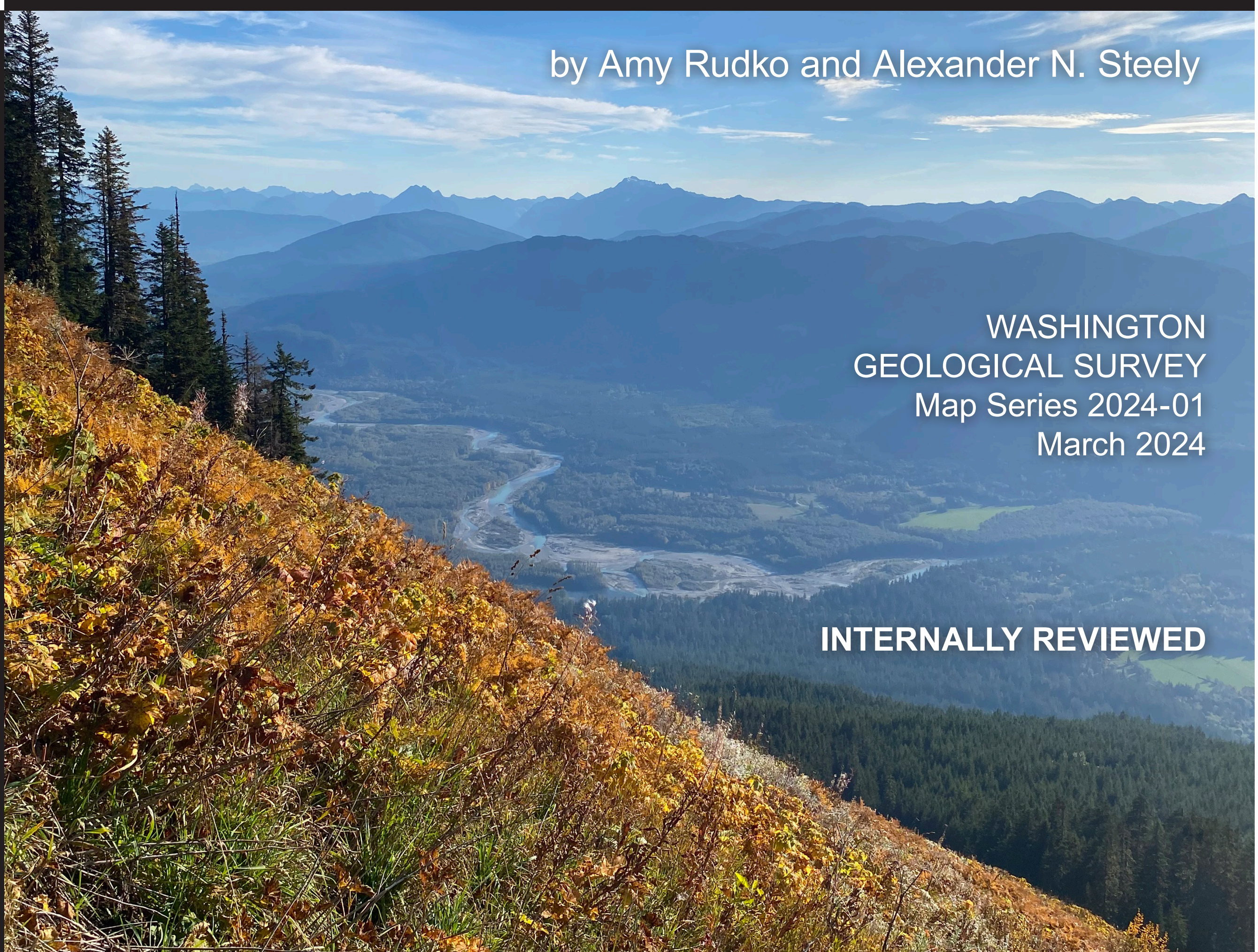
NATURAL RESOURCES

AGGREGATE RESOURCE INVENTORY OF SKAGIT COUNTY, WASHINGTON



by Amy Rudko and Alexander N. Steely

WASHINGTON
GEOLOGICAL SURVEY
Map Series 2024-01
March 2024

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WASHINGTON STATE DEPARTMENT OF
NATURAL RESOURCES
WASHINGTON GEOLOGICAL SURVEY

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This publication has been subject to an iterative technical review process by at least one Survey geologist who is not an author. This publication has also been subject to an iterative review process with Survey editors and cartographers.

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Cover Image: View to the south of the Skagit River from Sauk Mountain. Photo by Amy Rudko.

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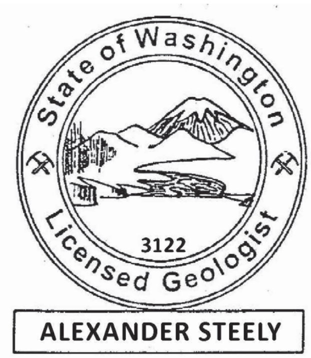

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ABSTRACT

This aggregate resource inventory for Skagit County identifies potential sources of aggregate—both sand and gravel, and bedrock (rock and stone)—using a combination of surficial and bedrock geologic mapping, subsurface information from boreholes and water wells, aggregate testing data, and records of current and historical mining activity. The aggregate resource classification scheme assesses both the quality and quantity of potential resources, and communicates that assessment using four classifications: Demonstrated, Inferred, Speculative, and Not a Resource. Areas that overlap with North Cascades National Park, Ross Lake National Recreation Area, federal wilderness areas, and National Wild River segment designations were not analyzed for this study. In total, our inventory classifies 319,431 acres of land as having the potential for economically significant aggregate resources, which is about 29 percent of the county's land area. For sand and gravel resources mapped as Demonstrated and Inferred (our highest-certainty resource classifications), we estimate 1.3 to 2.9 billion cubic yards of aggregate (2.1 to 5.3 billion tons). Due to the difficulty of quantifying the thickness of bedrock aggregate resources, we did not estimate their volume or tonnage.

Approximately 17,716 acres (6%) of areas we identify as potential sources of aggregate may be inaccessible for resource extraction because they are on land classified as developed according to the National Land Cover Database. A service-area analysis reveals a possible high stress on the limited number of active aggregate mines in the central and eastern portion of the county to serving the aggregate needs of maintaining Highways 20 and 530. An additional analysis explores opportunities to minimize transportation costs by prioritizing future sources of aggregate nearest to areas of aggregate demand. This assessment uses a road-network transportation analysis that identifies 41 percent of the aggregate resource areas in our inventory as being within a 20-mile driving distance from a variety of points of aggregate demand.

INTRODUCTION

Overview and Purpose

Sand, gravel, and bedrock may be mined or quarried to produce raw materials known as construction aggregate. Construction aggregate is used in the manufacturing of asphalt, concrete, and other critical materials for roads, homes, businesses, and bridges. While there are other types of aggregate, this project focuses on construction aggregate. The use of the term 'aggregate' throughout this pamphlet refers to construction aggregate. Effective planning for the needs and uses of aggregate resources faces a number of challenges. Although aggregate resources are sometimes thought of as ubiquitous, in reality they are deposited only in specific geologic areas, and their quality and quantity can vary significantly. Additionally, aggregate resources are not uniformly distributed throughout the state, and transporting these resources has many costs, including fuel and time spent on long deliveries, physical wear of roadways by large trucks, and greenhouse gas emissions. Furthermore, once land has been developed, any aggregate resources present beneath the surface are no longer accessible for extraction. For these reasons, identifying and protecting sources of aggregate is critical to promoting sustainable economic development and ensuring the health, safety, and high quality of life enjoyed by people in Washington State.

In 1990 the Washington State Legislature enacted the Growth Management Act (GMA) to guide planning for growth and development in Washington State. To meet the goals of Washington Administrative Code (WAC) 365-190-070, the Washington Geological Survey (WGS) is publishing county-scale aggregate-resource maps. These publications are intended to aid county and city planners and other local officials with land-use planning decisions related to identifying and designating aggregate resources of long-term significance. We also intend these publications to aid policy makers in assessing the importance of Washington State's nonrenewable sand, gravel, and bedrock resources. Furthermore, these publications may benefit engineers, transportation departments, and industry by identifying areas where geologic conditions suggest the presence of aggregate resources.

Inventory Products

This publication consists of two parts: (1) this pamphlet, which includes our rationale, data sources, methods, and a county-level summary of results; and (2) a Map Sheet that shows our resource inventory, the locations of active, historical, and small mines, aggregate testing locations, and subsurface record sites. The geospatial data used to develop the Map Sheet are available as a zip file download package with accompanying metadata on the *GIS Data and Databases* page on our website. An interactive web-based version of the multi-county Aggregate Resources Database is also available on the WGS Geologic Information Portal at geologyportal.dnr.wa.gov.

Study Area

Skagit County is located in northwest Washington, spanning the Puget Lowland to the North Cascades (Fig. 1). The population of Skagit County is approximately 129,253 according to the 2020 federal census. We do not intend for this publication to suggest that lands with aggregate resources and special ownerships or designations (such as county or state parks, tribal land, or conservation areas) should be re-designated to allow mining activities. Rather, we recognize that the underlying geologic phenomena that create aggregate resources do not stop at property boundaries, so we map their full geologic extent and entrust policymakers, land-use planners, and mine operators to make decisions that best implement their priorities and constraints. Approximately 240,000 acres of land within North Cascades National Park, Ross Lake National Recreation Area, Glacier Peak Wilderness, Mount Baker Wilderness, Noisy-Diobsud Wilderness, and Illabot Creek National Wild River designated area were not analyzed for this inventory because they have federal protection that restricts the development of new mines.

Previous Aggregate Resource Studies

Loen and others (2001) mapped a small portion of northwest Skagit County in a map titled "Reconnaissance investigation of Sand, Gravel, and Quarried Bedrock resources in the Bellingham 1:100,000-scale quadrangle." The map focused on active permitted mine sites at the time of its publication.

Dethier and Safioles (1983) mapped potential sand, gravel, and quarry rock sources in the Port Townsend 1:100,000-scale quadrangle, which includes a portion of southwest Skagit County. The scope of their work included material of lower quality than our study's quality threshold standards. Both Loen and others (2001) and Dethier and Safioles (1983) were reviewed for this aggregate resource inventory of Skagit County.

