NATURAL RESOURCES

AGGREGATE RESOURCE INVENTORY OF SPOKANE COUNTY, WASHINGTON

by Amy Rudko and Alexander N. Steely

WASHINGTON
GEOLOGICAL SURVEY
Map Series 2024-02
November 2024

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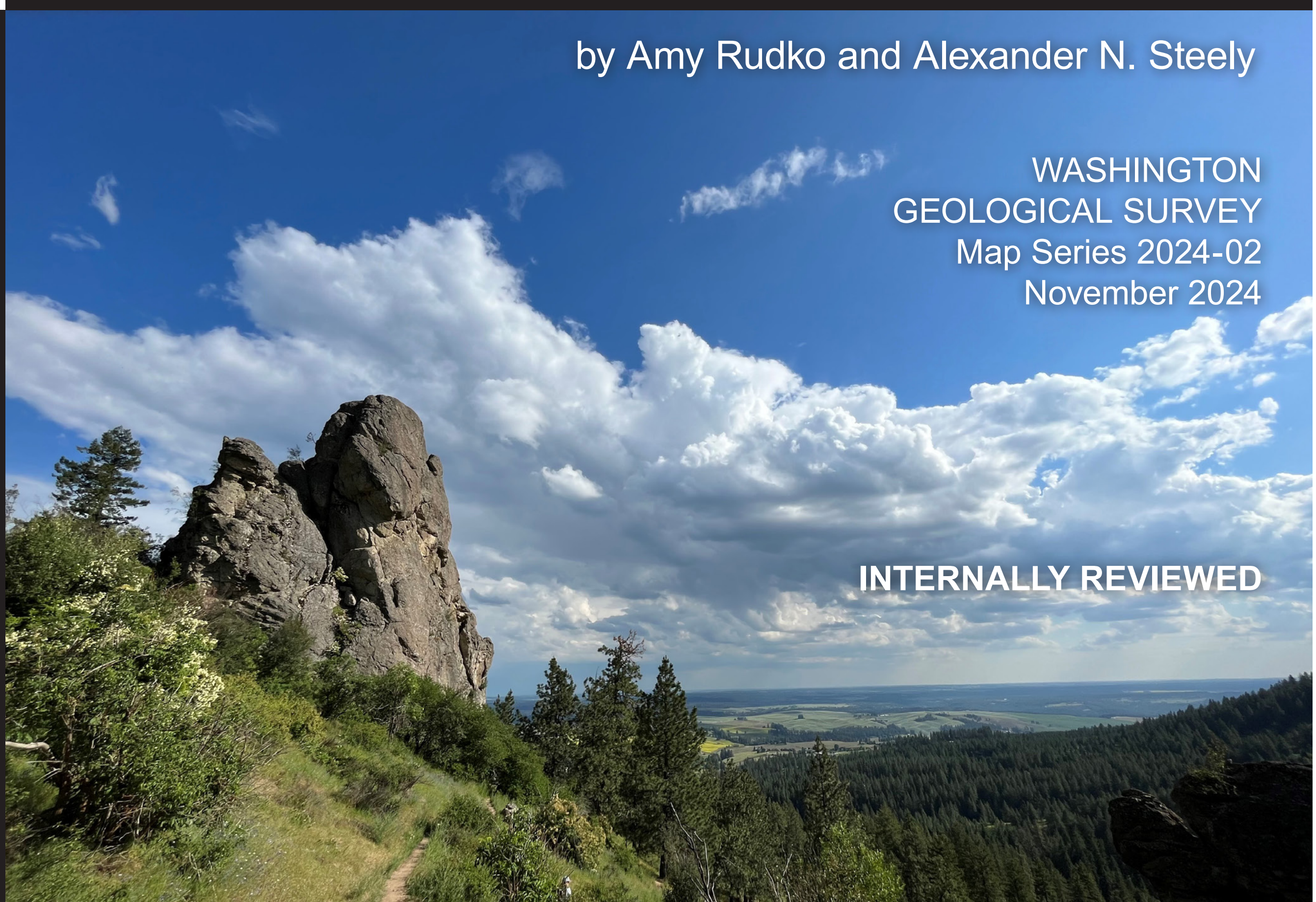

WASHINGTON STATE DEPARTMENT OF
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This publication has been subject to an iterative technical review process by at least one Survey geologist who is not an author. This publication has also been subject to an iterative review process with Survey editors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

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Washington State Department of Natural Resources
Washington Geological Survey

Mailing Address:
1111 Washington St SE
MS 47007
Olympia, WA 98504-7007

Street Address:
Natural Resources Bldg, Rm 148
1111 Washington St SE
Olympia, WA 98501

Phone: 360-902-1450
Fax: 360-902-1785
Email: geology@dnr.wa.gov
Website: www.dnr.wa.gov/geology

WGS website

Publications and Maps:
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Cover Image: Big Rock in the Dishman Hills Conservation Area. Photo by Kelsay Stanton.

