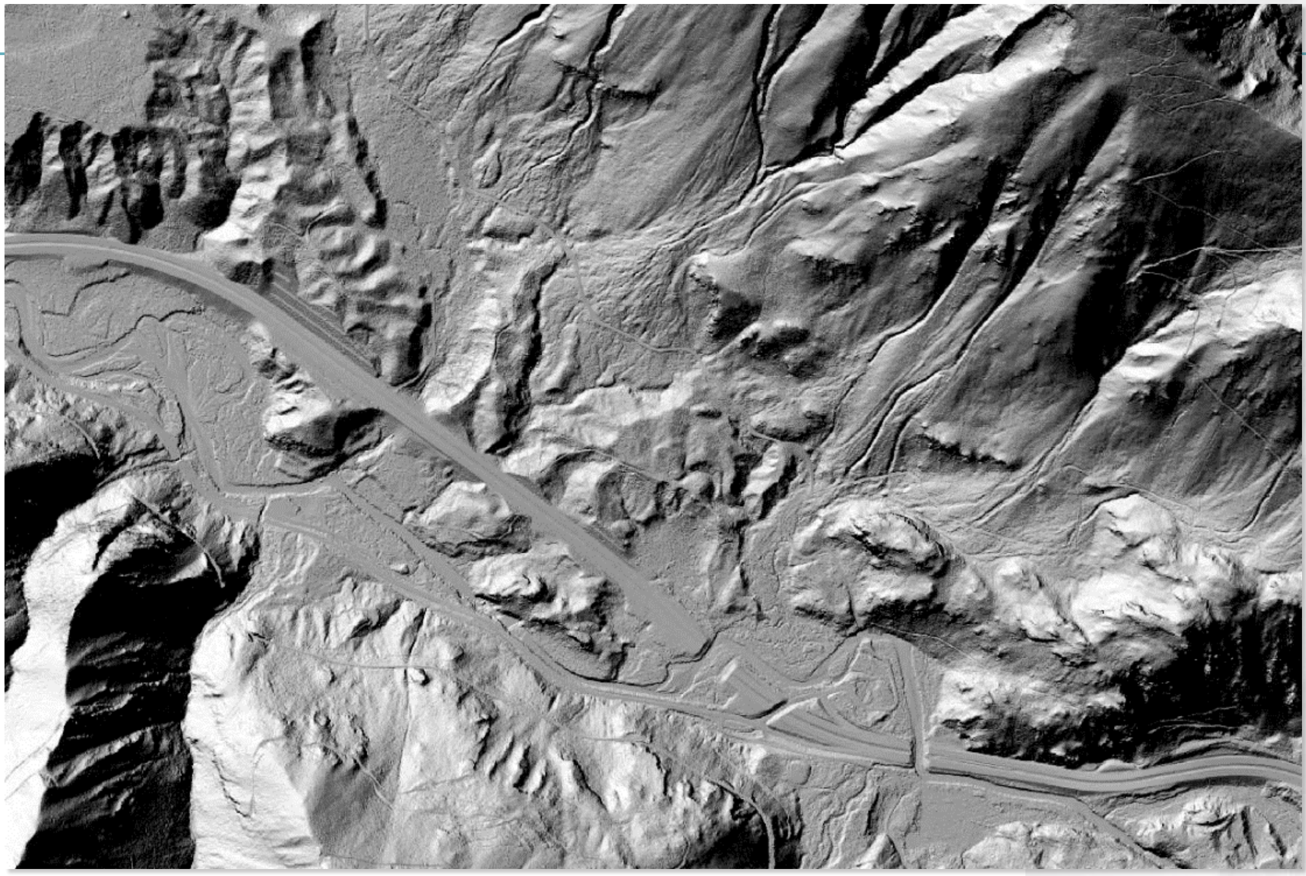


Figure 12. Lidar data from 2016 over Highway 90 in King County. Having wide-area lidar data over a road network delineates possible hazards that may impact safety or infrastructure, such as rock falls and river crossings.

for WGS hazards, landslides, and mining functions. The goal of using lidar is to inform communities of potential hazards in advance of events similar to the SR-530 landslide. If this bears true, more than $100 million dollars may be saved in emergency response costs per event, a comparable cost to the Aldercrest–Banyon landslide in 1998. Given the accuracy and nature of the lidar data, it also improves the ability to make critical decisions and avoid errors. WGS now requires that hazard mapping areas and tsunami inundation study areas have lidar coverage because it reduces errors and avoids the need to remap areas multiple times. WGS believes that other business areas will ultimately discover the same value in lidar data, and require it as a starting point for all projects and programs.

Once statewide lidar coverage is complete, collection won't be "done".

Lidar Plan Priority Areas

The current plan map (Fig. 13) documents the areas of Washington that have: no current lidar data; available lidar data that is greater than ten years old and of lower resolution or quality; or areas that need to be upgraded to a QL1 (8 ppsm density). The map breaks down the areas needed into aggregate priority areas to help focus collection activities and planning. The plan focuses on priority areas rather than collection years, recognizing the fact that other agencies or companies may develop requirements within the next year that cause them to focus on a particular part of the plan sooner than anticipated.

Figure 13 shows these priority areas as determined by the Planning and Coordination Team and the stakeholder group. The priority areas are ranked from highest priority (1) to lowest priority (5). Overall, the priority areas are based on: (1) counties that are currently pursuing collection opportunities, (2) areas that are adjacent to current or ongoing collection areas, (3) hazard areas or areas requiring habitat restoration, and (4) areas with little to no lidar data. White or blank areas already have high-quality lidar data available. Table 1 describes each priority area and how it was ranked based on state requirements.

Refresh cycle

Once statewide lidar coverage is complete, collection won't be "done". Areas that change frequently will warrant updated collections, and advances in technology and computing capabilities may have a large impact on what can be achieved.

A five-year refresh rate is preferred by most user groups, yet is difficult to obtain given the size of Washington and the cost. A more realistic scenario is a five-year refresh rate in certain key areas, including: (1) counties with high population density, (2) areas with a higher probability for change or requirements for hazard mitigation, and (3) coastal areas requiring monitoring of coastal erosion and change. Other areas throughout the state may be refreshed at a rate of 10–15 years. A preliminary map of possible lidar refresh cycles, based on watershed administrative units (WAUs) that surround population growth areas, hazard areas, and coastal areas, represents the minimum area that would need to be refreshed on a five-year basis (Fig. 14).

Table 1. Priority areas and a description of how the areas were ranked.

	PRIORITY AREA	PRIORITY DETERMINATION AND DESCRIPTION
1	Central and Northern Counties, Thurston County	Addresses wildfire, agriculture engineering, civil planning projects, and hazard mapping concerns. Adjacent to current mapping efforts.
2	Central Western Washington, Asotin County	Updated collections will address hazard mapping, salmon recovery, and conservation efforts. Asotin currently has very little lidar coverage and it is needed to address wildfire and geologic hazard concerns.
3	Southwestern Washington	There is either no lidar coverage, or lower quality data for this region. New lidar coverage is needed to address forestry needs and hazard mapping.
4	Olympic National Park, Colville area	Current lidar over Olympic National Park is low resolution and lower quality. Updates are required for salmon restoration efforts and water quality. Lidar over the Colville area is needed for forest health and wildfire concerns, as well as broader hazard mapping.
5	Eastern Klickitat, Walla Walla, and Whitman Counties	Collection at the QL1 level is needed to maintain consistency and usability of lidar data across the region. Updated lidar will address rangeland management, soil survey development, and agriculture needs.

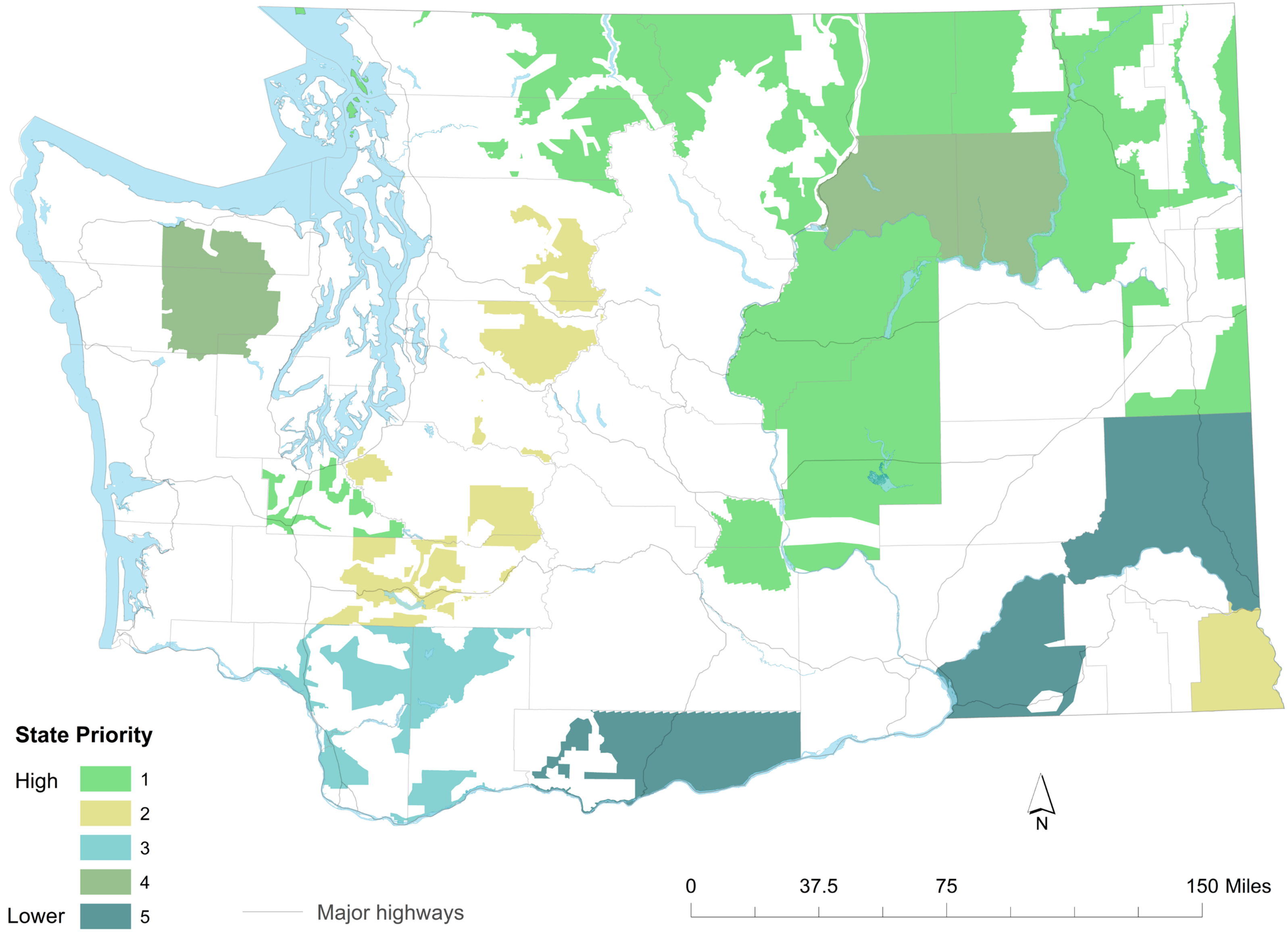


Figure 13. State priority map for completing lidar coverage across the remainder of Washington State.