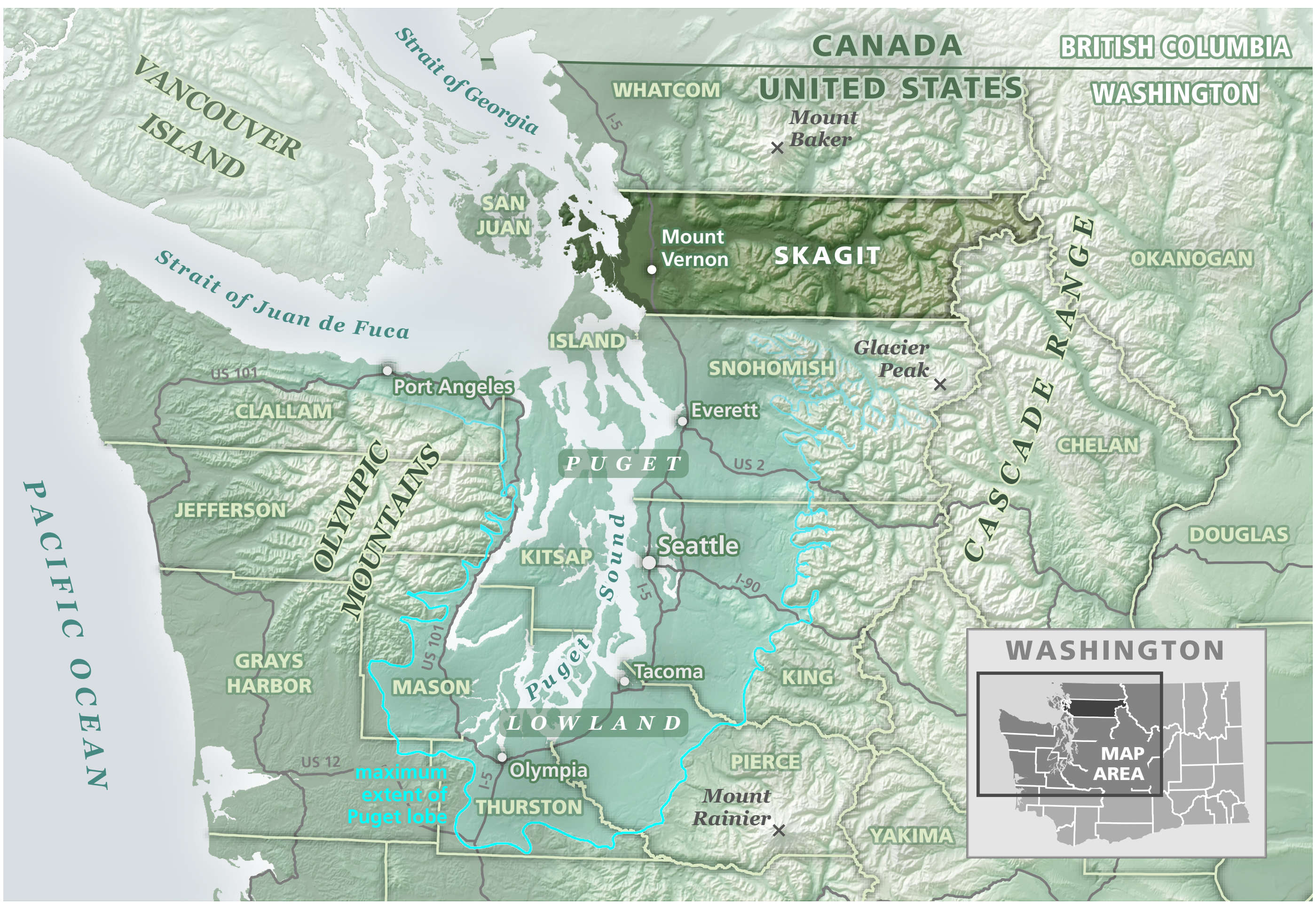

Figure 1. Location of the study area, Skagit County, within western Washington State. Blue line indicates the maximum extent of the Puget lobe. We omit the maximum extent of the Puget lobe from the northern portion of the map because its location is uncertain there.

GEOLOGY OF AGGREGATE RESOURCES IN SKAGIT COUNTY

Here we summarize the geologic history of Skagit County as it relates to aggregate resources. Our aim is to explain the geologic processes that control the distribution of aggregate resources, providing the reader with a sense for the natural systems that our methods quantify. For further details and discussion of the geologic history of this region, the interested reader should consult the detailed and well-written geologic unit descriptions and summaries provided in the source maps for this report, which are listed on the Map Sheet.

Summary Geologic History

ACCRETED TERRANES

The complex geology of the North Cascades arises from sustained subduction along the western margin of North America, resulting in the accretion of many terranes. These accreted terranes are grouped into three domains: the Northwest Cascades Thrust System, the North Cascades Crystalline Core, and the Methow terrane, the last of which is only partially included in the study area. Each domain contains multiple accreted terranes, as well as plutons that intruded the terranes during accretion. The Northwest Cascade Thrust system includes rocks of the Nooksack Formation, Chilliwack River terrane, Bell Pass mélange, and the Easton Metamorphic Suite. (Tabor and others, 2003; Lapen, 2000). These terranes have been thrust over each other, folded, uplifted, and eroded, exposing rocks from a range of depths with different ages and characteristics (Tabor and other, 2003). The Chuckanut Formation was then deposited over the top of this thrust system, and intruded by volcanoes and plutons (Tabor and others, 2002). The North Cascades Crystalline Core includes rocks of the Chelan Mountains terrane, Skagit Gneiss Complex, and many different plutons and batholiths, among others unlisted here (Tabor and others, 2003; Lapen, 2000). Bordered by the Straight Creek fault on the west and the Ross Lake fault zone on the east, the rocks of the North Cascades Crystalline Core have been uplifted 15–25 km relative to its adjacent domains (Tabor and others, 2003). The Methow terrane just barely crops out in the study area in the far eastern tip of the county. The rocks in this domain that are relevant to the aggregate study area are the intrusive Golden Horn and Black Peak batholiths (Stoffel and McGroder, 1990). On the far west side of the county, the geologic history of accreted terranes continues. Fidalgo Island is made up of the Fidalgo ophiolite sequence, part of a terrane accreted to North America during the Cretaceous (Washington Geological Survey, unpublished geologic map of the Port Townsend 1:100,000-scale quadrangle, 2024).

VOLCANIC HISTORY

During the Eocene, eruptive events produced the Barlow Pass Volcanics, Oso Volcanics, and other unnamed volcanic rock. These Eocene volcanic rocks range from basalt to rhyolite and include some sedimentary interbeds (Dragovich and others, 2002a, 2002b, 2003a, 2003b, 2004a, 2004b, 2006).

Subduction driven arc-volcanism initiated around 40 Ma, depositing a range of volcanic rocks and emplacing multiple plutons throughout the area. Later uplift and erosion removed these surficial volcanic deposits, exposing deeper plutons and batholiths which are the only surviving evidence of the earliest phase of volcanism. The ongoing modern phase of Cascade arc-volcanism started 5–7 Ma, producing a number of active volcanic vents between British Columbia and northern California, including Mount Baker and Glacier Peak near the study area (Hildreth, 2007). Glacier Peak is located south of the study area, but deposits from its many eruptive events over the last 15,000 years have traveled through the study area via the Sauk and Skagit Valleys (Tabor and others, 2002).

FRASER GLACIATION

Skagit County has been glaciated many times in the past two million years. During the most recent glacial event—the Fraser glaciation—a thick ice sheet known as the Puget Lobe overrode most of Skagit County. As the ice sheet advanced, it deposited advance outwash and lacustrine deposits, then overrode those deposits with ice-contact and sub-glacial deposits such as till. By about 16,000 years ago, the Puget Lobe reached its maximum extent south of Olympia, about 100 miles south of Skagit County (Fig. 1; Polenz and others, 2015). As the ice sheet continued to recede, meltwater and glacial deposits from the ice sheet flowed into a glacial lake that occupied the drainages of the Skagit, Sauk, and Baker rivers. The retreat of the ice sheet out of the Puget Lowland was interrupted by a brief readvance called the Sumas stade. The Sumas stade moved the glacial terminus to just north of Skagit County. Glacial outwash from the Sumas stade traveled south through the Samish River valley toward the Skagit River valley, depositing outwash and glacial delta deposits near the Butler Hill area in northern Skagit County (Dragovich and others, 1998). When the ice sheet had receded enough to expose the Strait of Juan de Fuca, drainage from the North Cascades to the Pacific Ocean was re-established.

Sand and Gravel Resources

For the purpose of this effort, we found it helpful to generalize previously mapped geologic units into simplified categories relevant to aggregate resource quality. The following sections provide brief summaries of these geologic materials. In general, the following geologic deposits are good sources of sand and gravel in the study area.

VASHON-AGE GLACIAL OUTWASH DEPOSITS

Geologic environments where there is good hydraulic sorting and rounding provide the highest-quality aggregate. For this reason, large modern and ancient river systems are often excellent sources of aggregate resources. A typical succession of glacial deposits in the study area includes sediments deposited by river systems emanating from the advancing glacier (advance outwash), deposits of the glacier itself as it advances and overrides its outwash plain (glacial till), and deposits from the river system emanating from the glacier as it retreats (recessional outwash). While the till directly deposited by glaciers does not typically produce good aggregate, the voluminous rivers of meltwater that emanate from glaciers efficiently round and sort the material crushed by the glacier into high-quality aggregate. Therefore, Vashon-age glacial outwash deposits are excellent sources of aggregate.

In Skagit County, we interpret advance outwash, recessional outwash, recessional alluvial fans, and glacial deltas as generally excellent sources of aggregate; many sand and gravel aggregate mines work in these deposits. Ideally, for aggregate extraction, the advance and recessional outwash would be separated by only a thin layer of till, making it possible to mine both deposits in one location. However, the reality of glacial deposition is more complex. During glacial advance, meltwater rivers deposit outwash sand and gravel in front of the glacier. Continued advancement leads to the glacier over-riding the advance outwash deposit and either scouring it away or covering it with a layer of glacial till. As the glacier retreats, it leaves behind a modified landscape of elongated hills and valleys (drumlins) and ice-dammed lakes. Meltwater from the glacier continues to flow through this modified terrain, depositing recessional outwash into low-lying areas of the landscape and forming deltas where rivers flowed into large lakes. These depositional processes produce varying thicknesses of glacial till between outwash deposits, complicating the accessibility of advance outwash deposits below the glacial till.

VASHON-AGE GLACIAL ICE-CONTACT AND ICE-MARGINAL DEPOSITS

Though the direct deposits of glacial ice (till or diamicton) are generally unsuitable for aggregate, other near-glacier deposits can be excellent sources of aggregate. We interpret near-glacier deposits that have a strong indication of the influence of moving water as potential sources of aggregate, such as eskers, kame terraces, stratified drift, ice-contact deposits, kame and kettle deposits, and pockmarked terrain. We consulted lidar elevation data extensively during the classification of these geologic deposits to ensure that surfaces that clearly had glacial drumlins (indicating the likely presence of glacial till) were classified as Not a Resource.

NONGLACIAL ALLUVIUM

Alluvium is a deposit left by a stream or river. For the purposes of this study, we refer to the generalized unit of alluvium (or older alluvium) as deposits left by non-glacial streams or rivers. Where a river is large enough to round and sort the material it carries (such as large modern rivers from the North Cascades), their deposits can be suitable for aggregate. Where alluvium is deposited by small and (or) intermittent streams, there is usually insufficient sorting and rounding, and the deposits are typically quite thin. Because of this, we generally only consider alluvium from large river systems to be suitable for aggregate, and usually require additional evidence to classify any alluvium deposits as potential sources of aggregate. Although large volumes of aggregate may exist along many river channels, alluvial mining can cause adverse impacts to aquatic and riparian habitat. Because of these concerns, environmental analyses related to the permitting and development of these potential aggregate sources should be done with great care (Norman and others, 1998). Further, under the National Wild and Scenic Rivers System, rivers classified as Scenic and Recreational have regulations that allow new mining operations, but with additional regulations. Below we discuss the depositional histories of the Skagit, Sauk, and Samish Rivers as they relate to aggregate resources in the study area.

Skagit River

Alluvial deposits in the Skagit River valley are sourced from metamorphic, plutonic, and volcanic rocks with reworked glacial deposits (Dragovich and others, 1998, 1999, 2000a, 2000b, 2004b). We generally map these deposits as sand and gravel resources based on the geologic unit descriptions, the geomorphology of the river, mining activity, and subsurface data availability and consistency. Starting in the northeast corner of the county, the Skagit River transitions over the course of about 50 river miles from a confined river valley to a highly sinuous river in a widened valley (J. Riedel, S. Sarrantonio, G. Seixas, J. Chan, North Cascades National Park unpub. report, 2022). Here, the high energy of the Skagit River lends to sufficient sorting and rounding for aggregate materials.

Beyond this portion of the Skagit River, although the subsurface records are more abundant, they describe less consistent quality sand and gravel deposits and increased fines and clay deposits as expected in a lower energy fluvial system. Where the Skagit River broadens into the Skagit River Delta, the potential for abundant sand and gravel diminishes. This area of the fluvial system includes nearshore and marsh deposits that do not contain quality aggregate materials. Therefore, they are classified as Not a Resource.