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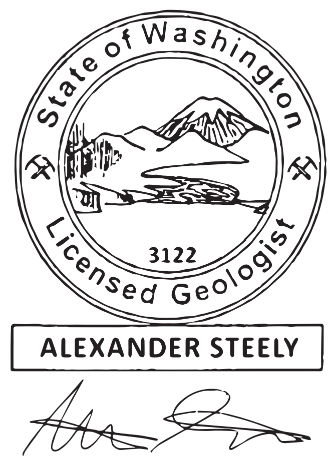

November 2024

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Aggregate Resource Inventory of Spokane County, Washington

by Amy Rudko and Alexander N. Steely

Washington Geological Survey
1111 Washington St SE
MS 47007
Olympia, WA 98504-7007

ABSTRACT

This aggregate resource inventory for Spokane 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 within the Turnbull National Wildlife Refuge were not analyzed for this study. In total, our inventory classifies 574,681 acres of land as having the potential for economically significant aggregate resources, which is about 51 percent of the county's land area. For sand and gravel resources mapped as Demonstrated and Inferred (our highest-certainty resource classifications), we estimate 7.4 billion to 26.4 billion cubic yards of aggregate (11.9 billion to 47.5 billion tons). Note that the ranges for volume and tonnage estimates in this inventory are larger than those in other counties we have mapped due to variability in subsurface records in Spokane County. Because of the difficulty of quantifying the thickness of bedrock aggregate resources, we did not estimate their volume or tonnage.

Approximately 97,000 acres (17%) of areas containing potential aggregate resources 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 indicates that active aggregate mines are well distributed, with only 29 percent of the county more than a 10-mile driving distance from an active mine. 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 89 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 to manufacture asphalt, concrete, and other critical materials for roads, homes, businesses, and bridges. While there are many types of aggregate, the use of the term 'aggregate' throughout this pamphlet refers to construction aggregate.

Jurisdictions face several challenges when planning for the usage of aggregate resources. Although aggregate resources are sometimes thought of as ubiquitous, 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 for uses other than aggregate mining, any aggregate resources present beneath the surface become inaccessible 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 assist local jurisdictions in meeting the requirements 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 mining activity; aggregate testing locations; and subsurface record sites. The geospatial data used to develop the Map Sheet, along with accompanying metadata, are available for download as a zip file through the GIS Data and Databases page on the WGS 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

Spokane County is located in eastern Washington and borders northern Idaho (Fig. 1). The population of Spokane County is 539,339 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 lands, or conservation areas) should be redesignated 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 policy makers, land-use planners, and mine operators to make decisions that best implement their priorities and constraints. The approximately 21,000-acre Turnbull National Wildlife Refuge was not analyzed for this inventory because of federal protections that restrict the development of new mines.

Previous Aggregate Resource Studies

This report is the first inventory of aggregate resources for the entirety of Spokane County. However, three previous geologic reports provide information related to mineral resources. Johnson and others (1998) compiled an edge-matched digital geologic map of Spokane County and its vicinity from previously published 1:100,000-scale geologic maps to aid in county land classification, hazard studies, and resource evaluations including sand, gravel, rock, and clay deposits. Derkey (1997) and Derkey and others (1998) conducted geologic mapping of the Mead and Dartford 7.5-minute quadrangles at 1:24,000 scale, and they included brief notes of mineral resource considerations for some rock units.

Taylor and others (2009) of the Washington State Department of Transportation (WSDOT) conducted a Geologic Assessment of Potential Aggregate Source Areas in Pend Oreille County, Washington. While the Pend Oreille report does not include areas within Spokane County, we reviewed the report's materials testing data for any rock units found in both counties.