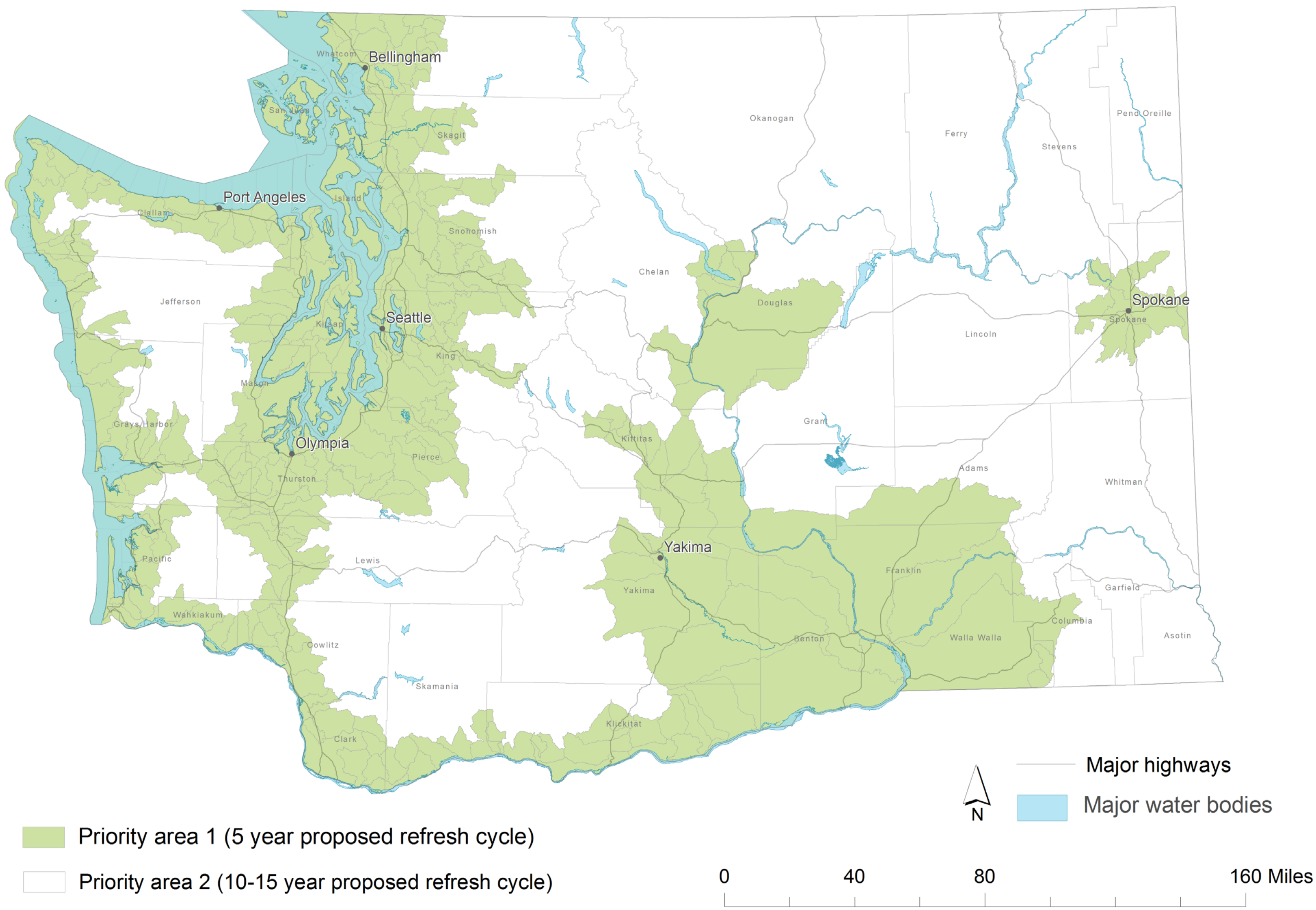


Figure 14. Proposed lidar refresh cycles for Washington State.

Partnerships across the state have played an important and critical role in the ability to extend state funding and collect large areas consistently and with high-quality lidar.

Implementation

In order to implement the collection plans outlined in the previous section, funding and resources need to be identified and set aside. This section describes current funding sources and collection methods.

State Funding

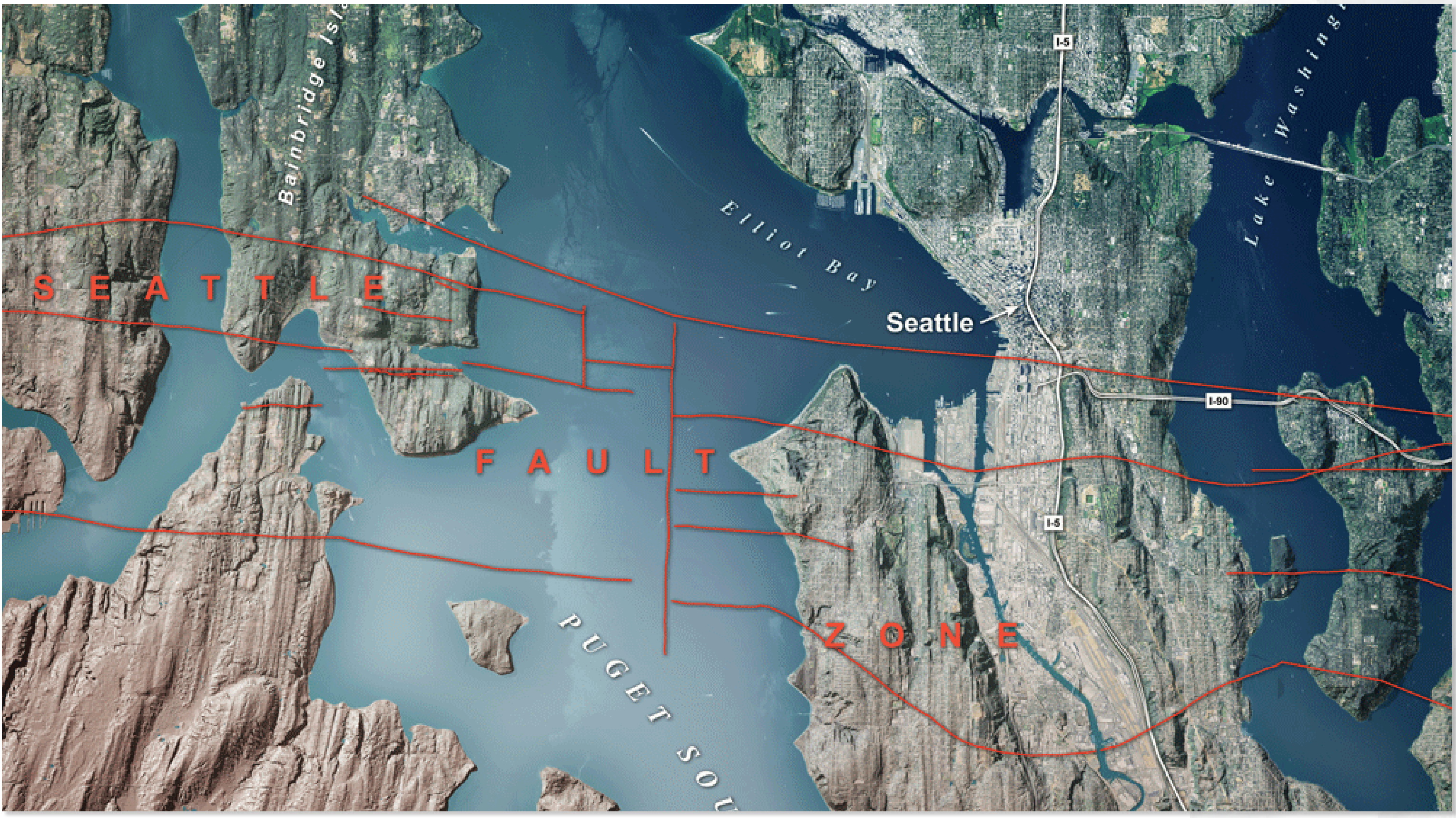
WGS has a set funding amount per biennium that is dedicated to lidar collection, which is identified as the primary "core" funding for the state. Each biennium the funding will be applied to the priority areas outlined in this plan. This funding must be spent within the biennium cycle, and no portion of it can roll over to the next biennium. This funding was established with RCW 43.92.025 and is subject to continued legislative approval. To expand the area of collection and maintain consistency, WGS applies for federal and state grant funding as well as looks for opportunities to partner with other state agencies, local partners, and federal agencies.

Partnerships

Partnerships across the state have played an important and critical role in the ability to extend state funding and collect large areas consistently and with high-quality lidar. For example, in the North Puget 2017 lidar collection project, funding came from Skagit, Snohomish, and Whatcom counties and significantly added to the coverage area. Funding from partners can also be used to provide additional deliverables, such as hydro-flattening. However, funding amounts from these partners are not set or necessarily pre-identified before the planning of each project. The Lidar Advisory Committee will therefore be essential for ensuring that stakeholders are aware of the areas that need data as well as the need to involve the Lidar Advisory Committee with the annual planning process. It is also essential that stakeholders understand the estimated costs and resource requirements for lidar collection in order to incorporate it into their planning processes. These cost estimates are listed in the *Resource Requirements* section of this plan.

Grants

Federal grant programs have been essential for Washington State, particularly the USGS 3D Elevation Program (3DEP), which offers federal matching



opportunities, expanding upon state funds and allowing for wide-area, consistent, high-quality collection. WGS plans to continue working with the USGS 3DEP program and apply for funding for the priority areas each biennium. WGS will also likely continue to work with the 3DEP contracting services to maintain consistency and quality across projects. Other state, local, and tribal agencies can also apply to the USGS 3DEP program. Other federal agencies, including the Natural Resources Conservation Service (NRCS) and the U.S. Forest Service (USFS), also contribute funds to the USGS 3DEP program if the project aligns with their areas of interest. Additionally, FEMA grants are often available for flood mapping activities. Washington agencies, counties, tribes and cities are encouraged to look into other state grant opportunities.