Sauk River

Sauk River alluvial deposits are sourced from eroding glacial deposits and Glacier Peak volcanic deposits from several eruptive events. During the Fraser glaciation, the Sauk River valley was influenced by glacial ice and deposits. For most of the Fraser glaciation, a large plug of glacial deposits to the west of the confluence of the Skagit and Sauk Rivers forced the Skagit River to drain south along the modern Sauk River channel instead of west along the modern Skagit Valley. Extensive recessional, ice-contact, and glacio-lacustrine deposits were deposited in the Sauk River valley at this time. As the Puget Lobe ice sheet receded north, the Skagit River breached the glacial deposit barrier and diverted its flow direction from the Sauk River basin to the modern Skagit River basin (Tabor and others, 2002).

An additional important influence on the course of the Sauk River is Glacier Peak, a volcano that has erupted many times in the last 15,000 years. Glacier Peak's volcanic deposits filled in the river basin, changing the flow direction of the Sauk River from southward to its modern northward course. Glacier Peak's volcanic deposits in the Sauk River valley include pyroclastic flows and lahar deposits, both of which include a mixture of ash, angular dacite fragments, and pumice (Tabor and others, 2002). Much of the Glacial Peak volcanic deposits are too weak to be considered a quality aggregate source. However, since alluvium in the Sauk River valley is a mixture of glacial deposits (higher quality) and volcanic deposits (lower quality), we generally classify sand and gravel resources in this area as Speculative.

Samish River

Samish River alluvial deposits are sourced from local metamorphic rocks and reworked glacial deposits. Near the end of the Fraser glaciation, glacial outwash from the Sumas stade traveled south through the Samish River valley toward the Skagit River valley, depositing outwash and glacial delta deposits near the

Butler Hill area in northern Skagit County. A thin veneer of Samish River alluvium, averaging about 24 ft thick, overlies these glacial deposits (Dragovich and others, 1998). Generally, we classify these as Speculative sand and gravel resources.

DEPOSITS THAT ARE TYPICALLY NOT A RESOURCE

In general, the following geologic deposits are not suitable sources of sand and gravel aggregate in the study area. In rare cases, some of our identified resource areas may intersect with these surficial geologic deposits if we found alternative data sources suggesting a good source of aggregate is present in the subsurface.

- Unsorted deposits (clay through boulders) that are compact (hard) are characteristic of deposition beneath a glacier; these glacial till deposits are unsuitable for aggregate due to their high clay and silt content and the difficulty of mining them. For similar reasons, we excluded drift, glaciomarine drift, and pre-Vashon-age glacial till or diamicton.
- Poorly sorted deposits often include clay and silt, which make it difficult to produce clean aggregate. Because of this, we generally interpret deposits such as alluvial fans, alluvium from small streams, old alluvium, altered land, and artificial fill as unsuitable for aggregate.
- Deposits that contain abundant fine-grained material (silt and clay) and (or) organic material (peat) are also unsuitable for aggregate because they typically do not contain sufficient sand and gravel. Because of this, we excluded glacio-lacustrine deposits, wetland deposits, peat or marsh deposits, and beach or nearshore deposits.
- Glacier Peak Quaternary volcanic and sedimentary deposits form extensive terraces in the drainages of the Suiattle, White Chuck, Sauk, and North Fork of the Stillaguamish Rivers. These volcanic deposits consist of lahars, pyroclastic flow deposits, alluvium, and reworked ash and silt (Tabor and others, 2002). These deposits are generally unsuitable for aggregate due to excessive fines and abundant weak, vesicular clasts.

Bedrock Resources

IGNEOUS BEDROCK

Eocene Volcanics

Rocks of the Barlow Pass Volcanics, Oso Volcanics of Vance (Dragovich and others, 2003a, 2003b, 2004b), and other Eocene volcanic rock (Dragovich and others, 2002a, 2002b, 2003a, 2004a, 2006) range from rhyolite to basalt, include intrusive dikes, extrusive flows and tuffs, and various amounts of interbedded sandstone. In general, we classify these units as a Speculative source of aggregate. Tabor and others (2002) describe the Barlow Pass Volcanics in the Sauk River 1:100,000-scale geologic map as containing primarily sandstone rather than volcanic rock. In this area we classify the rocks of the Barlow Pass Volcanics as Not a Resource.

Stocks, Plutons, and Batholiths

Intrusive igneous rock bodies, including stocks, plutons, and batholiths, are abundant in the study area. These rocks represent large volumes of magma that slowly cooled below the Earth's surface. The study area includes the following mapped igneous intrusions: Golden Horn batholith, Black Peak batholith, Stock at Granite Lakes of Tabor and others, Chaval Pluton, Hidden Lake Stock, Jordan Lakes Pluton, and Granodiorite of Mount Despair (Tabor and others, 2002, 2003; Stoffel and McGroder, 1990). We interpret these units as potential sources of aggregate and generally classify them as Inferred or Speculative.

METAMORPHIC BEDROCK

In general, metamorphosed igneous rocks are durable enough to be used for aggregate, and metasedimentary rocks are not. Many of the accreted terranes in the study area contained both igneous and sedimentary parent rocks before they were metamorphosed. Where metasedimentary units were mapped in detail and abundance, we classify these weaker units as Not a Resource.

San Juan and Fidalgo Islands

Fidalgo Ophiolite Complex

The Fidalgo Ophiolite is a sequence of rocks interpreted as a slice of oceanic crust sourced from a volcanic arc (Brown, 1977). From bottom to top, this includes ultramafic rock, layered gabbro and pyroxenite, sheeted dikes, extrusive volcanic rock, deep sea sedimentary rock, and turbidites (Washington Geological Survey, unpublished geologic map of the Port Townsend 1:100,000-scale quadrangle, 2024). Of these units, the meta-igneous rocks are interpreted as potential aggregate resources based on their geologic unit descriptions and successful mining activity. Within the 1:24,000-scale Anacortes South and La Conner quadrangles (Dragovich and others, 2000a), where the ophiolite sequence is mapped in detail, we did not consider the metasedimentary rock as a source of aggregate.

The Lummi Formation

The Lummi Formation is a package of oceanic rock that crops out in the eastern San Juan Islands (Lapen, 2000). The formation includes metamorphosed sedimentary and igneous rocks. The metabasalt and metagabbro are interpreted to be potential sources of aggregate based on their geologic unit descriptions.

Goat Island Terrane

The Goat Island terrane contains mid-ocean ridge basalt, ultramafic rock, greenstone, and metasedimentary rock (Dragovich and others, 2004b). In the study area, there are just a few outcrops of greenstone that we speculate to be potential sources of aggregate based on their geologic unit description.

Northwest Cascades Thrust System

Greenstone of the Helena-Haystack mélange

The Helena-Haystack mélange is characterized by blocks of a wide variety of lithologies in a serpentinite matrix (Tabor and others, 2002). Greenstone blocks erode out of the matrix as steep resistant mounds. We speculate these greenstone blocks to be a potential source of aggregate based on their geologic unit description and the existance of several small mining operations.

Greenstone of the eastern mélange belt

The eastern mélange belt is characterized by mafic volcanic rock, chert, and ultramafic rock (Tabor and others, 2002). We classify the greenstone unit in the mélange as a Speculative source of aggregate.

Exotic Rocks of the Bell Pass mélange

The Bell Pass mélange includes schist, gneiss, meta-igneous rock, as well as a variety of exotic clasts in a matrix of phyllite and semischist. This jumble includes meta-igneous rocks, exotic blocks of gneiss from the Yellow Aster Complex, and ultramafic rocks from the Twin Sisters Dunite (Tabor and others, 2003). In general, we speculate the exotic gneiss and dunite are a potential source of aggregate based on their geologic unit descriptions.

North Cascades Crystalline Core

Chelan Mountains Terrane

The Chelan Mountains terrane includes rocks of the Cascade River Schist, the Napeequa Schist, and meta-igneous rocks of the Marblemount pluton (Tabor and others, 2002). In general, we interpret the meta-quartz diorite and Flaser gneiss of the Marblemount pluton to be potential excellent sources of aggregate based on their geologic unit descriptions, passing materials testing data, and successful mining history.

Skagit Gneiss Complex

The Skagit Gneiss Complex includes banded gneiss and orthogneiss (Tabor and others, 2003). In the study area, Eldorado orthogneiss, orthogneiss of Marble Creek, and Tonalite of Cascade Pass are considered potential sources of aggregate based on their geologic unit descriptions.

Easton Metamorphic Suite

The Easton Metamorphic Suite includes the Shuksan Greenschist and Darrington Phyllite units (Tabor and others, 2003). The Shuksan Greenschist has undergone high-pressure, low-temperature metamorphism, resulting in a unit that includes varying rock qualities. In the study area, the Shuksan Greenschist is widespread, but lacks abundant materials testing data and successful mining history. In general, we speculate that the Shuksan Greenschist could be a potential source of aggregate. However, prior to mining we suggest gathering more site-specific information to ensure its quality is high enough to pass materials testing requirements.

BEDROCK TALUS

In the North Cascades there are areas of loose, unconsolidated, and unsorted sedimentary deposits mapped as talus or talus-like deposits (Stoffel and McGroder, 1990). When mapped adjacent to igneous or metamorphic bedrock units classified as potential rock and stone resources, such as granitic batholiths, these bedrock talus deposits are classified as potential resources as well.

ROCKS THAT ARE TYPICALLY NOT A RESOURCE

Typically, sedimentary bedrock units do not meet the minimum quality threshold to be considered a quality, durable aggregate source. Sedimentary rocks are typically fragile, soft, or brittle. Due to these qualities, fluvial sedimentary units, marine sedimentary units, and volcaniclastic units are not considered potential aggregate resources. This includes rocks of the Chuckanut Formation, rocks of Bulson Creek, the sandstone interbeds of the Barlow Pass Volcanics, and various marine sedimentary rock units throughout the study area.

Limestone, however, is an outlier to our sedimentary bedrock generalization as it can be used both as a crushed-stone aggregate and as an essential chemical ingredient of cement (Danner, 1966). These are two different commodities that have different chemical and physical requirements. For the scope of our project, we only consider the crushed-stone use of limestone. Historically near the town of Concrete, limestone of the Chilliwack Group has been mined for use in cement production (Horton and San Juan, 2016), indicating that it has the correct chemical properties for cement products. However, modern aggregate testing indicates that rocks of the Chilliwack Group do not meet the physical quality threshold for crushed-stone aggregate (Washington State Department of Transportation, 2023a). We encourage readers who are interested in limestone sources for cement production to consult geologic maps and other data to learn more about this specific resource.

Like sedimentary rocks, metasedimentary rocks typically do not meet our quality threshold criteria. For this reason schist, phyllite, and metachert rocks are not considered potential aggregate resources, so we classify them as Not a Resource. This includes the Darrington Phyllite, Mount Josephine semischist and phyllite, metagreywacke of the Lummi Formation, metasedimentary rocks of the Helena-Haystack Mélange, Rinker Ridge slate and phyllite, metasedimentary rocks of the Chilliwack Group, metasedimentary rocks of the eastern mélange belt, Cascade River Schist, Napeequa Schist, Chiwaukum Schist, metasedimentary rocks of the Goat Island terrane, and the metasedimentary rocks of the Fidalgo Ophiolite sequence (Tabor and others, 2002; 2003; Lapen, 2000; Washington Geological Survey, unpublished geologic map of the Port Townsend 1:100,000-scale quadrangle, 2024).

A NOTE ON ULTRAMAFIC ROCK

Ultramafic rock has the potential to contain asbestiform minerals. Asbestos is the general term for several minerals belonging to the serpentine and amphibole groups that have similar properties. Asbestiform minerals are composed of very thin, long fibrous crystals that can be harmful to humans. Asbestos is frequently associated with serpentinite and partially serpentinized ultramafic rock (however, not all ultramafic rock is serpentinite bearing). For this project we did not exclude areas that have been mapped as potentially bearing asbestos, such as historical mine sites that have produced asbestos or asbestos byproducts. We encourage land use planners to review the hazardous mineral datasets available on the Washington Geological Survey's Geologic Information Portal and any site-specific information as they make their mineral resource lands decisions.