GEOLOGY OF AGGREGATE RESOURCES IN SPOKANE COUNTY

Summary Geologic History

Here we summarize the geologic history of Spokane County. Our aim is to explain some of 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 geologic unit descriptions and summaries provided in the source maps for this report, which are listed on the Map Sheet.

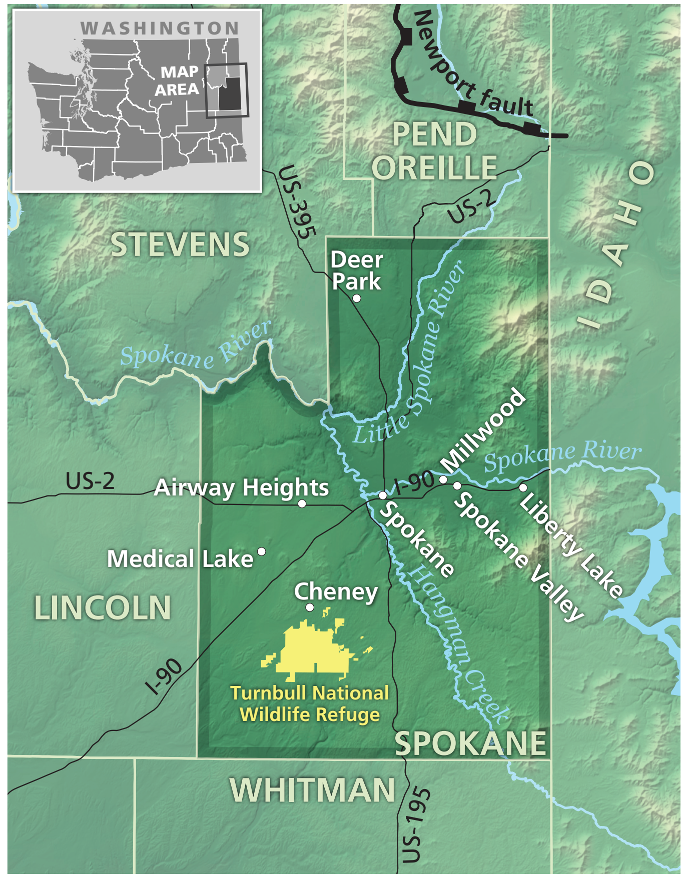

Figure 1. Geographic overview of the study area, Spokane County, within eastern Washington State. Newport fault geometry from Waggoner (1990a).

MESOPROTEROZOIC THROUGH EOCENE

Spokane County has exposures of the some of the oldest rocks found in Washington. While many of these rocks do not necessarily meet our quality thresholds, their distribution and geologic history are nonetheless important for understanding the availability of aggregate resources in Spokane County. These Mesoproterozoic to Eocene (approximately 1.6 Ga to 34 Ma; Ga = 'billions of years ago'; Ma = 'millions of years ago') rocks are part of the Priest River metamorphic core complex, which juxtaposes an uplifted core of both high-grade metasedimentary rocks and igneous intrusive bodies against relatively lower-grade to non-metamorphosed rocks across the Newport low-angle normal fault (Harms and Price, 1992). The Precambrian sedimentary record consists of the Mesoproterozoic Belt Supergroup (ca. 1.48–1.38 Ga) and Deer Trail Group (<1.36 Ga), and the Neoproterozoic Buffalo Hump Formation (<760 Ma) (Brennan and others, 2021; Joseph, 1990; Waggoner, 1990a,b). These sedimentary units are typified by sandstone, siltstone, shale, and conglomerate, with minor limestone and dolostone (Joseph, 1990; Waggoner, 1990a,b). Through deep burial generated by tectonic deformation, these rocks, in some places, have been metamorphosed to quartzite, schist, gneiss, and marble (Joseph, 1990; Waggoner, 1990a,b). For instance, the Hauser Lake gneiss, a common metamorphic rock in Spokane County, is the metamorphic counterpart to the unmetamorphosed Pritchard Formation from the lowest part of the Mesoproterozoic Belt Supergroup (Doughty and others, 1998).

A suite of Cretaceous granitic rock (the Spokane granite) intrudes the Proterozoic metasedimentary country rock and is generally exposed north and east of the city of Spokane (Doughty and Price, 1999). These rocks make up the main body of the Spokane dome of the Priest River metamorphic core complex (Stevens and others, 2016).