Contracting

WGS has developed a lidar contract for other Washington stakeholders and agencies to use. This allows groups who need lidar coverage in other priority areas to work on meeting their requirements, as well as being able to meet project and program needs outside of a biennium timeline. This contract

The largest costs associated with lidar collection are for the acquisition and processing of the data as well as for storage and dissemination.

also supports consistency between projects and allows for collection in areas that already have lidar data that need to be refreshed due to environmental change or events. An example of this kind of project is San Juan County; the county identified a need for updated lidar data that did not necessarily fall within the other priority areas identified by this plan. Therefore, the county and WGS worked together to develop a project for the winter of 2019 in order to achieve refreshed lidar coverage for San Juan County.

Resource Requirements

The largest costs associated with lidar collection are for the acquisition and processing of the data as well as for storage and dissemination. This section reviews the estimated costs for these resources.

Lidar acquisition and processing costs

There are several ways to estimate lidar costs for Washington State. Several vendors collect lidar in the Pacific Northwest. Their costs vary given mobilization differences, crew and asset sizes, as well as by quality, services provided, and ability to work with large-scale projects. WGS currently uses a price matrix to estimate costs for their projects, and also uses estimated costs based on past USGS 3DEP projects in the state. All of these cost estimates have acquisition and processing of the data included. These costs are subject to change, and an effort will be made to update them in each iteration of the State Lidar Plan. Current lidar costs based on WGS contract and USGS 3DEP estimated costs are listed in Table 2.

It should also be noted that the terrain and level of difficulty, as well as the products and services required (for example, bathymetry or orthoimagery) may influence the quotes for an individual project. For those considering a lidar project, contact WGS for consultation and coordination with statewide activities.

Table 3 uses the cost estimates listed in Table 2 to estimate the acquisition and processing costs required to complete high-quality (QL1) coverage for the remainder of the state and update deficient data.

Table 2. Current estimates of lidar acquisition costs, based on square mileage area and pulse density. A density of 2 ppsm is not recommended by this plan.

PROJECT AREA SIZE (SQUARE MILES)	COST PER SQUARE MILE BY PULSE DENSITY		
	8 PPSM	15 PPSM	2 PPSM
1–100	Case by case	Case by case	Case by case
101–200	$783	$882	$423
201–500	$624	$723	$320
501–1500	$505	$612	$289
1501–3000	$454	$553	$258
3000+	$451	$538	$249
USGS 3DEP specification	$516		$321

Table 3. Estimated lidar costs for each priority area as shown in Figure 13.

	PRIORITY AREA	SIZE (SQUARE MILES)	QL1 ESTIMATED COSTS BASED ON USGS PAST PROJECTS
1	Central and Northern Counties, Thurston County	12,767	$6,587,772
2	Central Western Washington, Asotin County	2,432	$1,254,912
3	Southwestern Washington	1,319	$680,604
4	Olympic National Park, Colville area	3,210	$1,656,360
5	Eastern Klickitat, Walla Walla, and Whitman Counties	4,583	$2,364,828
	TOTAL AREA	24,311	$12,544,476

Storage and Dissemination Costs

Lidar is a dense data resource, with a high cost for information storage and dissemination. Additionally, it is best practice to retain all lidar data, regardless of age, in order to aid in change detection. The fundamental data format, the point cloud, is also becoming critical to provide, given that the information it contains is not always easily reproduced in a more condensed raster product. These point clouds are also becoming larger with better technology. Therefore, an ongoing cost and challenge will be to store, maintain, and disseminate an ever-growing collection of lidar datasets.

It is best practice to retain all lidar data, regardless of age, in order to aid in change detection.

Refresh Cycle Costs

Tables 2 and 3 only estimate the costs for completing high-quality coverage, they do not estimate the costs for refreshing the data. For areas where data is required by stakeholders in the near future, Table 2 can be used to estimate refresh costs. When a more concentrated effort begins for refreshing the state lidar coverage, the State Lidar Plan will be updated to include estimated costs for each area.

Technical Specifications and Standards

Unless otherwise specified by funding sources or acquisition partners, the most current version of the Washington State Department of Natural Resources Lidar Acquisition Technical Specifications Document (WGS lidar technical specifications document, Appendix B) will be used to define the parameters of new lidar projects.

The WGS technical specifications document adheres to and references the USGS Lidar Base Specifications 1.3 (or most current) document, with a few notable exceptions where the minimum specifications are higher:

- For all new acquisitions, the aggregate first return pulse density will be 8.0 points per square meter or higher. Overall, the equivalent Quality Level for all Washington State acquisitions is QL1 or higher.

- By default, survey conditions will be conducted during the leaf-off and snow-free period for the survey area. This requirement may be relaxed for higher elevation survey areas where the number of deciduous trees is limited, in areas where overall vegetation is limited, or when snow and terrain conditions provide a challenging environment that narrows the collection timeframe considerably.
- The collection will be designed such that there is at least 50 percent sidelap and 100 percent double coverage for each flightline.
- In addition to a bare earth surface model, a first return surface model is required to be delivered as well, generated from the highest collected return (disregarding noise) for each raster cell.
- Additionally, the data is required to be delivered in NAVD88 vertical datum, NAD83-HARN (or CORS96 labeled as HARN for GIS purposes) Washington State Plane South.
- Hydroflattening (setting each inland water body at a single consistent elevation and systematically "stepping" down rivers downstream) is currently optional unless specifically requested or when a project is being completed in conjunction with the USGS 3DEP program. The addition of a hydroflattened DEM as a standard product will be continuously discussed with Washington stakeholders.

The USGS Lidar Base Specification 1.3 (or most current version) may also be used for survey control standards, vertical and horizontal accuracy standards, metadata standards, tiling schemes, and naming conventions. Conversely, the WGS technical specification document lists conventions and standards that may also be used (Appendix B).

Lidar Products and Deliverables

A list of standard lidar products is given in the WGS technical specification document. Information on standard formats and technical requirements can also be found there. At a minimum, WGS requires the following products:

- **All-return classified point cloud**—This product is the primary lidar data, needed by users who want to generate their own surfaces, look at vegetation structure (Fig. 15), examine infrastructure, or conduct more in-depth analyses.

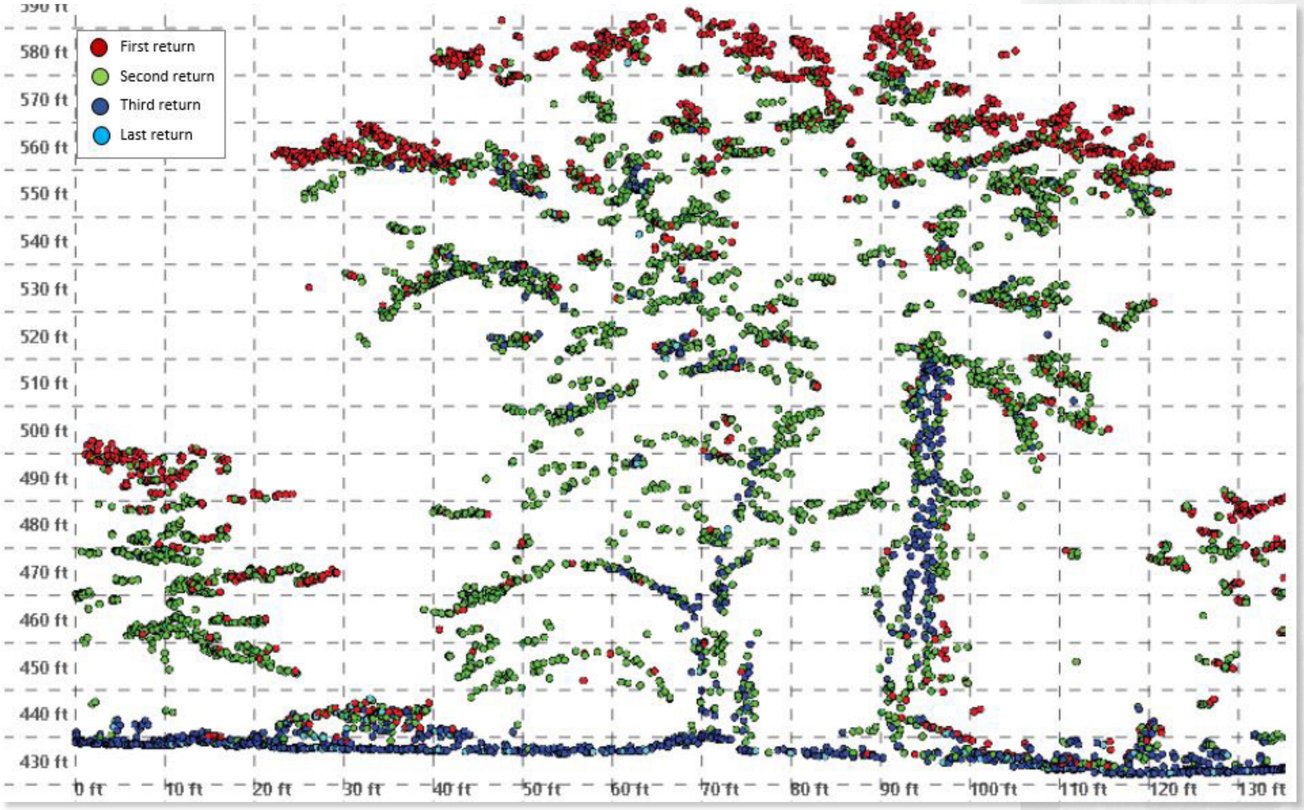


Figure 15. All return classified point cloud. Whereas a raster surface only captures one aspect of the data (lowest returns, first returns) the point cloud represents all returns and can be very useful for understanding the 3D nature of objects. Here the whole structure of a tree is represented.

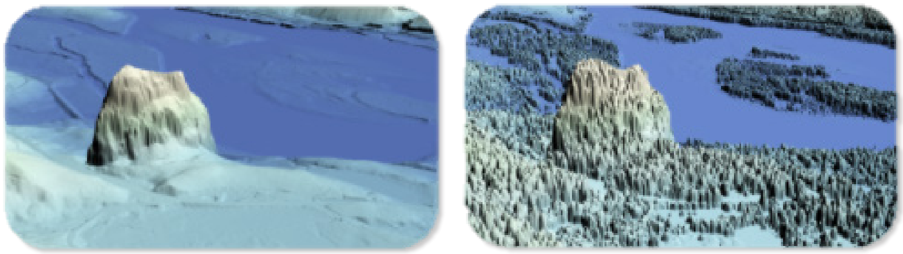


Figure 16. Example of a bare earth DEM (left), vegetation and structures are removed. Example of a first-return DEM (right), which includes vegetation and man-made structures.