METHODS

Overview

To map aggregate resource areas, we compiled geologic units from previously published geologic maps and refined their geometry based on subsurface geology, aggregate testing, and current and historical mining activity. We classified potential aggregate resources based on the quality, quantity, and certainty of the resource, and then performed proximity and land-use analyses on the results.

This section describes the data we used, our resource classification scheme, and our classification workflow. We also describe how we calculated the volume and tonnage of resources, how we determined how much of our classified resource areas are inaccessible due to land-use development, and how we calculated the proximity of resources to potential aggregate markets.

Sources of Data

In preparation for classifying aggregate resources throughout the study area, we compiled surficial and bedrock geologic mapping, subsurface information from boreholes and water wells, aggregate testing data, and any other available datasets. These data sources are described in more detail in the sections below.

SURFACE GEOLOGY DATA

Geologic maps vary in the level of detail they provide about the types of rocks and deposits that yield usable aggregate. In general, the most-detailed mapping is completed at 1:24,000 scale, and these publications often have excellent descriptions of the geologic units that were mapped. For this analysis, the most useful 1:24,000-scale geologic maps are those that have a lidar basemap (typically those published in the mid-2000s and thereafter), as these provide a high level of detail for mapping the extent of different geologic units. Where 1:24,000-scale geologic maps are not available, we used less detailed 1:100,000-scale maps. We utilized the geology of the Port Townsend quadrangle from a new lidar-informed 1:100,000-scale map that is nearing completion but not yet published.

We compiled the surface geology from all published geologic maps within Skagit County with scales greater than or equal to 1:100,000 (see geologic data sources on the Map Sheet). There are fourteen 1:24,000-scale maps in Skagit County covering about 40 percent of the county. Two of these maps have a lidar basemap.

SUBSURFACE DATA

Two main data sources provide direct information about materials found underground, and both require drilling. The first is water wells, which are drilled in a variety of locations, most commonly for residential water supply. While drilling water wells, the driller notes what type of material they are drilling through and this information is provided to the Department of Ecology, where it is made publicly available. The other type of subsurface information comes from geotechnical borings. Similar to water wells, these are holes drilled in the ground, but they differ in that the materials are reviewed and described by a trained professional for the purpose of evaluating the geotechnical properties of the subsurface. Therefore, the information from geotechnical borings is often much more detailed and accurate. However, most borings are relatively shallow (typically less than 20 ft) whereas water wells often reach depths of a few hundred feet.

We used both water wells and geotechnical borings to help constrain the thickness of potential resources and to identify and characterize the thickness of overburden (sediments above an aggregate deposit that must be removed before mining). Subsurface data enable us to identify areas where a resource exists beneath a thin layer of material that we would not classify as a resource based only on the geologic mapping (for example, a thick layer of outwash sand and gravel beneath a thin layer of glacial till at the surface).

To compile subsurface records for our analysis, we gathered records from a subsurface database developed by WGS (Washington Geological Survey, 2023a). The subsurface database contains records from many sources including water wells and geotechnical boreholes. In total, 696 subsurface records were used for this project.

AGGREGATE TESTING DATA

In order to determine the quality of potential aggregate resources, we reviewed aggregate testing data that assess the ability of a given sample to withstand the standard Los Angeles (LA) Abrasion test and the Washington Degradation test. Our aggregate quality threshold required an LA Abrasion test result of <30 percent and Washington Degradation test result of >30 percent, as specified in the 2023 standards for Hot Mix Asphalt (HMA). Current and historical test data are available from the Washington State Department of Transportation (WSDOT) Aggregate Source Approval (ASA) database (WSDOT, 2023a). For this project, WSDOT provided us with test-site spatial data that are viewable on their ASA Web Mapping App. We downloaded and digitized all available ASA report attributes to the site location data for the county (161 sites and 167 test results). Sometimes these reports only include a test result from just the LA abrasion or the Degradation tests. For these partial reports, we interpret the result as Incomplete Pass or Incomplete Fail, depending on the result from the available test. In addition to WSDOT data, we collected one sand and gravel sample and six bedrock samples in summer 2023 from gravel pit and bedrock quarry sites located on land managed by Skagit County and the Washington State Department of Natural Resources (DNR). These samples were tested by WSDOT's Materials Lab and the results are reported in Appendix A. Our samples represent a broader range of rocks and deposits than the existing testing data captured.

SURFACE MINE LOCATION DATA

We used the locations of active, inactive, historical, and state operated aggregate mine sites to help guide our classification of resources. We assumed that active permitted surface mines are likely located in good sources of aggregate, while inactive, historical, and small mining operations may be located in good sources of aggregate, but with less certainty. We accessed the locations of current active permitted mines from the DNR Surface Mine Reclamation Program (SMRP) database (Washington Geological Survey, 2023b), and were provided access to SMRP records of inactive (cancelled or terminated) permitted mines,

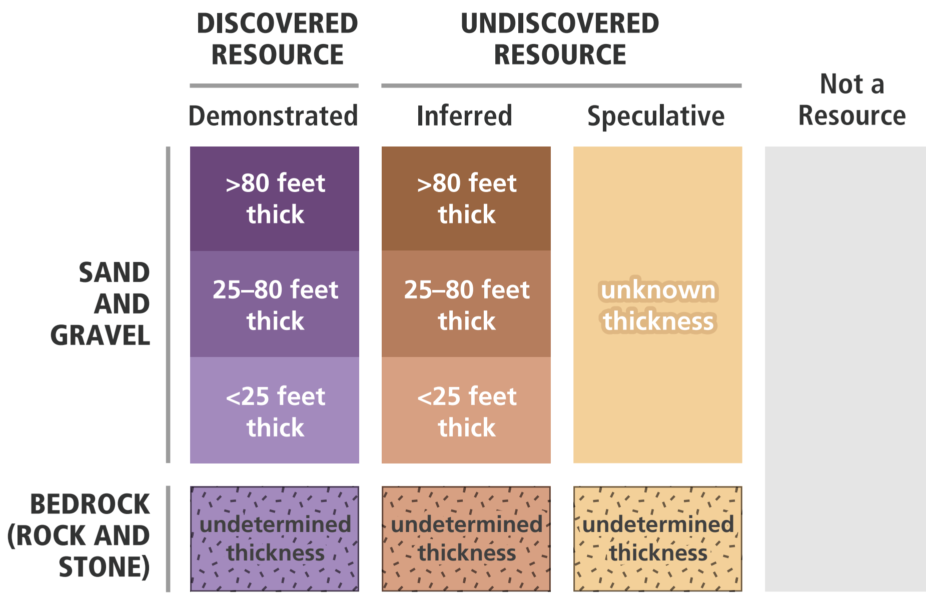

Figure 2. Generalized aggregate resource classification scheme used in this study. In general, the level of knowledge and certainty decreases from Demonstrated resources to Speculative resources; regions classified as Not a Resource may or may not have a high level of knowledge and certainty. Note that bedrock resources are mined for rock and stone commodities and we use these terms interchangeably.

permit boundaries, and reclaimed boundaries (Robert Berwick, Washington Geological Survey, written commun., 2023). As of September 2023, there were 34 active permitted mines and 56 inactive (cancelled or terminated) permitted mines in Skagit County. In addition, we received information from SMRP's Chief Reclamation Geologist and regional surface mine specialist on active permitted sites that have transitioned from resource extraction to site reclamation (Rian Skov and Joe Lydon, Washington Geological Survey, written commun., 2023). We also included prospect- and mine-related point features (points that were not included in the SMRP database) from 1952–1998 digitized USGS topographic maps (Horton and San Juan, 2016). This included 93 gravel, borrow, or sand pits and 56 open pit mines or quarries within Skagit County. From DNR's managed lands database we included 81 rock pit locations on DNR-managed lands. These point locations could represent active or inactive pits, quarries, or stockpiles on DNR-managed lands and are primarily used as sources of rock for forest roads used for timber sales.

LIDAR

Airborne lidar is detailed topographic data collected by airplane, typically with a horizontal resolution of 3 ft and a vertical accuracy of <1 ft. It provides a detailed view of the land surface that can be used to interpret geologic phenomena. We used lidar to check that the map units on each geologic map matched the landforms seen in the lidar. In some limited cases we also used lidar to provide a basis for adjusting the boundaries of resource polygons when the geologic mapping was either insufficiently detailed or there was a mismatch in adjacent published maps. In areas that have been mined, we use lidar elevation data to estimate the volume of material removed from a mine site. For Inferred and Demonstrated sand and gravel resources that lack subsurface data or other thickness information, we use lidar elevation data to estimate resource thickness. We used lidar data collected between 2003 and 2019 from seven different lidar projects that cover about 77 percent of Skagit County (Washington Geological Survey, 2003, 2008, 2013a, 2013b, 2015, 2017, 2020).

LANDSLIDE DATA

Landslide areas and deposits are generally not good sources of aggregate. For this reason, we chose to exclude areas that intersect with the best available landslide mapping for Skagit County, which is WGS's Washington State Landslide Inventory Database (Washington Geological Survey, 2023c). This dataset shows landslides compiled from a variety of sources, spanning the past few decades. In several situations there are landslide polygons mapped from different projects that fully or partially intersect. Rather than pick and choose which landslide polygon is most detailed, most accurate, or most recently mapped, we chose to include all overlapping polygons. This represents the maximum extent of the mapped landslide area according to the landslide compilation data. In some situations, very small landslide polygons (typically those <75 ft wide) were merged with the surrounding resource or non-resource area to achieve readability at 1:24,000 scale. Additionally, where landslides have been mapped over water, we chose to represent the water boundary in our data. In one case, we referenced lidar to more clearly delineate a landslide polygon that grouped alluvial and mass wasting deposits together. Note that at the time of our analysis, there was no lidar-informed landslide inventory for Skagit County based on the protocol of Slaughter and others (2017). The absence of landslide data in a particular location does not necessarily mean that landslides are absent or that there is no landslide risk. The inclusion of these landslide data into our study is not intended as a substitute for a detailed investigation of potential slope instability by a qualified practitioner.

Resource Classification Scheme

OVERVIEW

Our classification scheme (Fig. 2) provides a framework for making consistent decisions and interpretations about aggregate resources from available data. Similar to other aggregate classifications (for example, California Division of Mines and Geology, 2000; Jennings and Kostka, 2014; Eungard and Czajkowski, 2015; Associated Earth Sciences, Inc., 2017) we divide resources by their quality and available thickness and impose threshold limits on what we consider a viable resource. The quality of aggregate varies substantially based on the type of rock or deposit from which it is sourced. Some uses of aggregate—such as gravel forest roads—can use lower-quality aggregate, whereas other uses—such as bridges—require high-quality aggregate. Because the use will dictate the characteristics of what is considered acceptable aggregate, we choose one of the most common uses—Hot Mix Asphalt—and assess quality based on the requirements of this product, as detailed by the 2023 Standard Specifications of the Washington State Department of Transportation (WSDOT, 2023c). This choice means that our quality thresholds (discussed further below) may be too restrictive for some low-quality aggregate uses, and too permissive for some high-quality aggregate uses.

Our generalized classification scheme divides our inventory into Demonstrated, Inferred, Speculative, and Not a Resource quality categories (Fig. 2). Demonstrated resources are those for which we have the highest level of certainty that they meet our quality thresholds; they almost universally have an active or recently active surface mine nearby, thus demonstrating their viability. Inferred resources are less certain than Demonstrated resources, but are more certain than Speculative resources; we infer their viability as an aggregate resource based on available data. Speculative resources have enough information for us to speculate there is a resource, but further work would be needed to confirm its existence and quality. Regions classified as Not a Resource may vary in level of knowledge and certainty.