In the Eocene, regional extension generated the Newport low-angle normal fault (Fig. 1) that juxtaposes high-grade metamorphic and intrusive rocks against low-grade sedimentary rocks. This faulting coincided with the intrusion of Eocene granitic rock and accommodated the exhumation of older Proterozoic and Cretaceous rocks (Doughty and Price, 1999).

COLUMBIA RIVER BASALT GROUP

The Columbia River Basalt Group consists of hundreds of basalt lava flows that erupted from about 17 Ma to 6 Ma (Reidel and others, 2013). The Columbia River Basalts cover most of eastern Washington and are over 2 mi thick in some places (Reidel and others, 2013). Of the seven basalt formations that make up the full Columbia River Basalt Group, three basalt formations are found in Spokane County: the Saddle Mountains Basalt, the Wanapum Basalt, and the Grande Ronde Basalt. During longer hiatuses between basalt eruptions, sediment accumulated on the surfaces of basalt flows forming sedimentary interbeds. In the study area the Columbia River Basalts are interbedded with Miocene sedimentary rocks of the Latah Formation (Reidel and others, 2013).

GLACIAL HISTORY

During the last glacial period, the Purcell Trench lobe of the Cordilleran ice sheet advanced and dammed the Clark Fork River approximately 50 mi northeast of Spokane County, thereby creating Glacial Lake Missoula (Fig. 2). Glacial Lake Missoula was about 2,000 ft deep and over 200 mi long starting near the present-day Idaho-Montana border (Baker and others, 2016; p. 8). Around the same time, the Okanogan lobe of the ice sheet advanced southward, blocking the Columbia River about 50 mi west of Spokane County creating Glacial Lake Columbia (Atwater, 1986). Between 19 ka and 15 ka (ka = 'thousands of years ago'), the ice dam that plugged Glacial Lake Missoula catastrophically failed many times, triggering multiple flood events (Atwater, 1986). These events, known as the Missoula floods, overtopped Glacial Lake Columbia and spilled through Spokane Valley. The floodwater passed through the area southwestward across eastern Washington, where it carved the Channeled Scabland and eventually reached the Pacific Ocean (Waitt, 1980). These floods deposited accumulations of sand and gravel that are up to several hundred feet thick in the study area (Johnson and others, 1998).