- **Bare earth surface model (Digital Elevation Model (DEM) or Digital Terrain Model (DTM))**—This is a derived raster dataset that filters out all points other than verified ground points and is used for slope stability studies, engineering, and modeling studies (Fig. 16).
- **First return surface model**—Represents the highest collected return from each cell (disregarding noise), delivered in a raster format. This deviates from the USGS Lidar Base Specification, but having a standardized first return surface model has proved useful for forestry and vegetation applications (Fig. 16).
- **Intensity images**—A derived raster that indicates the strength of the return to the instrument (Fig. 17). This product can be useful for understanding the hydrology at the time of collection, or distinguishing features such as buildings and roads. These structures often have stronger returns than ground or trees.
- **Survey report**—The survey report includes information on the project itself, such as location, dates of data collection, a description of the lidar acquisition and ground survey techniques and results, as well as an accuracy assessment. These reports are very useful for anyone needing to understand how the collection was conducted, how accurate the data is, and what the best use of the data is.
- **Collection area index and footprint**—A geographic representation of the area that was collected for the project, as well as an index of the individual tiles (DEMs, point clouds, and all raster data delivered) that are included in the delivery.

Figure 17. Intensity image. Intensity images represent the strength of the returned measurement to the lidar system.

- **Ground control points and calibration points**—These points help people understand how accuracy was measured for the dataset, and allow them to evaluate the points themselves to understand the accuracy for their own needs. These products also help in the QA process.
- **Recorded aircraft trajectory data, or smoothed best estimate of trajectory (SBET)**—These data record the aircraft position and altitude with attributes for the date and time of each flightline. They are used when the exact time of collection is needed (for example, comparative vegetation studies during a particular season, or looking at low tide data).
- **Formal metadata**—In XML format, as described by the WGS technical specification document.

Additional products may be required based on the project. Examples include: orthoimagery, specific quality assurance rasters, hydroflattened surface models and associated breaklines, bathymetric surface models, and bathymetric coverage vector data.

It is anticipated that this plan will be reviewed annually in May by the Lidar Advisory Committee.

Maintenance of the Acquisition Plan

All plans need to be maintained to reflect changes from the community and changes in technology and priorities. It is anticipated that this plan will be reviewed annually in May by the Lidar Advisory Committee. Depending on the feedback, changes will be made to the plan. Minor changes are expected annually with potentially more substantial changes every two years, coordinating with the biennial budgeting cycle of the State. The next biennial cycle is July 2019–June 2021.

See Figure 18 for a timeline of the State plan and meeting activities. The Lidar Advisory Committee will meet in June to discuss any changes to the plan as well as upcoming acquisition opportunities and again in October to review the upcoming acquisition season.

Figure 18. Timeline for lidar collection in 2020.

Data Management Plan

Washington's lidar datasets are maintained and managed using best practices by two WGS staff members who provide data stewardship, quality assurance, and standardizations. This section reviews standard data formats expected for lidar data, as well as storage estimates and current distribution methods.

All lidar data collected by WGS is publicly available, along with the public datasets that have been donated to WGS by other agencies and organizations.

Data Formats and Sizes

Lidar data and derivative datasets are typically comprised of:

- Point cloud data, generally in a LAS or compressed LAZ format.
- Raster products for digital elevation models and intensity images.
- Vector products for ground control, breaklines, and flight data.
- XML metadata.
- Text formats for survey reports.

Additional information on data formats can be found in Appendix B, or the most current version of the USGS Lidar Base Specification. Overall, lidar data is large in size—by using a recent 3DEP lidar project to gauge the modern size and density of data for the QL1 data, it is estimated that the storage needed for Washington State, at a similar or equal quality level, is 275 TB. This does not account for the historical datasets already available, which currently comprise over 100 TB of data, or reoccurring collections.

Data Storage, Backup, and Archival

DNR and the Information Technology Division within the agency maintain enterprise-level agency data, as well as data backup, restoration, and disaster recovery response. The lidar data is backed up weekly, and copies are maintained in a secure off-site location. Additionally, all original lidar data, as delivered or received, is archived by an off-site cloud provider.

Data Sharing and Distribution

All lidar data collected by WGS are publicly available, along with the public datasets that have been donated to WGS by other agencies and organizations.

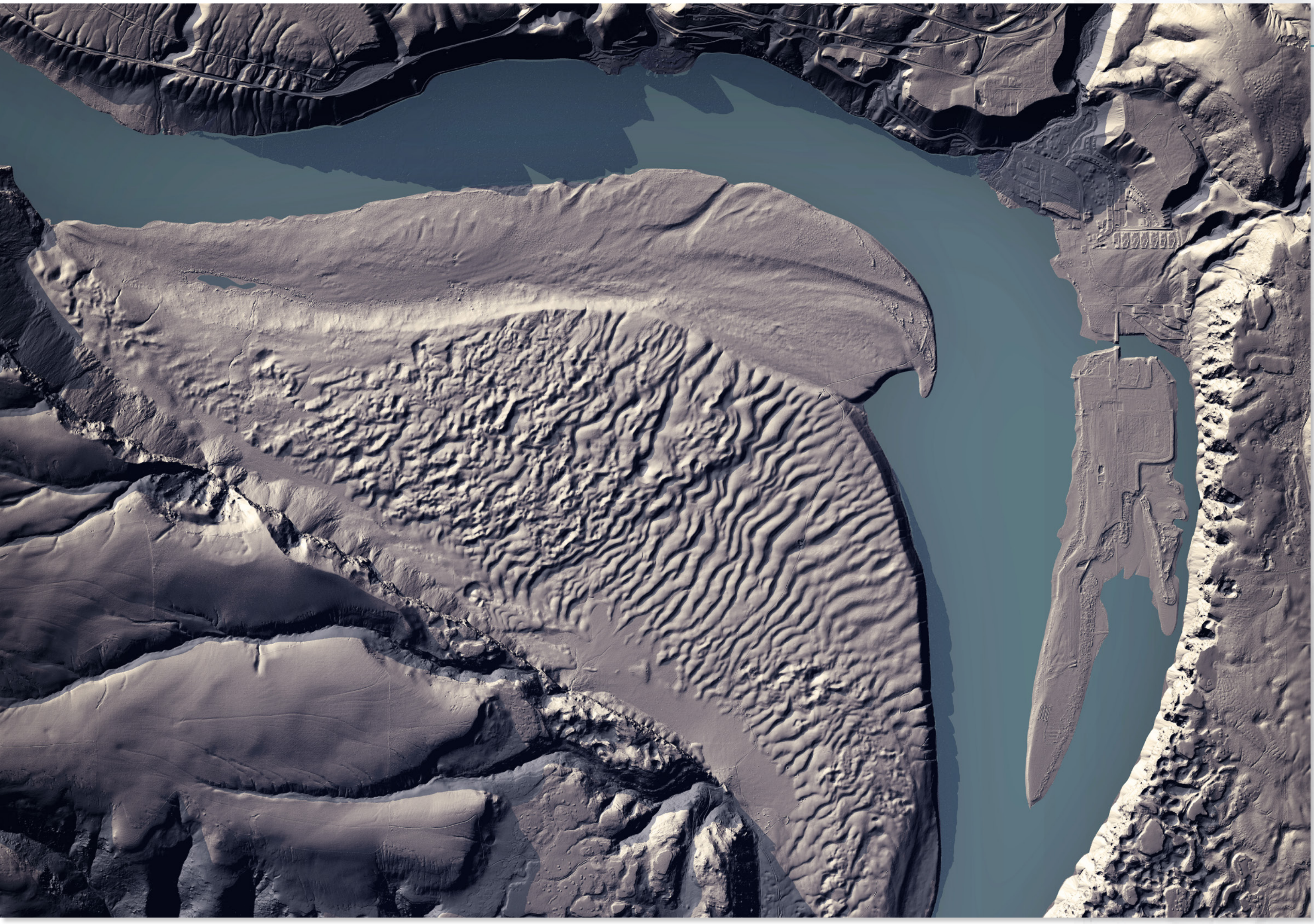
As this plan is reviewed each year, challenges will be discussed with the stakeholder group to identify solutions.

Currently, the Washington Lidar Portal (http://lidarportal.dnr.wa.gov) is the primary method of data distribution. Point cloud data, digital elevation model quadrangle tiles, hillshade quadrangle tiles, and survey reports are available in LAZ, TIFF, or PDF formats. Additional data may be available, such as break-lines, intensity images, or ground control points, though the presence of these additional products is dependent on the project. Any of the additional data or original data is available upon request.