For sand and gravel resources, we subdivide Demonstrated and Inferred resources into three bins according to their estimated thickness: <25 ft thick, 25–80 ft thick, and >80 ft thick (Fig. 2). Resources that are <25 ft thick may be too thin to be economically viable for resource extraction because the cost of extraction may be greater than the value of the aggregate material. We included these potentially thin resources in the inventory to acknowledge that changes to extraction cost or aggregate value may make them economically viable in the future. Because the thickness of bedrock resources is difficult or illogical to quantify in most geologic situations, we did not divide bedrock into thickness categories.

DETERMINING RESOURCE QUALITY

To make consistent classification decisions and ensure transparency in our decision-making process, we developed a detailed set of criteria for classifying resource polygons based on their quality (Table 1). The left side of Table 1 lists the types of data we considered in our resource classification workflow, and describes the typical characteristics of supporting evidence for each quality classification: Demonstrated, Inferred, Speculative, and Not a Resource.

Table 1 should not be interpreted as a simple decision tree. To overcome the challenge of missing, inconsistent, and (or) conflicting data on aggregate quality and thickness, we apply a holistic review process that considers all evidence available. While Table 1 is a complete description of our decision process, it was purposefully designed to allow for some latitude in classification to avoid biasing too heavily against a resource simply because we lacked detailed evidence of its quality or thickness. Note that Table 1 generally ranks input data types from high priority at the top to lower priority at the bottom, acknowledging that some types of evidence provide greater discriminating power than others.

Resource Classification Workflow

OVERVIEW

Here we describe how we produced the aggregate resource inventory by compiling data sources and interpreting them using our resource classification scheme (Table 1). Although we began by compiling geologic units at the best available scale, the boundaries of our mapped resource polygons may deviate from the geologic source data wherever we refined their extents based on additional data.

WORKFLOW

We started by compiling all of the data described in *Sources of Data* while excluding land that falls outside the scope of our work. For Skagit County, we excluded areas that intersect with the WGS landslide database, North Cascades National Park, Ross Lake National Recreation Area, Glacier Peak Wilderness, Mount Baker Wilderness, and Noisy-Diobsud Wilderness. We clipped the remaining data to the shoreline of 1:100,000-scale geologic maps. River and lake boundaries present in the 1:24,000-scale geologic mapping were retained. For the southern portion of the Skagit River delta where the braided fluvial system is mapped dramatically differently between the 1:100,000-scale and 1:24,000-scale geologic maps, the shoreline differences needed to be reconciled. For this area of the map, we blended the following data to achieve a reasonable representation of the water boundaries: the Port Townsend 1:100,000-scale quadrangle data were used to represent the Skagit Bay shoreline and the Swinomish Channel, and the Utsalady and Conway 1:24,000-scale quadrangles' more detailed fluvial boundaries were used to map the inland portion of the braided fluvial system of the Skagit River delta. Following these steps produced a database of geologic unit polygons bounded by a seamless shoreline, excluding areas with landslides and outside of federally protected park, recreation, and wilderness lands.

Resource classification began with reviewing the geologic unit descriptions and classifying units that were very unlikely to be resources as Not a Resource. We then determined which of the remaining geologic units had aggregate mining or aggregate testing history, and if the results were favorable for aggregate quality. Where there is an active surface mine boundary according to the Surface Mine Reclamation Program database, we used this boundary for a Demonstrated resource. Areas surrounding an active surface mine were in some cases classified as Speculative or Inferred based on our classification scheme (Table 1). Any areas within active permitted mine sites we knew to be undergoing

Table 1. Holistic decision table describing the types, consistency, and quality of evidence that support each of the aggregate quality classifications (Demonstrated, Inferred, Speculative, and Not a Resource). Reading down the table provides a description of the typical evidence that supported the quality classification of a resource polygon. Not all data were available for all resource polygons, and when data conflicted, we generally gave higher priority to data types listed higher in the table. The Not a Resource classification may or may not have a high level of knowledge and (or) certainty.

	More data available, data more consistent ⟷		*Less data available, data less consistent*	
Resource-quality input data	**Demonstrated**	**Inferred**	**Speculative**	**Not a Resource**
Higher priority evidence **Material description of sand and gravel or bedrock** Sources: Geologic and geomorphic maps (1:24,000 to 1:100,000 scale), subsurface data, and other geologic descriptions when available	Material descriptions are typically consistent and indicate a good-quality resource* with minor, if any, material of lesser quality. Example: A 1:24,000-scale geologic map describes in detail a well-sorted gravelly glacial outwash deposit.	Material descriptions vary in level of detail and (or) indicate the resource quality varies and may include some minor material that is not of good quality.* Examples: A 1:24,000-scale geologic map describes in detail a unit that contains mostly sand and gravel but also lenses of till, or a 1:100,000-scale geologic map describes a unit that generally contains sand and gravel.	Material descriptions vary in level of detail and (or) indicate the resource may include minor to moderate amounts of lower-quality material.* Example: A 1:100,000-scale geologic map describes a glacial ice-contact unit which may contain a mixture of good material (esker gravels) and low-quality material (clayey till).	Material descriptions available indicate material does not meet our aggregate resource material requirements.* Example: A 1:24,000-scale geologic map describes a poorly sorted glacial till with significant clay content.
Active permitted mining activity Sources: SMRP records of active mines	Typically intersects with or adjacent to active (permitted) aggregate mines or quarries.	Sometimes adjacent to active (permitted) aggregate mines or quarries.	Rarely near or adjacent to active (permitted) aggregate mines or quarries or reclaimed areas.	Rarely near or adjacent to active (permitted) aggregate mines or quarries.
Subsurface data (where available) Sources: Water-well logs, geotechnical borings	Subsurface data are typically available, well-located, evenly distributed, and indicate good-quality aggregate material throughout the resource area.	Subsurface data are typically available, but may be located with variable precision. Generally indicate good-quality aggregate material. Some records may indicate lower-quality material.	Subsurface data are sometimes available, located with variable precision, have uneven distribution, and (or) indicate variable quality aggregate material.	Subsurface data may or may not be available. Where available, data generally indicate material does not meet our aggregate resource material requirements.*
Other Mining activity (if available) Sources: SMRP records of inactive mines, USGS topo maps	Typically intersects with or adjacent to small mining operations, inactive (cancelled or terminated permit) aggregate mines or quarries, or historical mining activity.	Sometimes intersects with or adjacent to small mining operations, inactive (cancelled or terminated permit) aggregate mines or quarries, or historical mining activity.	Sometimes intersects with or adjacent to small mining operations, inactive or reclaimed (cancelled or terminated permit) aggregate mines or quarries, or historical mining activity.	Rarely intersects with or adjacent to historical or small mining operations or reclaimed areas.
Aggregate testing data (where available)	Test results are sometimes available. Available results typically pass our testing thresholds.†	Test results are sometimes available, but may be inconsistent. Available results sometimes pass our testing thresholds.†	Test results are rarely available and often inconsistent. Available results sometimes pass our testing thresholds.†	Test results are rarely available and often inconsistent. Available results typically fail our testing thresholds† or are incomplete.
Lower priority evidence **Consistency of evidence**	Most to all data indicate a good-quality resource; rarely data may indicate lower quality material.	Most to some data indicate a good-quality resource; some data may indicate lower-quality material.	At least some data indicate a good-quality resource; some data may indicate lower-quality material.	Most to all data indicate that the material is not a good aggregate resource; rarely data may indicate a good-quality resource.
Criteria that all resource polygons must meet (Demonstrated, Inferred, and Speculative polygons)	(1) When subsurface data are available and indicate the presence of an overburden, it is typically <10 feet thick with a stripping ratio of 1:3 or better (the overburden should be no more than a third of the resource thickness). (2) Mapped polygon is larger than 1 acre and not too narrow (generally >200 feet across at its narrowest dimension).			Criteria (1) or (2) are not met.

* Good-quality sand and gravel resource: Material description indicates sand and gravel with little to no organic material, silt, or clay. These deposits are typically unweathered, generally stratified, moderately to well rounded, and well sorted. Good-quality bedrock resource: Material description indicates little to no weathering, little indication of physical or chemical alteration, and other details that correspond with strong and durable rock.

† We adopt the 2023 specifications for Hot Mix Asphalt (HMA) as our aggregate testing threshold: LA Abrasion values of <30% and Washington Degradation values of >30%.

reclamation (or had already been fully reclaimed) were classified as Speculative, since reclaimed mines are sometimes mined again. Inactive, historical mines, and small mining operations may or may not be classified as a resources depending on the availability of site speific data in their vicinity (Table 1).

We used subsurface data (in conjunction with geologic unit descriptions and cross sections) to estimate the thickness of each resource polygon and modify the boundaries of the geologic unit polygons that form the initial basis of our inventory. Subsurface records were classified as Good, Bad, or Thin. Subsurface records that indicate >25 ft of good aggregate material were interpreted as Good; those that indicate material unsuitable for aggregate or with <10 ft of good aggregate material, or with >10 ft of non-resource overburden, were interpreted as Bad. Subsurface records that indicate <25 ft of good aggregate material were interpreted as Thin since aggregate resources <25 feet thick may not be economically viable to extract. For all records, the actual thickness of aggregate material and overburden (if present) was also recorded, and these data were used to estimate the average thickness (and therefore the thickness classification) of each resource polygon.

In three general scenarios, data from subsurface records led us to modify a resource boundary from that of the original geologic unit polygon.

1. A resource boundary was expanded (or reduced) to include (or exclude) a specific subsurface record.
2. Where a substantial difference in the thickness of the aggregate material existed within a single geologic unit, the polygon was split into separate resource polygons with different thicknesses.
3. In places where a relatively thin (<10 ft thick) surficial geologic unit considered Not a Resource overlies a thick deposit of good aggregate material we reclassified the area as a resource. This occurs in Skagit County where thin glacial till—Not a Resource—is underlain by glacial advance outwash deposits—an excellent resource. To ensure that we did not overlook potential resource areas covered by thin overburdens, we reviewed data from subsurface records and lidar.

The suitability of alluvial deposits (those from non-glacial streams and rivers) as aggregate resources depends on the size of the river system and the geology and geometry of the drainage basin. We assumed that deposits from small or seasonal streams are not significant resources because they are typically poorly sorted, relatively thin, and narrow. However, deposits from major river systems such as the Skagit, Sauk, and Samish Rivers, could be sources of aggregate because such rivers typically produce well sorted, thick, and extensive sand and gravel deposits. Our workflow included reviewing all alluvial geologic units and excluding those that are too thin, too restricted in area, and those that are likely to be poorly sorted. We did not consider any land-use or environmental restrictions (such as stream buffers) in our resource mapping.

Our geologic data were compiled from 1:24,000-scale and 1:100,000-scale sources, and there are sometimes inconsistencies where these maps meet at their boundaries. We used lidar data to reinterpret these areas for our resource mapping. This process sometimes resulted in the modification of resource polygons in order to create a cohesive, county-wide map. In general, our data are intended to be used at no finer a scale than the geologic map from which they were sourced. In some situations, very narrow portions or slivers of resource polygons (typically those <75 ft wide) were trimmed, extended, or merged to achieve readability at 1:24,000 scale.

Estimating Resource Volume and Tonnage

We estimated resource volume in cubic yards and weight in tons using simplified geometries, estimates of thickness, and assumed values for recoverability and aggregate unit weight. We only estimated volume for Demonstrated and Inferred sand and gravel resources because we generally lacked thickness information for Speculative sand and gravel resources and did not determine the thickness of bedrock resources. We present all of our equations and assumptions below so that the end user can understand our methods and alter or update our assumed values based on new, improved, or additional information.

FACTORS THAT AFFECT USABLE RESOURCE

Several factors affect the amount of aggregate that can be recovered from a potential resource, and we explicitly considered five of them: resource area, thickness of the resource, how much of the actual geologic deposit is usable as aggregate (geologic recoverability), how much the land surface deviates from our assumption of uniform flatness (topographic recoverability), and how much of the usable material must be kept on site for reclamation purposes (operations recoverability).