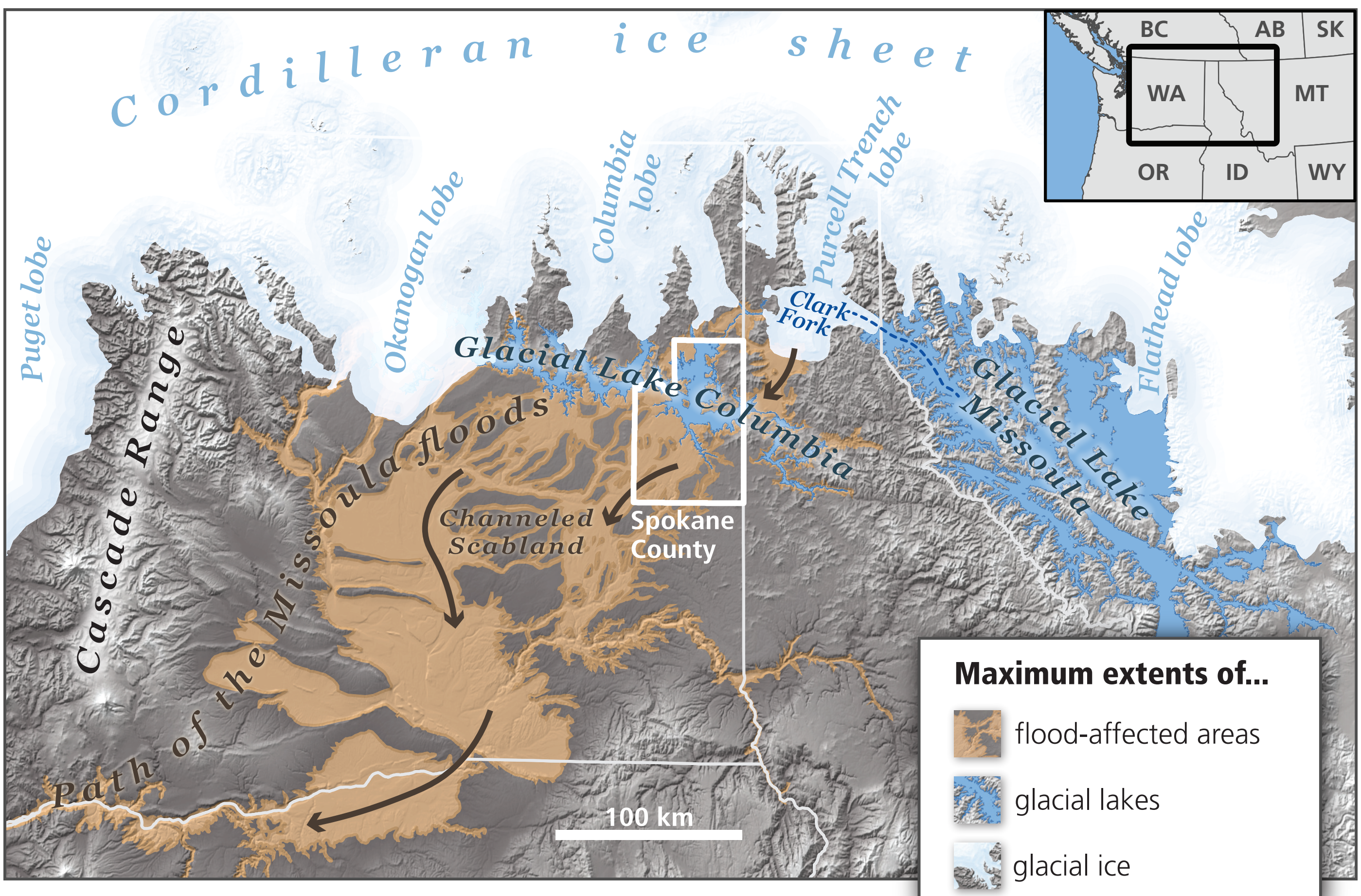

Figure 2. Location of Spokane County relative to glacial lakes Columbia and Missoula, the path of the Missoula floods, and the Cordilleran ice sheet. Arrows indicate the general path of glacial floodwaters. Reconstruction shows the maximum extents of glacial ice, glacial lakes, and flood affected areas during the regional last glacial maximum (between approximately 19 ka and 15 ka). Reconstructions adapted from O'Connor and others (2020).

Sand and Gravel Resources

For this effort, our approach was to generalize previously mapped geologic units into simplified categories relevant to the quality of aggregate resources. The following sections provide brief summaries of these geologic materials.

GLACIAL FLOOD DEPOSITS

Glacial flood deposits are the primary source of sand and gravel aggregate in the Spokane area (Johnson and others, 1998). There are 39 sand and gravel mine sites with active permits in Spokane County that mine glacial flood deposits. There are abundant materials testing data that support the quality of aggregate sourced from glacial flood deposits, with 129 passing and incomplete-passing tests and only 13 failing and incomplete-failing tests. Glacial flood deposits—which can be several hundred feet thick—represent deposition from several individual flood events that originated from Glacial Lake Missoula (Johnson and others, 1998). In general, glacial flood deposits are poorly to moderately sorted and predominantly include sand and gravel, with varying amounts of clay, silt, pebbles, cobbles, and boulders. In some places in the study area, flood deposits were mapped in greater detail and subdivided into deposits that predominantly consist of fine-grained material with less abundant gravel, or gravel with less abundant fine-grained material. Deposits mapped in the primary floodwater path can be greater than 500 ft thick and are mapped as flood-channel deposits (Derkey, 1997). For this report, flood deposit units containing primarily either sand or gravel were grouped because both represent potential aggregate resources. Flood deposits that predominantly consist of fine sand, silt, and clay are classified as Not a Resource. At seven mine sites in Spokane County, for example the Grove Road and Interstate pits near Marshall, glacial flood deposits have been mined down to Columbia River Basalt rock. These seven permitted sites extract both the glacial flood deposits and the Columbia River Basalt rock. To learn more, the interested reader should consult the detailed unit descriptions of the source maps for this report, which are listed on the Map Sheet. Since their initial deposition, some glacial flood deposits have been reworked by water or wind and redeposited as alluvium or eolian deposits.