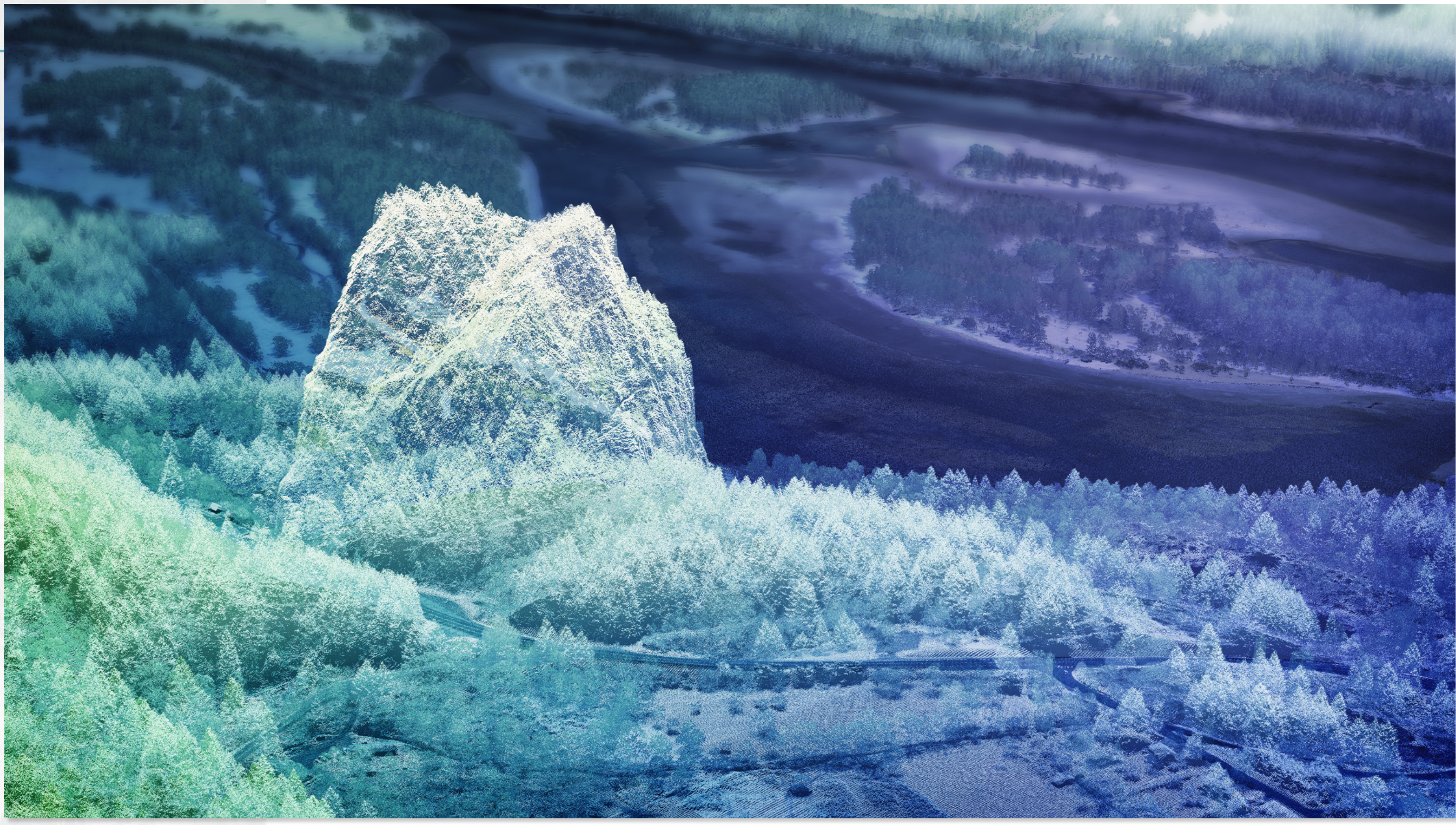
Future Challenges

As this plan is reviewed each year, challenges will be discussed with the stakeholder group to identify solutions. Identified here are the following initial challenges facing statewide lidar data collection:

- **Federally owned land**—Washington State has several large national parks, military installments, and federally owned areas, many of which are isolated from populous areas, or where the State may not be able to respond to hazards. Without at least some funding from the parks or federal landowners, it is hard to justify collection in these areas. Priority Area 3, which includes Olympic National Park, is one example.
- **Rural areas of the state**—There are several eastern counties in the State that have low populations and very little funding to contribute to lidar or imagery collection. At this point, federal agencies are interested in and capable of either acquiring data or partnering with the state, but it is unknown if that will continue.
- **Tribal Nations**—Unfortunately, there is concern that lidar data could be used to discover cultural resources. This plan needs to balance understanding hazards and wildfire potential, and mapping habitat and wildlife areas, with protecting and respecting cultural resources and addressing management concerns from our tribal partners.
- **Changing data formats**—The National Geodetic Survey is in the process of converting the nation to datum 2022, which will change the national horizontal datum, vertical datum, and geoid model. Another data change is the USGS change of archival file format from LAS to LAZ, a compressed version of the point cloud data. While this will save on storage, most users will need to decompress the data in order to use it with standard GIS software.



- **Communicating value to executive leadership**—Many of our stakeholders at the Lidar Advisory Committee meeting expressed the need to create materials regarding the value of lidar, the benefits, and the return on investment for their leadership.
- **Making the most of the data**—Lidar data is extremely valuable for analyses that affect safety and habitats. However, training on how to use lidar to its fullest potential, creating derived products for users, and developing techniques to facilitate sharing (for example, rest services for common features) will go a long way toward demonstrating value.
- **New technologies**—Lidar is a technology and as such is constantly changing. There may be opportunities in the future to expand this plan



to include mobile lidar for infrastructure evaluations and terrain data in general and not just lidar (for example, phodar). Newer technology which allows greater than QL1 resolution data will need to be incorporated, stored, and distributed. There is also the need to include bathymetry in the Washington plan and we will continue to monitor for opportunities to include this technology.

- **Funding**—Funding will often be an issue in the future, and questions remain about how to cross fiscal years to purchase the data. State and county partners identified this as an issue to be solved.

Additional References

Below are links to further resources that expand on particular topics related to lidar, lidar data collection, and applications. This is not an exhaustive list.

Story Maps

- **Washington State bare earth story map—**Explains what lidar is and showcases the use of lidar data for Washington geology. [https://wadnr.maps.arcgis.com/apps/Cascade/index.html?appid=36b4887370d141fcbb35392f996c82d9]
- **Washington State Lidar Plan story map**—Companion story map for this plan, expected to be available on the WGS lidar website in May 2019. [https://wadnr.maps.arcgis.com/apps/Cascade/index.html?appid=b93c17aa1ef24669b656dbaea009b5ce]
- **Other state lidar story maps**
    - **Indiana**— Indiana Statewide Lidar Planning & Status. [https://arcg.is/1GOj1z]
    - **Florida**— Florida Statewide Lidar. [https://arcg.is/1zvjbq]
    - **California**— California Lidar: A Critical Investment. [https://arcg.is/Gnz80]

USGS National Map (USGS NM)

- **Viewer**—https://viewer.nationalmap.gov/advanced-viewer/
- **Service Endpoints**—https://viewer.nationalmap.gov/services/
- **Data Downloads**—https://viewer.nationalmap.gov/basic/
- **3DEP Viewer**—https://apps.nationalmap.gov/3depdem/

NOAA US Federal Mapping Coordination Map

- **Interactive Map**—Provides outlines for federal areas of interest for lidar data collection. [https://www.seasketch.org/#projecthomepage/5272840f6ec5f42d210016e4/about]

Appendix A

The following representatives were in attendance at the Lidar Advisory Committee meeting in September 2018 either in person or via phone.

AGENCY	NAME
DNR	Chuck Hersey
DNR	Jeff Ricklefs
DNR	Stephen Slaughter
ECY	Jerry Franklin
ECY	Christina Kellum
ECY	Rich Kim
NRCS	David Brower
NRCS	Collin McCormick
NWIFC	Bruce Jones
RCO/GSRO/PSP	Greg Tudor
San Juan County	Dan Root
City of Seattle	Allen Grissom
Skagit River System Cooperative	Tim Hyatt
Thurston County	Mark Biever
Thurston County	Tami Faulkner
Thurston County	Kevin Hansen

AGENCY	NAME
USFS	Pete Heinzen
USFS	Mark Riley
USGS	Scott Bennett
USGS	Tom Carlson
USGS	Ralph Haugerud
WSDOT	George Comstock
WSDOT	Rich Daniels
WSDOT	Jeff Graham
WSDOT	Elizabeth Lanzer
WSDOT	Jordyn Mitchell
WSDOT	Pete Townsend

Interested stakeholders who could not attend the meeting:

AGENCY	NAME
DNR/Aquatics	Tim Strickler
DNR/Forest Practices	Hans Berge
DNR/Forest Practices	Liv Bowden
DNR/Forest Practices	Joe Shramek
DNR/Geology	Jessica Czajkowski
DNR/Geology	Guy McWethy
Kittitas County	Karen Hodges
City of Longview	Ruth Bunch
NRCS	Bobby Burken
Puget Sound Partnership	Jennifer Burke
Quinault Nation	Tony Hartrich

AGENCY	NAME
Thurston County	Nate Kale
Thurston County	Kelly Alfaro Haugen
USGS	Steve Angster
USGS	Brian Sherrod
Yakama Nation	Ryan DeKnikker
Yakima Basin Fish and Wildlife Recovery Board (YBFWRB)	Alex Conley
Tulalip Tribes	Michelle Totman
Trout Unlimited	Crystal Elliot-Perez
Skagit County	Josh Greenberg
State Conservation Commission	Brian Cochrane

Appendix B

Lidar Acquisition Technical Specifications

This document was developed by the Washington State Department of Natural Resources—Washington Geological Survey, hereafter referred to as DNR. The intention of this document is to inform contractor(s) of the technical requirements for lidar acquisition collected under contract.

1. Data Acquisition

Returns per pulse	At minimum 3 returns, including first and last return
Design pulse density per swath	≥4 points per square meter (ppsm)
Aggregate first return pulse density	≥8 ppsm, unless otherwise specified
On ground laser beam diameter	Between 10 cm and 40 cm
Laser scan angle	±15° from nadir (30° overall)
Swath overlap	At least 50% sidelap, designed for 100% double coverage
Survey conditions	No significant snow cover or cloud cover, limited standing water and no flooding. Leaf-off conditions are preferred. See Section 5 for further discussion.

2. Spatial Reference

Vertical datum	NAVD88 using Geoid03 for compatibility with horizontal datum or latest geoid model as described by the National Geodetic Survey
Horizontal datum	NAD83–HARN (CORS96 labeled as HARN may be used for GIS purposes)
Projection	Washington State Plane South
Units	US Survey Feet

3. Survey Completeness

Coverage	No voids between swaths, no voids due to cloud cover or instrument failure
Swath overlap	≤10% no overlap per project, no randomly selected 1,640.5 ft by 1,640.5 ft (500 m by 500 m) area with less than 50% double coverage
Aggregate pulse density	With exception to non-scattering areas (such as water, wet asphalt), first return aggregate pulse density must be ≥95% specified density over entire project area. For any random 98.5 ft by 98.5 ft (30 m by 30 m) area within swath overlap, first return aggregate pulse density must be ≥80% specified density

4. Survey Accuracy

Absolute vertical accuracy	≤9 cm vertical RMSE as measured on planar near-horizontal surfaces
Absolute horizontal accuracy	≤30 cm, optionally required as defined in Section 8
Swath to swath reproducibility	≤6 cm vertical RMSE as measured between overlapping swaths

5. Lidar Survey design

Special consideration should be given to each project in terms of compactness of survey area, contiguous collection, and weather and seasonal constraints. Each project area must be a contiguous area no smaller than the specified minimum survey area as indicated by the Contractor, but may range to well in excess of 2,000 mi^2. Effort will be made to make areas of interest (AOIs) compact, without serrate margins, large internal gaps, and narrow extensions. In order to maximize efficiency, survey outlines shall be finalized by DNR after consultation with the Contractor. The survey project area must include a minimum buffered area of 100 m around the original project area to ensure data quality at the edges. The survey project area must also include all land area within a survey and the area of all water bodies with minimum dimension less than one-half mile. Larger water bodies, except for a 100 m-wide seaward buffer along a shoreline, must be excluded from the calculation of the survey area.