Low and high resource-thickness values, which we used to calculate ranges of resource volume and tonnage, were estimated from the minimum and maximum thicknesses reported in available subsurface data within the resource polygon and (or) unit descriptions from geologic maps. Resource thicknesses

Table 2. Recoverability values used in this study.

Variable	Conditions	Recoverability
Geologic recoverability (R_{gl} and R_{gh})	Glacial outwash deposits	80–90%
	Ice-contact and ice-marginal deposits	75–85%
	Alluvial deposits	75–85%
Operations recovery factor (R_w)		90%
Topographic recoverability (R_t)	Flat surface	95%
	Gently undulating surface	90%
	Gently incised surface	85%
	Moderately incised surface	80%
	Strongly incised surface	75%
	Deep and pervasively incised surface	70%

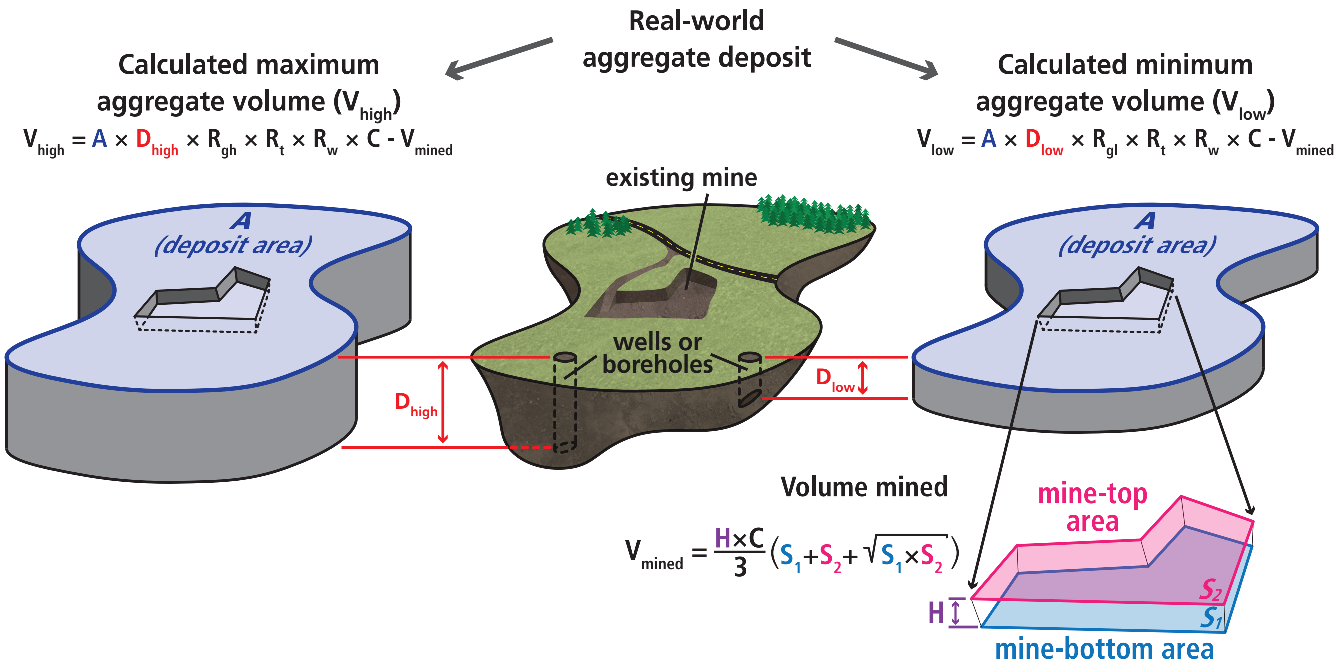

Figure 3. Method used to calculate the volume of a resource polygon. If a surface mine was present, we subtracted the volume of material that had already been removed from the volume of the whole aggregate deposit. Variables are explained in Table 3.

exclude any overburden. The surface area of each aggregate resource polygon was calculated from our resource inventory map.

We used a range of geologic recoverability values based on the primary geologic material present in the deposit (Table 2). High geologic recoverability means that most of the material in the deposit is usable as aggregate and requires only minimal processing. Low geologic recoverability means that there may be some portions of the deposit that are not usable or require extra processing (for example, too much fine-grained material or dispersed lenses of glacial till). We employ a topographic recoverability factor to account for the amount of material that has been removed by erosion. High values (90–95%) indicate a relatively flat surface in the region where we are estimating volume; lower values (70–90%) indicate more rugged topography or the presence of deep gullies or canyons (where some of the aggregate resource has potentially been removed by erosion). We use a single operations recovery factor (90%) because we assume 10 percent of the total material must remain on site.

ESTIMATING VOLUME AND TONNAGE

We modeled the three-dimensional shape of each aggregate resource as its mapped polygon extruded to its thickness (Fig. 3). If the resource polygon contains a surface mine, then we modeled the volume of the mine as a frustum (a truncated pyramid) and subtracted the mined volume from that of the whole resource polygon (Fig. 3).

The low and high volumes for each resource polygon (V_{low} and V_{high}) were calculated using:

Equation 1. $$V_{\mathrm{low}} = A \times D_{\mathrm{low}} \times R_{\mathrm{gl}} \times R_{\mathrm{t}} \times R_{\mathrm{w}} \times C - V_{\mathrm{mined}}$$

Equation 2. $$V_{\mathrm{high}} = A \times D_{\mathrm{high}} \times R_{\mathrm{gh}} \times R_{\mathrm{t}} \times R_{\mathrm{w}} \times C - V_{\mathrm{mined}}$$

Where A is the area of the resource polygon in acres, D_{low} and D_{high} are the low and high values for the thickness of the resource in feet, R_{gl} and R_{gh} are the low and high values for the geologic recoverability factor, R_{t} is the topographic recovery factor, R_{w} is the operations recovery factor, C is a conversion

Table 3. Explanation of variables and abbreviations.

Abbreviation	Meaning
A	Surface area of the deposit (in acres)
V_{low} V_{high}	Low and high estimates of resource volume (in cubic yards)
T_{low} T_{high}	Low and high estimates of resource tonnage (in tons)
D_{low} D_{high}	Low and high estimates of average resource thickness/ depth (in ft)
R_{gl} R_{gh}	Low and high estimates of geologic recoverability (as percent, see Table 2)
R_{w}	Operations recovery factor (assumed to be 90%)
R_{t}	Topographic recovery factor (as percent, see Table 2)
C	Conversion factor from acre-ft to cubic yards (1,613.33 cubic yards per acre-ft)
W_{low} W_{high}	Low and high estimates of aggregate weight (ranges from 1.6 to 1.8 tons per cubic yard)
V_{m}	Volume of material removed by active aggregate mine (cubic yards)
H	Average measured mine height (ft)
S_1	Area of aggregate mine floor (in acres) (bottom of the excavated area within the mine)
S_2	Area of top of aggregate mine (in acres) (disturbed area within the permit boundary)

constant from acre-feet to cubic yards, and V_{mined} is the volume of material already removed by mining in cubic yards.

To approximate the volume of material removed by any active mines within a resource polygon (V_{mined}), we determined the average mine height (H, in feet) from lidar and the mine bottom and top areas in acres (S_1 and S_2 respectively) from the most recently available lidar, HXIP (Hexagon Imagery Program) aerial imagery (2021–2022 for Skagit County), or by consulting the most recent mine operators report for estimated mine depth (Fig. 3). V_{mined} was calculated with:

Equation 3. $$V_{\text{mined}} = \frac{H \times C}{3}\left(S_1 + S_2 + \sqrt{S_1 \times S_2}\right)$$

To convert our volume estimates (Equations 1 and 2) into tonnages (T_{low} and T_{high}), we used:

Equation 4. $$T_{\text{low}} = V_{\text{low}} \times W_{\text{low}}$$

Equation 5. $$T_{\text{high}} = V_{\text{high}} \times W_{\text{high}}$$

Where W_{low} and W_{high} are aggregate weights of 1.6 and 1.8 tons per cubic yard, respectively (Koloski and others, 1989). This range represents the low and high estimates of dry densities of aggregate materials.

ACCURACY OF ESTIMATES

Aggregate deposits are products of complex natural systems and many factors can affect the amount of usable aggregate in any region. Our approach to estimating volume and tonnage tries to account for the inherent uncertainty around our input variables (listed in Table 3) by integrating low and high values into our calculations. We chose a conservative range of input values for thickness of deposit, geologic recoverability, and aggregate weight to provide a higher likelihood that the true total volume and tonnage of aggregate fall within our estimated range. Our volume and tonnage estimates are based only upon publicly available data and therefore lack the detailed data about aggregate quality and quantity that many, if not most, mine operators have available to them. Because of this, detailed site-specific information and analysis should generally be viewed as a more robust indicator of local aggregate quality and quantity than this county-level report.

Developed Land Classification

Aggregate resources on land that has already been developed are generally unavailable for extraction. Our inventory workflow method did not consider the current land use in deciding the quantity and quality of a resource. This resulted in an inventory that overestimates the amount of available resource where there is significant developed land. To mitigate this effect, we used data from the National Land Cover Database (NLCD) to estimate how our resource polygons are impacted by existing development. The NLCD categorizes land-use at 30-m (328-ft) resolution across the entire country (Dewitz, 2023). We considered developed land to be any region the NLCD categorizes as low-, medium-, or high-intensity developed land. We accessed the 2021 data release of the NLCD from mrlc.gov/viewer in September 2023. These data were added to our working GIS database and we then calculated the portion of each resource polygon covered by land classified as developed. In our results we present estimates of area, volume, and tonnage with and without this analysis to help illustrate the effect of land development on resource availability.

Resource Proximity to Markets Analyses

The proximity of plentiful, high-quality aggregate resources to locations where such resources are needed is an important consideration for both planners and mine operators. The cost of aggregate (and its economic feasibility) is largely controlled by how far it must be trucked from source to sites where it is needed; a county in which resources are located far from where they are needed will have higher aggregate costs and consequently higher construction costs. Furthermore, reducing aggregate transport distance directly reduces the number of miles driven by heavy vehicles on state and county roads, thereby reducing potential vehicle accidents, road wear, and carbon emissions. Given the significant costs of aggregate transport, it makes sense to plan for the long-term availability of resources in a variety of locations.

To evaluate the accessibility of current and potential future aggregate resources to communities in Skagit County, we performed two analyses. The first calculates aggregate transportation distances along roads and ferry routes from active mines in Skagit County. This analysis reveals areas in the county that have limited road and ferry transportation access (typically undeveloped areas) and areas that are far from active permitted aggregate mines (‘aggregate deserts’). These ‘aggregate deserts’ are areas that might benefit from lower aggregate transportation costs if closer aggregate resource deposits were developed. In this analysis, we used the locations of permitted surface mines in Skagit County actively extracting material and calculated a 20-mile service area from each of these sources of aggregate along the public road transportation network. Our analysis used 14 active permitted surface mines, including some county operated mines. Our analysis excluded any mines that have canceled or terminated permits and active permitted mines that have little to no material left to extract or are in the reclamation phase (Rian Skov and Joe Lydon, Washington Geological Survey, written commun., 2023). We did not consider the quality, quantity, or type of aggregate available at the active mines included in our analysis. To keep this scenario focused on Skagit County, we did not include any permitted mines from neighboring counties in this analysis, though such mines could possibly supply aggregate in some situations.

The second analysis explores the spatial relationship between our inventory’s potential aggregate resource areas and several aggregate demand points in Skagit County. Aggregate demand points are locations that use aggregate resources. For this analysis, our aggregate demand points represent four cities and 11 large, future transportation projects. We include the cities of Burlington, Sedro-Woolley, Anacortes, and Mount Vernon (locations on Fig. 1) because they participate in aggregate needs and use planning under the Growth Management Act and have populations larger than 1,000 people. Aggregate demand points for the four cities are located near major road intersections near the centroid of the city boundary and therefore may not align with the traditional mapped city centers. From Skagit County’s 2023–2028 Transportation Improvement Program, we selected

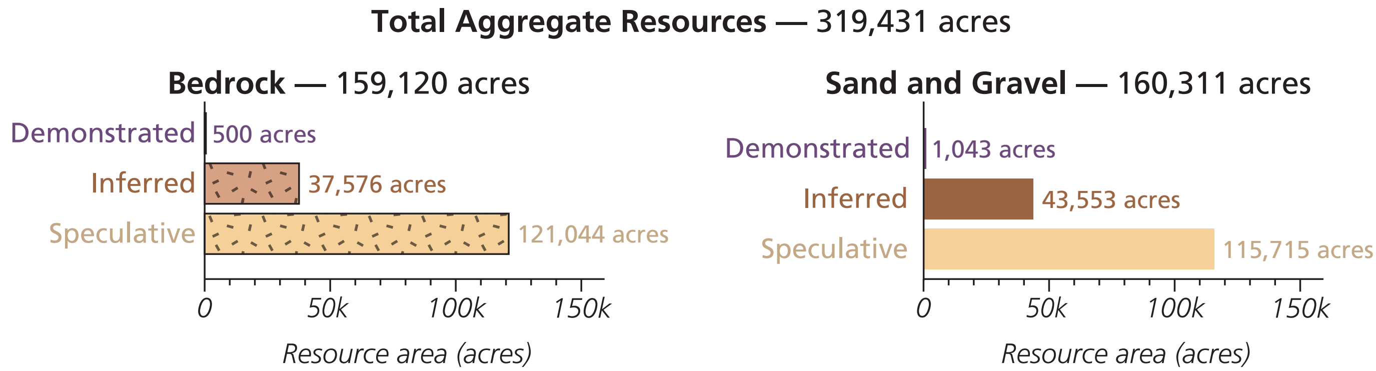

Figure 4. Distribution of material types and quality classifications of inventoried aggregate resources in Skagit County.

the locations of 11 upcoming projects that require aggregate resources (Skagit County, 2023). For projects that include stretches of roadway, the aggregate demand point was placed around the midpoint of the line segment. In this analysis, we modeled a 10- and 20-mile driving distance from the 15 aggregate demand points. This analysis shows which aggregate resource areas from our inventory are close to populated areas and future construction project sites in need of aggregate resources, presenting an opportunity to source aggregate closer to where it is needed and reduce transportation costs.

For both proximity analysis scenarios, we used the 'Service Area' solver tool within the Network Analyst extension using the 'asyncServiceArea' service in ArcGIS Pro 2.9.5 Desktop. The Service Area solver tool uses road data from ArcGIS Online's network dataset. In one situation we opted to customize the default transportation network to exclude truck travel over the Skagit River (Marblemount) Bridge. At the time of the study, this bridge is closed to trucking heavy loads such as aggregate from a nearby quarry. For our analyses we used the default settings for the 'Trucking' travel mode. In general, this travel mode models a transportation network fit for large trucks by avoiding truck restricted roads and using preferred truck routes. We assume that this transportation network, the travel mode settings, and the driving distances are representative of aggregate transport in the study area. The driving distances are intended to reflect a feasible distance analysis, but may not reflect the distance analysis needs of all readers.

AGGREGATE RESOURCE INVENTORY RESULTS

Resource Estimates

Our results identify Demonstrated, Inferred, and Speculative sand-and-gravel and bedrock aggregate resources in Skagit County (see Map Sheet). In total, we identify 319,431 acres of land as having the potential for aggregate resources, about 29 percent of the county's land area (Table 4). This total is divided into 160,311 acres of sand and gravel aggregate resources and 159,120 acres of bedrock resources (Fig. 4). For sand and gravel resources mapped as Inferred and Demonstrated (our two highest-certainty classifications), we estimate 1.3 to 2.9 billion cubic yards of sand and gravel aggregate—approximately 2.1 to 5.3 billion tons (Fig. 5). For comparison, Washington State produced approximately 39 million tons of sand and

Table 4. Area, volume, and tonnage estimates for potential aggregate resources in Skagit County broken down by aggregate type, classification, and land-use filtering. Bolded numbers are for all resources mapped in the county without filtering for land use. Numbers in parentheses refer only to resources located in areas that are classified as undeveloped in the NLCD. We do not report volume or tonnage for bedrock resources.

	Area in acres	Low volume in millions of cubic yards	High volume in millions of cubic yards	Low tonnage in millions of tons	High tonnage in millions of tons
Sand and gravel					
Demonstrated	**1,043** *(955)*	**68** *(61)*	**127** *(117)*	**109** *(97)*	**228** *(210)*
Inferred	**43,553** *(40,798)*	**1,229** *(1,170)*	**2,821** *(2,681)*	**1,966** *(1,872)*	**5,078** *(4,827)*
Speculative	**115,715** *(102,138)*				
Subtotal	**160,311** *(143,891)*	**1,297** *(1,231)*	**2,948** *(2,798)*	**2,075** *(1,969)*	**5,306** *(5,037)*
Bedrock/rock and stone					
Demonstrated	**500** *(492)*				
Inferred	**37,576** *(37,310)*				
Speculative	**121,044** *(120,022)*				
Subtotal	**159,120** (157,824)				
Total area of all aggregate resources					
Total	**319,431** *(301,715)*				

Bold = entire inventory
(Italics) = undeveloped areas only

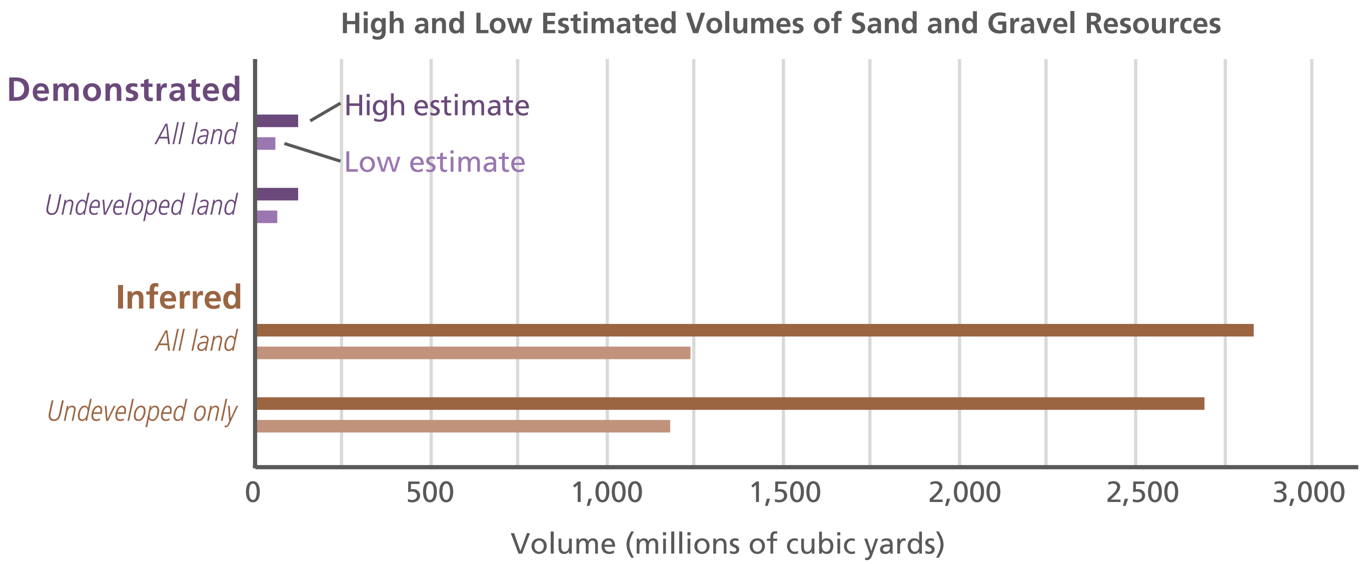

Figure 5. Volume estimates of Demonstrated and Inferred sand and gravel aggregate resources. 'All land' denotes volumes for the full inventory without consideration of land use, while 'undeveloped land' filters the inventory to only areas classified as undeveloped by the NLCD.

gravel aggregate in 2021 (USGS, 2023). Due to the difficulty of quantifying the thickness of bedrock aggregate resources, we did not estimate their volume or tonnage.

DEMONSTRATED RESOURCES

Demonstrated resources are those for which there is the most evidence that the geologic deposit meets or exceeds our threshold criteria; these are the deposits that we are the most certain about and they are almost always near an active or recently active mine. Within the county, there are a total of 1,543 acres of Demonstrated resources (Table 4), which include 1,043 acres of sand and gravel resources and 500 acres of bedrock resources. We estimate between 68 million and 127 million cubic yards of sand and gravel within this category (Fig. 5). Based on the NLCD data, about 8 percent of the Demonstrated sand and gravel resources are located on developed land; about 2 percent of Demonstrated bedrock resources are on developed land. Demonstrated resource areas contain 26 active permitted mines.

INFERRED RESOURCES

Inferred resources are those for which there is often good geologic and subsurface evidence that the deposit meets or exceeds our threshold criteria, but we may lack specific confirming data or there may be inconsistent lines of evidence; these are deposits that we infer to be a good source of aggregate, but some additional geologic study is probably necessary. Within Skagit County, there are a total of 81,129 acres of Inferred resources (Table 4), which include 43,553 acres of sand and gravel resources and 37,576 acres of bedrock resources. We estimate Inferred resources contain between 1.2 and 2.8 billion cubic yards of sand and gravel (Fig. 5). According to the NLCD data, about 6 percent of Inferred sand and gravel resources and about 1 percent of Inferred bedrock resources are on developed land.

SPECULATIVE RESOURCES

Speculative resources are those for which there is some evidence, often in the form of geologic unit descriptions, that suggests the deposit aligns with our criteria, but we lack sufficient data to make a more certain determination. These are deposits that we speculate could be a good source of aggregate, but additional geologic study is necessary. Within the county, there are a total of 236,759 acres of Speculative resources (Table 4), which include 115,715 acres of sand and gravel resources and 121,044 acres of bedrock resources. Because we lack thickness information for Speculative resources, we do not estimate their volume or tonnage. According to the NLCD data, about 12 percent of Speculative sand and gravel resources and about 1 percent of Speculative bedrock resources are on developed land.

Impact of Developed Lands

Current land use was not a factor in classifying aggregate resources throughout the county because our inventory is based on underlying geologic phenomena. However, we used land cover data from the National Land Cover Database (NLCD) to estimate the area of aggregate resources that may no longer be accessible due to development. Overall, about 6 percent of the total area we classified as potential aggregate resources—about 17,608 acres—is considered developed and likely to be inaccessible for resource extraction. Total areas of potential aggregate resources in undeveloped areas are provided in Table 4.

Resource Proximity to Markets Results

Because aggregate resources are heavy and can only be sourced from specific geologic depositional areas, there are significant economic, physical, social, and environmental costs that factor into the placement of aggregate mines. Our proximity analyses are not intended to suggest which land or resources should or should not be protected for future aggregate extraction. Nor are these analyses intended to define significant travel distances for all readers. Rather, they are meant to illustrate how the location of aggregate mines and resources may affect the cost of transporting aggregate resources from source to market.

The first proximity analysis models a 20-mile service area around actively extracting mines in Skagit County (Fig. 6). We interpret the areas outside of the 20-mile service area as possible 'aggregate deserts', meaning they appear to be far from actively extracting aggregate mines and therefore may require transportation of aggregate resources from farther away. Figure 6 shows that approximately 57 percent of the study area in the county could be interpreted as a 20-mile aggregate desert. Some of these areas may be outside the 20-mile service area because they lack roads (for example, areas in Mount Baker–Snoqualmie National Forest or on Cypress Island). Figure 6 shows that the eastern portion of Skagit County along State Route 20 requires aggregate to be delivered from relatively distant mines from within the county, incurring higher aggregate transportation costs. This analysis also reveals a higher stress on the limited number of active aggregate mines in the central and eastern portion of the county to serve the aggregate needs of maintaining State Routes 20 and 530.