Weather and seasonal constraints pose a significant challenge for lidar collection in Washington State. In general, surveys shall be completed in conditions that are snow-free, low water and stream flow, leaf-off, no fog or smoke, no low clouds, and no tall crops. Meeting all of these conditions may be very challenging, and therefore it is a requirement that the DNR and the Contractor agree on all permissible survey conditions based on the project requirements. If data acquisition during specific tide levels, stream or reservoir levels, dates, or if specialized processing is required (as described in Section 8), DNR and the Contractor may negotiate a price supplement to compensate the Contractor for the additional cost arising from the specific requirements.

Areas of extreme local relief and (or) poor access are more difficult to survey because of: (1) inability to maintain a near-constant aircraft height above ground, (2) occasional occultation of the GPS satellite constellation, (3) difficulty in adequately distributing GPS base stations and ground control points, and (4) within-swath variations in ground elevation that exceed the depth of field of the lidar instrument. In such circumstances it may be advisable to relax the specifications laid out in this technical specification. Any such relaxation must be approved by the DNR and may be associated with a lower price to be negotiated between the DNR and the contractor.

6. Lidar Survey Execution

The spatial reference and survey accuracy outlined above must be well documented in the survey report to fully describe the GPS procedures and instrumentation used to establish the coordinate framework and vertical datum. Additionally, the procedures by which the Contractor collects and processes ground control points (GCPs) for the purposes of undertaking lidar data quality control must also be documented in this report, and signed off by a Washington State Licensed Surveyor.

The Contractor shall make all GPS measurements with dual frequency Ll-L2 receivers with carrier-phase correction. All GPS measurements must be made during periods with Positional Dilution of Precision (PDOP) less than or equal to 3.0 and with at least six satellites in common view of both a stationary reference receiver and the roving receiver.

The Contractor's stationary reference receivers must be located at existing NGS marks or at new marks. In the case of an existing mark, its location must be verified by processing one GPS session of at least two hours duration and comparing the computed position with the position published by NGS. Each new mark must be located by tying to one or more NGS Continuously Operating Reference Stations (CORS) by static GPS methods. If the distance to the nearest CORS is less than 80 km, the Contractor must use at least two independent GPS sessions, each at least two hours long. If the distance to the nearest CORS is greater than 80 km, the Contractor must use at least two sessions each at least four hours long.

At least two GPS reference receivers must be in operation during all lidar data collection, sampling positions at greater than or equal to 1.0 Hz. The roving GPS receiver in the aircraft must sample positions at greater than or equal to 2.0 Hz. Differential GPS baseline lengths shall be no longer than 30 km.

GCPs, used for both survey calibration and assessment of absolute vertical accuracy, must be established using GPS or other techniques that result in vertical and horizontal accuracies of 1.5 cm root-mean-square-error (RMSE) or better. Dependent upon terrain and accessibility it is suggested that GCPs be strongly clustered for calibration purposes, and that GCP clusters be uniformly distributed throughout the project area. Vertical accuracy must be assessed by the Contractor by calculating and averaging the distances between GCPs that are not clustered and a surface interpolated from lidar first returns. A minimum of points used for the accuracy assessment will be based on the survey area, as described by the ASPRS Positional Accuracy Standards guide (ASPRS, 2014) with a minimum of 20 points for project areas less than 500 km^2. At least 20% of flight line swaths must contain points in this subset and the maximum distance between these GCPs must be no less than one-half the maximum distance across the survey area. In the report of survey, the Contractor must document the identity, published position, and measured position of all existing NGS marks used for reference stations. The locations of new marks must be described, along with their measured positions and the identity and published positions of CORS to which their locations were tied. The Report of Survey must describe the technique(s) used to establish GCPs and document the positions and residuals of all GCPs used to evaluate survey accuracy. The report must also describe all steps taken to calibrate each aircraft's onboard inertial measurement unit (IMU) and sensor offsets and settings.

In general, lidar surveys will be conducted in time periods of good weather without influence of snow, atmospheric aberrations (fog or smoke), or standing water. However, if there is a specific requirement for collection during a time period or event, the Contractor must consult with and gain approval from DNR in order to proceed in conditions that are less than favorable.

7. Deliverables

The required deliverables for each project through this contract are described below:

- **Survey report**—The survey report must be delivered in a digital text format, either .pdf or .docx is preferred. This report must include:
    - Project overview with information including project name, location map, date collection was ordered, acquisition window, delivery date, project AOI, project total area flown, specified units, coordinate system and datum, and list of options requested.
    - Description of LiDAR acquisition, including map of flightlines indicating dates of collection, table of acquisition parameters including information about the aircraft, sensor, acquisition settings, flight elevation.

- Report of the ground survey, including reference map and table listing monuments used and location, and a detailed description of GPS procedures used in establishing the reference network and control points for the project. A shapefile or other georeferenced digital format that records the location and height (orthometric) shall be included as a digital appendix to the report.
- Washington State licensed Surveyor certification.
- Calibration report for the system(s) used in the data acquisition.
- Specific information indicating what projection, datum, epoch of adjustment, and geoid was used for the survey.
- Contractor's assessment of accuracy, including relative (swath to swath) accuracy, absolute (with respect to GCPs) accuracy, presented both as summary statistics and in histogram form. Vertical accuracy shall be reported to meet the guidelines of the National Standard for Spatial Data Accuracy (Federal Geographic Data Committee (FGDC), 1998) and ASPRS Guidelines for Vertical Accuracy Reporting for Lidar Data (American Society for Photogrammetry and Remote Sensing (ASPRS), 2004).
- Contractor's assessment of pulse density over the project area, including maps showing design pulse density and ground return densities by quarter-quadrangle and histograms of both density parameters.
- Summary table of deliverables, listing file formats and total number and data volume of each deliverable, paths on the delivered hard drive, a standardized description of the data tiling scheme, and a checklist of all deliverables.

- **Ground control points**—A shapefile or other georeferenced digital format that records the location and orthometric height shall be included. Additional attributes that may be included are ellipsoidal height and a description of the ground cover type where the measurement was taken.
- **Aircraft trajectories**—Recorded aircraft trajectory data (Smoothed Best Estimate of Trajectory (SBET) files) must be in Esri shape file format or ASCII format, with aircraft position (easting, northing, and elevation), attitude (heading, pitch, roll, yaw) and GPS time recorded at regular intervals of one second or less. The data files may include additional attributes such as PDOP and estimated positional and velocity errors. Lidar flightlines shall also be provided as lines in Esri shapefile format, attributed with project name, and date of acquisition of each flightline.
- **All return point cloud**—The point cloud must be delivered as laser data (LAS) files, version 1.2 or higher, or as specified in a Purchase Order. LAS version 1.4 or most current version is preferred. The point cloud must list all valid returns, with all fields populated. LAS attributes must include, at a minimum, class number, class name, line number, GPS seconds per week, echo label (such as only, and last), easting, northing, elevation, intensity, scan angle, echo number, and system gain or scanner. At minimum, the USGS LiDAR specification 1.2 (USGS, 2014), or most current version thereof, point classification scheme should be used. Adhering to this basic point classification scheme will ensure projects can meet the USGS 3D Elevation Program requirements if needed at a later point. No points should retain a classification of ‘0’. Additional classification requirements are optional and may require an additional charge (see Section 8 for optional services and deliverables). Red, Green, Blue Infrared (RGBI) values must be attributed when applicable. No duplicate entries are permitted. Time must be reported to the nearest microsecond or better. Easting, northing, and elevation must be reported to the nearest 0.01 m (nearest 0.01 ft). Classification of ground returns must be as complete as is feasible and

without avoidable return misclassification. Point-Cloud LAS data must be delivered in 1/100th USGS 7.5-minute quadrangle (0.75 minute by 0.75 minute) tiles or as specified in a Purchase Order.

- **Bare earth surface model**—Raster of ground surface, interpolated via triangulated irregular network. Surface models shall have no tiling artifacts and no gaps at tile boundaries, or artifacts such as pits, birds, striping, or aliasing. Idealization of the landscape in the course of constructing surface models should be avoided. In particular, any triangulated network or grid from which ground surface raster models are interpolated should not include breaklines derived from other data sources. Areas outside survey boundary shall be coded as NoData. Internal voids (such as open water areas) shall be coded as NoData. Rasters shall be a 32 bit pixel depth floating point grid (IMG, GeoTiff, Esri grid format acceptable) at a 3 ft cell resolution (unless otherwise specified in the Purchase Order), snapped to the corner, and will be tiled to 1/4th USGS 7.5-minute quadrangle tiles.
- **First return surface model**—In addition to the bare earth model, a raster shall be generated from the highest collected return for each cell. Cells without first returns will be coded as NoData. This dataset must conform to the same file, grid format, and quality measures as the bare earth surface model.
- **Intensity images**—Raster of first-return intensity. Intensity shall have been normalized if the sensor or combination of sensors used on the project allows. Grids must be georeferenced 8-bit pixel depth (unless otherwise specified in the Purchase Order), grayscale GeoTiff format at a 1.5-ft cell resolution, and will be tiled to 1/4th USGS 7.5-minute quadrangles.
- **First return point density raster**—A raster showing the number of first return classified returns per resolution cell over the project area. Rasters shall be an 8-bit pixel depth grid (img, GeoTiff, Esri grid format acceptable) at a 98.5-ft cell resolution (equivalent to 30 m cell resolution, unless otherwise specified in the Purchase Order), snapped to the corner, and will be a mosaicked product to cover the entire project extent.
- **Swath density raster**—A raster showing the number of swaths collected per resolution cell. Rasters shall be an 8-bit pixel depth grid (IMG, GeoTiff, Esri grid format acceptable) at a 1,640.5 ft cell resolution (equivalent to a 500 m cell resolution, unless otherwise specified in the Purchase Order), snapped to the corner, and will be a mosaicked product to cover the entire project extent.
- **Pilot area**—For projects that are larger than 500 mi^2, the contractor shall provide a full set of deliverables over one 1/4th USGS 7.5-minute quadrangle tile over the project area. The pilot shall be delivered in advance of the final deliverables in order to allow DNR and any partners to evaluate the quality of the data, as well as formats and data structures.
- **Formal metadata**—See Section 10 for formal metadata requirements.

8. Optional Services and Deliverables

Several optional datasets, products, or specification changes may be requested by DNR in a Purchase Order for each new project. These options are enumerated below:

- **High resolution ground point density raster**—A raster showing the number of ground-classified returns per resolution cell over the project area. Rasters shall be an 8 bit pixel depth grid (IMG, GeoTiff, Esri grid format acceptable) at a 3 ft cell resolution (unless otherwise specified in the Purchase Order), snapped to the corner, and will be tiled to 1/4th USGS 7.5-minute quadrangle tiles.