The second proximity analysis models a 10- and 20-mile transportation distance outward from 15 points of aggregate demand; four cities (Burlington, Sedro-Woolley, Anacortes, and Mount Vernon); and 11 large, future transportation projects, showing which potential resources are close to areas that use aggregate (Fig. 7). About 24 percent of potential aggregate resources are within 10 miles of the aggregate demand points, and about 41 percent are within 20 miles. About 59 percent of the potential aggregate resources are more than 20 miles from the selected aggregate demand points. Resource areas close to populated areas and construction project areas present an opportunity to source aggregate closer to where it is needed and reduce transportation costs. Resource polygons that fall outside of these transportation zones may represent future aggregate resources that could serve future populations or different populated areas outside of this analysis.

CONCLUSIONS

This report inventories and classifies potential aggregate resources of long-term significance with the goal of assisting county and city planners and other local officials with land-use planning decisions related to the Growth Management Act. Our inventory identifies 319,431 acres—about 29 percent of Skagit County's land area—as having the potential for aggregate resources. A little more than half of the inventory, 159,120 acres, represents sources of bedrock aggregate while 160,311 acres represent sand and gravel resources. For sand and gravel resources mapped as Demonstrated and Inferred, we estimate 1.3 billion to 2.9 billion cubic yards of aggregate (2.1 million to 5.3 billion tons). An analysis of the proximity of resources to areas of aggregate demand reveals that approximately 41 percent of our inventory falls within a 20-mile drive from 15 assumed points of aggregate demand. We also find that only approximately 17,716 acres—or 6 percent—of areas we identify as potential aggregate resources may be inaccessible for resource extraction because they are on land classified as developed according to the NLCD.

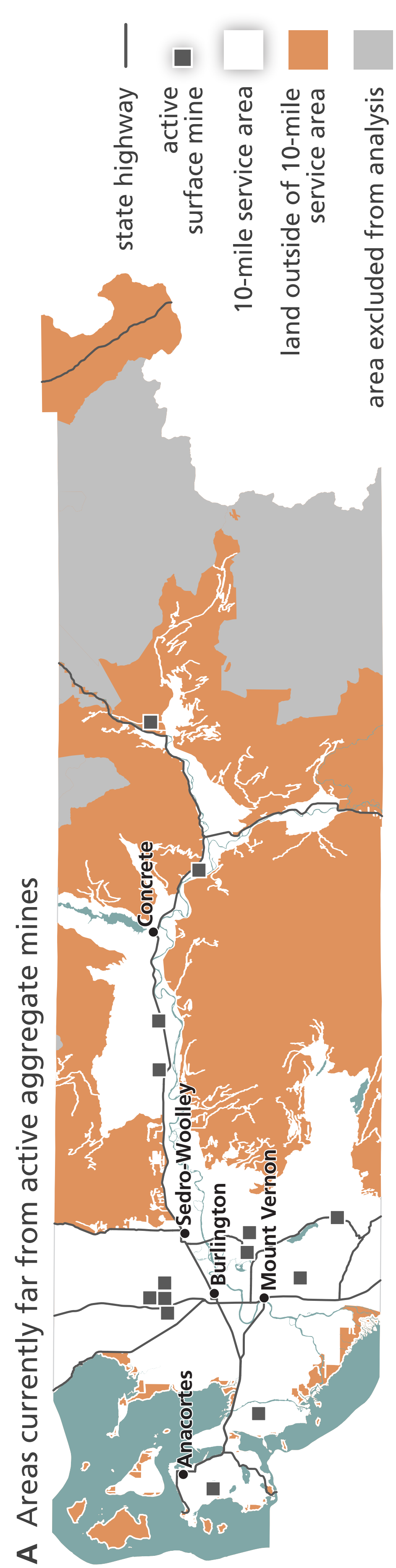

Figure 6. Proximity analysis using currently active aggregate mines in Skagit County and a 10-mile service area. Gray shading shows areas excluded from the analysis; orange shading highlights areas that fall outside of the service area and may experience higher aggregate transportation costs.

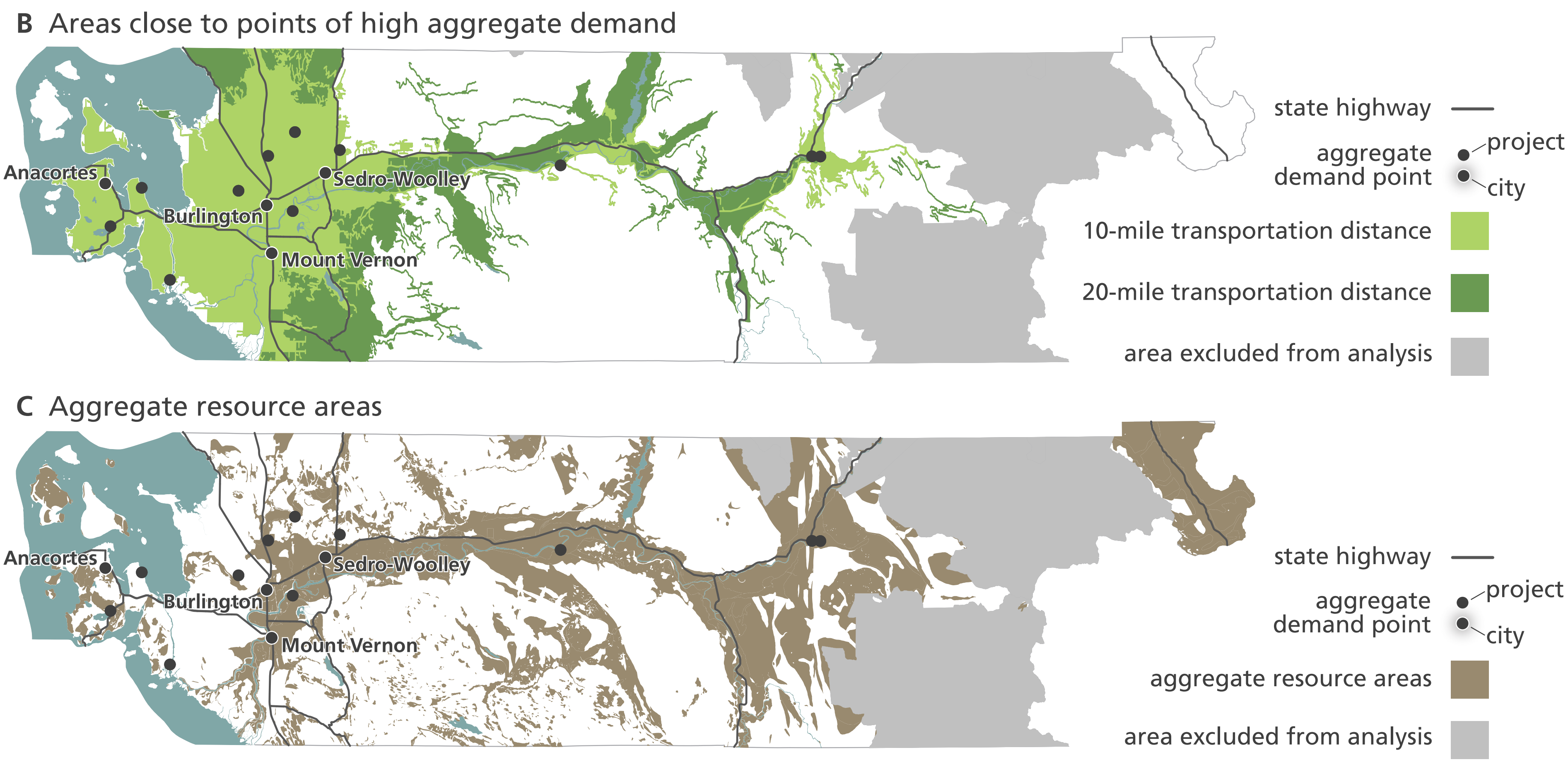

Figure 7. Proximity analysis showing a 10-mile and 20-mile outward service area from fifteen points of aggregate demand: 4 cities (Burlington, Sedro-Woolley, Anacortes, and Mount Vernon), and 11 upcoming projects from Skagit County's 2023–2028 Transportation Improvement Program that require aggregate resources (Skagit County, 2023).

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Appendix A. New Aggregate Testing Data

We collected and tested seven new aggregate samples to provide additional constraints on the quality of some geologic materials that were not well represented by existing testing data. Each sample was collected from DNR state land pit sites or currently permitted aggregate mines in coordination with mine operators. We collected two five-gallon buckets at each site. No additional processing was needed prior to laboratory analysis. All the samples were sent to WSDOT Materials Laboratory for testing according to standard practice described in the Washington Department of Transportation Materials Manual (WSDOT, 2023b) in August, 2023. The results are provided below in Table A1.

Table A1. New aggregate testing data from this study.

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-ST-1	8/14/2023	11	66	Pass
Latitude	48.52789	Sampling Notes: Sampled from unit Jmv_h (Dragovich and others, 1999). Sampled from base of high wall at Skagit County Public Works's Dukes Hill site.		
Longitude	-122.23553			
Generalized Aggregate Unit	Metamorphic bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-ST-2	8/14/2023	23	49	Pass
Latitude	48.35310	Sampling Notes: Sampled from unit Evr (Dragovich and others, 2006). Sampled from DNR state land's rock pit site “Red Rock” at the base of quarry wall.		
Longitude	-122.13206			
Generalized Aggregate Unit	Igneous bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-ST-3	8/14/2023	24	17	Partial Fail
Latitude	48.33957	Sampling Notes: Sampled from unit Qgo_e (Dragovich and others, 2002a). Sampled from DNR state land's rock pit site “Confluence” from what appeared to be the base of an active wall. Top soil “overburden” had been removed from the top portion of the wall and this sample did not include any top soil material.		
Longitude	-121.55300			
Generalized Aggregate Unit	Glacial outwash deposits			
Commodity	Sand and gravel			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-ST-4	8/14/2023	25	17	Partial Fail
Latitude	48.37431	Sampling Notes: Sampled from unit Jsh_s (Dragovich and others, 2002a). Sampled from DNR state land's rock pit site “Pinkerton.” This site consisted of 5–20 ft of exposed rock that appears to have been blasted along a road cut.		
Longitude	-121.52796			
Generalized Aggregate Unit	Metamorphic bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-ST-5	8/16/2024	29	10	Partial Fail
Latitude	48.37996	Sampling Notes: Sampled from unit Ju_s (Whetten and others, 1980). Sampled from DNR state land's rock pit site “Bald view.” Sample collected at base of slope of outcrop that appears to have been blasted and possibly crushed previously.		
Longitude	-122.03921			
Generalized Aggregate Unit	Metamorphic bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-ST-6	8/17/2023	34	27	Fail
Latitude	48.33736	Sampling Notes: Sampled from unit Ju_{hl} (Dragovich and others, 2004a). Sampled from DNR state land's rock pit site “Foothill Crane” from the base of a 20–30 ft exposed wall that appears to have been blasted previously.		
Longitude	-122.06827			
Generalized Aggregate Unit	Ultramafic bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-ST-7	8/17/2023	27	64	Pass
Latitude	48.31669	Sampling Notes: Sampled from unit $J\bar{T}\!Rmv_e$ (Dragovich and others, 2004a). Sampled from DNR state land's rock pit site “FM-Tool” from a large, recently crushed stock pile near base of a 25-30 ft active quarry high wall.		
Longitude	-122.06059			
Generalized Aggregate Unit	Metamorphic bedrock			
Commodity	Rock and stone			