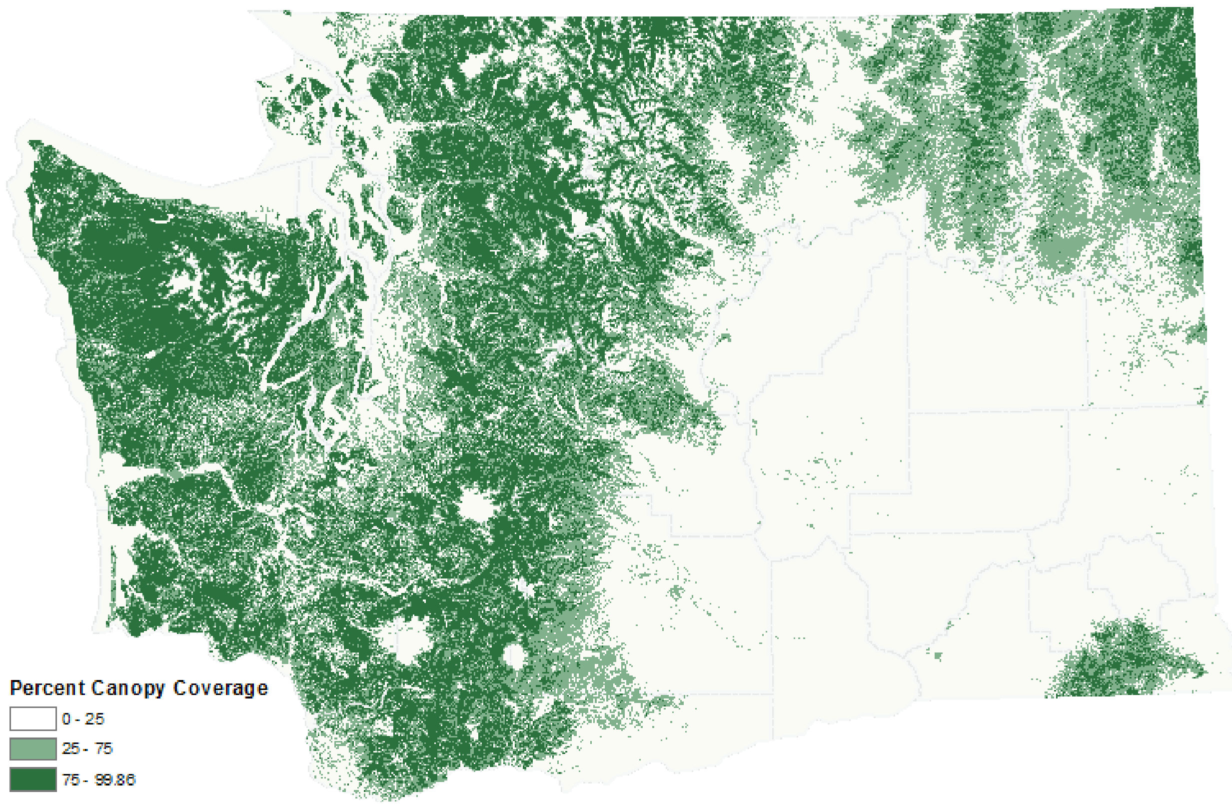


Figure B1. Percent canopy coverage across Washington State.

- **High resolution first return point density raster**—A raster showing the number of first return classified returns per resolution cell over the project area. Rasters shall be an 8 bit pixel depth grid (IMG, GeoTiff, Esri grid format acceptable) at a 3 ft cell resolution (unless otherwise specified in the Purchase Order), snapped to the corner, and will be tiled to 1/4th USGS 7.5-minute quadrangle tiles.
- **Collection of higher resolution data**—Under this option, the design pulse density of the project must be ≥15 ppsm.
- **Collection of lower resolution data**—By default, the design aggregate pulse density for each project under this contract will be ≥8 ppsm, as that has proved to have maintained both high quality and foliage penetration capability. However, there are several areas in Washington State that do not have dense canopy cover, and lower aggregate pulse densities may be appropriate. Given the percent canopy cover for the state in the figure above, 2 ppsm may be appropriate for 0–25% canopy, 4 ppsm for 25–75% canopy, and 8 ppsm appropriate for 75% canopy coverage and higher. Higher density collection may be required within this low density area for specific types of land cover; such as riparian or agricultural environments. For each project, the considerations for pulse density due to vegetation, intended application, and utility will be considered and must be approved by DNR before this option can be implemented in the Purchase Order. If a lower density option is approved, this may result in a reduction of collection costs.

- **Addition of hydro-flattened DEM**—DNR and its partners may choose to have additional bare-earth DEMs created, in which water bodies have been modified by the Contractor. All standard bare-earth DEM specifications apply except that, in addition, the Contractor will apply hydro-flattening to all water impoundments, natural or manmade, that are larger than two acres in area, to all streams that are nominally wider than 30 ft, and to all non-tidal boundary waters bordering the project area regardless of size. All bare-earth DEMs will be hydro-flattened as described in "Lidar Base Specification Version 1.2 (USGS, 2014), or the most current version thereof. Delivery of the breaklines used in hydro-flattening must also be provided, projected in the same coordinate reference system and units as the DEM, and saved in Esri feature class format with appropriate metadata.
- **Addition of hydro-enforced bare earth DEM**—DNR and its partners may require additional processing of the bare-earth DEM to include hydro-enforcement. This would require that overlaying culverts, bridges, and raised surfaces that obstruct the natural flow of water in a lidar representation be removed or edited in order to allow for correct hydrologic modeling. In this case, the final hydro-enforced DEM is required to have all culverts and obstructions removed, centerlines of streams and rivers which continuously flow downhill "burned" into the DEM, spurious pits or sinks filled, and water bodies such as lakes and reservoirs leveled according to hydo-flattened DEM standards. An additional section in the survey report describing the methodology used to hydro-enforce the DEM and verification of proper hydrologic flow is required under this option. Delivery of the bounding polygons of reservoirs and lakes, along with stream and river centerlines will also be provided, projected in the same coordinate reference system and units as the DEM, and delivered in Esri feature class format with appropriate metadata.
- **Consideration of tidal waters**—Tidal water bodies are defined as any water body that is affected by tidal variations, including oceans, seas, gulfs, bays, inlets, salt marshes, and large lakes. Significant value is gained by collecting these areas at low tide as additional ground is accessible and it allows for easier integration with bathymetric near shore data. However, incorporation of this requirement is challenging because low tide times vary significantly throughout the year, as well as the magnitude of the tide and geometry of the shoreline. Because of this, specified capture of low tidal conditions may bear additional cost. As it is the intent to represent as many ground points as possible, discontinuities along the shoreline that are the result of varying collection times will be retained in the data and DEM. Vertical and horizontal discontinuities within the water body resulting from tidal variations are expected and may be retained in the data and represented in the final DEM.
- **Bathymetric lidar**—Collection of bathymetric lidar may be requested by DNR and its partners to capture riverine systems, lakes, and the near shore environment. A green wavelength lidar sensor must be used to collect this data. All specifications for standard, topographic lidar collection will remain the same with the following exceptions:
  - Data voids within underwater areas will be allowed where depth and turbidity prevent returns from the bottom
  - Corrections shall be made for refraction
  - Vertical accuracy standards for submerged topography will be relaxed to 30 cm RMSE
  - Aggregate pulse density requirements will be reduced to 5 ppsm

- **Four-band orthoimagery fused with lidar point cloud**—DNR and its partners may require collection of 4-band orthoimagery over the same project area as lidar under this option. With this option, the lidar data acquired must be collected according to the same specifications as defined in this document with the addition of the RGB and infrared imagery information populated in the LAS files under the appropriate field within the header. Additional GCPs and aerial targets should be collected as necessary to perform bundle adjustments on the imagery. The orthoimages themselves must be supplied in an 8 bit GeoTiff format using the 1/100th quadrangle tiling scheme outlined in Section 9. Delivered orthoimages shall have 100% coverage without obvious tile boundary artifacts and minimum vertical offsets due to seam lines. All other parameters such as resolution, sun angle, degree of shadow in a scene, as well as timeframe for collected orthoimages in relationship to the lidar data, will be described in each Purchase Order in order to take varying requirements and seasonal conditions into consideration.
- **Corridor acquisition**—DNR may specify a linear feature like a road, stream, or utility corridor as the project area of interest. These features typically produce AOIs that do not meet the requirements for compactness, however represent important collection requirements. Corridor collection will meet all other specifications for a standard lidar collection, but may be subject to the differing costs defined by a linear mile of survey. All other options may be applied to a corridor collection.
- **Full classification of lidar point cloud**—Under this option, a full classification scheme for the point cloud will be specified in the Purchase Order. At a minimum, the classification values used should be those specified in the ASPRS LAS 1.4 specification (ASPRS, 2013) and the USGS Lidar specification 1.2 (USGS, 2014), or the most current versions of each. Other classification values can be used by the Contractor to denote more specific features, such as vehicles, paved and unpaved roads, wires, towers, railways, walls, and bathymetric features. Under this option, the additional classifications and requirements for feature sizes to be collected will be specified in the Purchase Order without limitation.
- **Supplemental vertical and horizontal accuracy assessment**—Additional accuracy assessments may be required in specific land cover classes or to evaluate the accuracy on steeper terrain. In this case, the Contractor will be required to collect at least 30 uniformly dispersed points in each land cover class as defined by the Purchase Order. Horizontal accuracy, while not typically required for lidar collections, may be requested. In this case, the use of reflective targets during acquisition or the collection of elevated control points (such as building corners and roof peaks) will be specified by the Purchase Order.
- **Precise Point Position (PPP) GPS methods**—For areas that are difficult to survey (see Section 5), use of Precise Point Position methods to process the data rather than use of a base station may be acceptable. Consultation with DNR and the Contractor is required to review survey difficulty, intent and desired accuracy for the collection, and other factors and to determine if a relaxation of survey techniques is warranted. If approved by DNR, this option will be implemented in the Purchase Order and may be associated with a reduction in costs.

9. Tiling Scheme, Naming Convention and File Formats

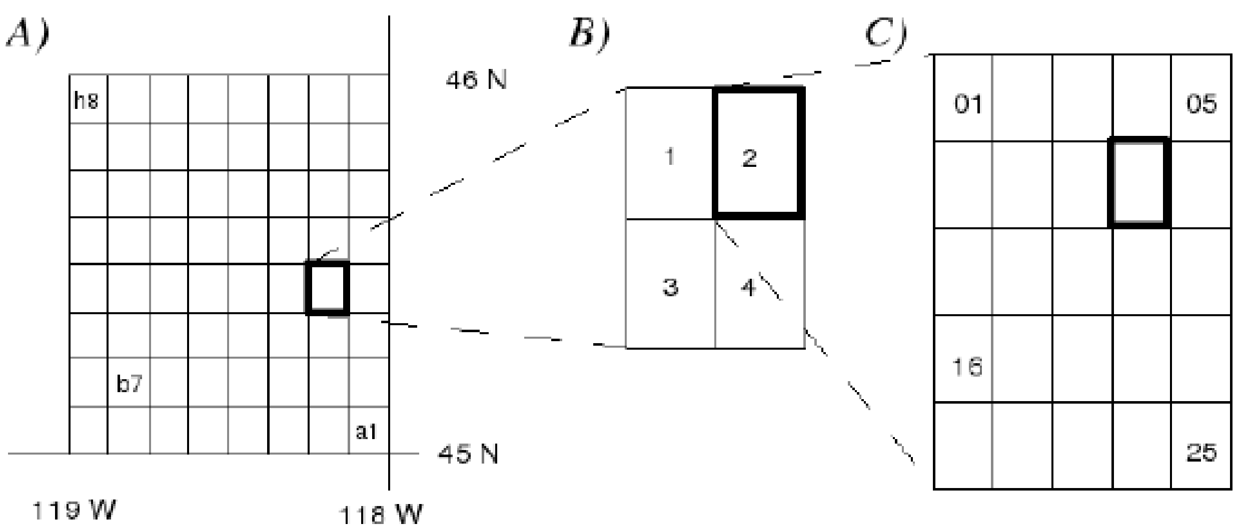
Data shall be delivered in tiles that are rectangular in geographic coordinates, correspond to standard USGS 7.5-minute quadrangles and divisions thereof, and are named according to the scheme:

qAAOOORCQ (quarter-quadrangle, 3.75-minute by 3.75-minute region)

qAAOOORCQNN (1/100th quadrangle, 0.75-minute by 0.75-minute region)

Where:

- AA is the integer north latitude of the SE corner of the 1° × 1° region that contains the quadrangle, OOO is the integer west longitude of the SE corner of the 1° × 1° region, R is the row, labeled from a to h, south to north, and C is the column, labeled from 1 to 8, east to west. That is, in diagram A below of the 1° × 1° region with a southeast corner at latitude 45°N, longitude 118°W, the highlighted quadrangle is q45118d2.
- Q is the quadrangle quadrant, which shall be numbered west-to-east, north-to-south, as is shown in Diagram B. That is, the highlighted quarter-quadrangle tile in diagram B is q45118d22.
- QNN identifies the 1/100th quadrangle, which shall be labeled by numbering the 25 divisions of each quarter-quadrangle west-to-east, north-to-south, as shown in Diagram C. That is, the highlighted tile in Diagram C is q45118d2209.



In general, a basic file structure for the deliverables should be adhered to as follows, unless otherwise specified by the Purchase Order:

<Project Directory>
- Metadata
- Point files
  - Classified LAS
- Raster files
  - Bare earth
  - Top surface
  - Intensity
- Vector files
  - Ground control
  - SBET files
- Survey report

The Contractor shall propose all details of file names, file formats, and file structure that are not specified here. The Contractor's proposed names and formats must be approved by DNR. GIS (Esri grids, shapefiles) must have complete and correct associated projection files. All files must be readable.

The Contractor shall reformat and re-deliver (1) any data that fail to meet format specification, (2) files with inconsistent or unreadable internal formats, or (3) GIS data with incomplete or incorrect associated projection files.

10. Formal Metadata Requirements

GIS-compatible data and files shall be explained with XML format metadata that follows the Federal Geographic Data Committee's (FGDC) Content Standard for Digital Geospatial Data. Metadata may be a single file that describes an entire survey or multiple files each of which describes a constituent part (for example, area A, area B, area C) of the survey. Metadata shall include, but are not limited to, the following:

Under Item Description

Title

Name of data file

Summary

An abstract summarizing the contents of the file including resolution and precision

Description

Project region, data description, units of measure, datum, tiling scheme

Time Period

Date(s) or range of dates of data capture

Data Set Credit

Name and address of the contractor who captured the data. Other credits can be listed to capture the explanation of the acquisition: funding agencies and partners, DNR as the administrator of the contract and provider of quality assessment

Use Limitations

No use limitations. The lidar data provided by the Contractor to DNR is in the public domain

Extent

Bounding coordinates for the project

Under Topics and Keywords

Theme Keywords

For example: Lidar, DEM, bare earth, DTM, DSM, elevation data, topography

Place Keywords

For example: Washington, county, region

Under Citation

Publication Date

Date of metadata publication

Under Citation Contacts

Responsible Parties

Contractor; sub-contractor (if applicable); funding contributors; data originator; QA responsible party; contact name, role, organization, and address

Under Resource Maintenance

Update Frequency

For example: "none planned" or "every 5 years")

Under Resource Constraints

Legal Constraints

Limitations of use

Under Spatial Data Organization Information

Indirect Spatial Reference

Tiling scheme if used

Under Spatial Reference

Horizontal Coordinate System Definition

Geographic coordinate system

Projected coordinate system

Horizontal datum

Ellipsoid name (the ellipsoid and the geoid model used to translate from ellipsoid to orthometric heights)

Horizontal units

Vertical Coordinate System Definition

Vertical datum

Vertical units

Under Data Quality

Process Step

Process description for manufacturer, model, and serial number of lidar instrument(s). May include separate specifications for scanning laser rangefinder, inertial navigation system, and GPS unit value(s) of instrument parameters during survey, including:

Nominal on-ground beam diameter

Pulse rate

Maximum number of returns recorded

Minimum separation between detected returns from a single pulse, expressed as a distance

Laser output power

Minimum return power required to produce a return

Beam wavelength

Frequency of GPS sampling

Frequency of IMU sampling

Nominal swath width

Nominal height of instrument above ground

Nominal single-swath pulse density

Nominal aggregate pulse density

Identity and assumed coordinates of reference survey monument(s)

Nature of vertical control (such as RTK GPS or water surface + tidal observations)

Calibration procedures

Return classification procedures

Positional Accuracy

Vertical Accuracy Report. Accuracy may be specified as RMSE or 95% confidence (indicate which). Vertical accuracy shall be reported for lidar measurements and, optionally, for the derived ground (bare-earth) surface model. XY accuracy of lidar measurements may also be reported. Shall include one or more of the following sections:

Accuracy as predicted by creator of survey

Accuracy as measured by creator of survey

Under Entity and Attribute Information

Overview Description, Entity, and Attribute Overview

Attribute descriptions if applicable (such as return point attributes in ASCII data or user bit field in LAS format). For all-return data, definition of return classification codes. Whether time is specified as GPS week and GPS second or Posix time. Any other relevant attribute information.

Under Distribution

Distributor

Distribution point of contact (for example 'Washington State Department of Natural Resources')

Standard Order Process

Ordering Instructions—web location, if applicable

Fees—There are no fees. This product is in the public domain‖

Distribution Liability

Absence of intellectual property restrictions

Under Metadata Reference Information

Metadata Contact

Details for author(s) of metadata

Metadata Standard Name

FGDC Content Standards for Digital Geospatial Metadata‖

Metadata Standard Version

FGDC version used

11. Delivery Schedule

The final delivery shall be made no later than 110 working days from end of data acquisition. The contractor should propose a preferred delivery schedule if additional processing and quality control time is anticipated. Contractor is encouraged to deliver products sequentially as they become available rather than all at one time. DNR will review and accept/reject products within 60 days of delivery.

Following a thorough Quality Assessment by DNR, data will be accepted or rejected based on specifications in this RFP. If it is determined that the delivered lidar data are insufficient to meet the RFP specifications, the Contractor will be required to reprocess and (or) re-fly problem areas within a timeframe agreed upon by DNR and the Contractor. In all cases, processing, delivery, acceptance, and payment must occur within a single biennium period.

12. Acceptance Criteria

Upon receipt of the deliverables, DNR staff will have 60 days to review the file structure, contents, reports, and products for compliance with the specifications of this document and those within the Purchase Order. If any deliverables do not meet the contract specifications, DNR staff will contact the Contractor for explanation, review, or redelivery to include but not limited to reprocessing or recollection of data or deliverables. If the data meets all specifications, DNR will officially accept the delivery and final payment will be issued.

Acceptance criteria will be based on the following quality assurance measures:

- Review of the survey report and deliverables to evaluate consistency with the Purchase Order and that stated formats, file volumes, and numbers are represented.
- Review of the naming convention and file structure to verify all files are present, valid (not corrupt), and can be read.

- LAS files reviewed for minimum and maximum file extents, projection, valid header information, and classification. Review of LAS statistics, such as maximum and minimum elevation and number of returns. Review of point classification to determine adherence to required classification scheme. Additionally, randomly selected 3,280 ft by 3,280 ft (approximately 1 × 1 km^2) areas will be selected to review point classification accuracy to ensure points have been reasonably portrayed, that no demonstrable errors are present, and that the classification scheme is applied consistently throughout the dataset.
- Swath to swath registration and vertical accuracy to test if specified tolerance is met.
- Void content will be reviewed to verify there are no voids due to clouds, instrument failure, or poor survey design or execution. Coverage will also be reviewed to ensure >90% overlap is maintained, as well as ground density tested to ensure ≥95% design aggregate pulse density conditions are met. For any random 98.5 ft by 98.5 ft (30 m by 30 m) area within swath overlap, first return aggregate pulse density must be ≥ 80% specified density.
- Bare earth model and first return surface model will be reviewed in terms of relative accuracy with regards to a reference DEM (lower resolution DEM to check overall terrain consistency), statistically to review outlier points, and visually to inspect unacceptable artifacts. Such artifacts may include, but are not limited to:
    - Seam lines produced from processing tiles or flight line misregistration
    - Scan line artifacts
    - Invalid bird/pit artifacts (spikes/wells)
    - Noise/improper filtering of the point cloud
    - Insufficient removal of vegetation or structures in the bare earth model

13. Intellectual Property Rights

DNR shall have unrestricted rights to all delivered reports and data. These reports and data will be placed within the public domain. This specification does not restrict the Contractor's rights to resell data, derivative products, or to reprocess data as the Contractor sees fit.

14. References

ASPRS, 2013, LAS Specification: Version 1.4–R13, July 2013. [http://www.asprs.org/wp-content/uploads/2010/12/LAS_1_4_r13.pdf]

ASPRS, 2014, Positional Accuracy Standards for Digital Geospatial Data, Version 1.0, November 2014. [http://www.asprs.org/a/society/divisions/pad/Accuracy/Draft_ASPRS_Accuracy_Standards_for_Digital_Geospatial_Data_PE&RS.pdf]

USGS, 2014, Lidar Base Specification, Version 1.2, November 2014. [https://pubs.usgs.gov/tm/11b4/pdf/tm11-B4.pdf]