The Spokane Aquifer

The Spokane aquifer is unconfined, consisting of unconsolidated sand, gravel, cobbles, and boulders deposited by Missoula flood events (Kahle and others, 2005). The aquifer is hundreds of feet thick in some places, and underlies about 135 sq mi in the Spokane Valley (Kahle and others, 2005). The Spokane aquifer has been designated as a “Sole Source Aquifer” by the United States Environmental Protection Agency and is noted to be one of the most productive aquifers in the world (Kahle and others, 2005). The people and industry of Spokane Valley rely on water from the Spokane aquifer. The geologic deposits that make up the Spokane aquifer also represent material that could be used as quality sand and gravel aggregate resources. Groundwater quality can be degraded from operations related to surface mining (Molenaar, 1988). Because of these concerns Spokane County Code section 14.620.270 requires special considerations and limitations for mining activities within the Spokane aquifer area. Although large volumes of aggregate may exist in and around the Spokane aquifer, for the reasons listed above, these materials may possibly never be used as aggregate resources.

NONGLACIAL ALLUVIUM

Alluvium is a deposit, typically including sand and gravel, left by a stream or river. For this study, we refer to the generalized unit of alluvium (or older alluvium) as deposits left by nonglacial streams or rivers. Rivers large enough to round and sort the material they carry, such as the Spokane River, Little Spokane River, and Hangman Creek, can produce thick deposits suitable for aggregate. Alluvium deposited by small and (or) intermittent streams is 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 alluvial deposits as potential sources of aggregate. Although large volumes of aggregate may exist along many river channels, mining alluvium 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 completed with great care (Norman and others, 1998).

DEPOSITS THAT ARE TYPICALLY NOT A RESOURCE

In general, the following geologic deposits are not suitable sources of sand and gravel aggregate in Spokane County. 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.

- Loess deposits—often identified as the Palouse Formation—consist of unstratified eolian silt, clay, sand, and ash, all of which are too fine to be used as a sand or gravel resource. In Spokane County, loess covers Columbia River Basalt anywhere erosive glacial floodwaters did not reach. Loess thickness ranges from >200 ft to <5 ft and averages about 20 ft (Joseph, 1990; Waggoner, 1990b).
- 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 interpret glaciolacustrine deposits; fine-grained glacial flood deposits; wetland deposits; and peat, bog, or marsh deposits as unsuitable for aggregate.
- Poorly sorted deposits often include clay and silt, which make it difficult to produce clean aggregate. Therefore, we generally interpret deposits such as alluvial fans, alluvium from small streams, altered land, and artificial fill as unsuitable for aggregate.

Rock and Stone Resources

IGNEOUS BEDROCK

Columbia River Basalt

The Columbia River Basalt Group is the most actively mined bedrock in Spokane County, with 22 active permit rock and stone mine sites. Abundant materials testing data support the quality of aggregate derived from Columbia River Basalt with 79 passing and incomplete-passing tests, and only 9 failing and incomplete-failing tests throughout Spokane County. For this report, the Wanapum Basalt, Grande Ronde Basalt, and Saddle Mountains Basalt formations are merged into the generalized aggregate unit 'Igneous bedrock' because of their similarities in the context of aggregate resources. In many areas, the Columbia River Basalts are capped with loess, glacial flood deposits, or nonglacial alluvium. Where there is evidence that overburden is a thin veneer (<10 ft thick), and therefore the underlying basalt may be accessible for aggregate mining, we mapped these areas as a Speculative rock and stone resource. In many areas where loess deposits are mapped, we were unable to estimate depth to bedrock because subsurface records were unavailable. This most likely resulted in underestimation of the area of rock and stone resources that only have a thin loess overburden, especially in the southeastern portion of the county.

Intrusive Rock

We speculate Eocene or younger granitic rock is a source of aggregate in Spokane County, while older (Cretaceous) intrusive rock is likely too weathered to be used as an aggregate resource. Although not actively mined for aggregate in the study area, Eocene Silver Point quartz monzonite, Rathdrum Mountain granite, Tumtum intrusive rock, and biotite granite in the Four Mound Prairie 7.5-minute quadrangle are all less weathered than Cretaceous granitic rock in the region and we classify them as Speculative sources of aggregate.

METAMORPHIC BEDROCK

Most Proterozoic rock in the study area is far too weathered, deformed, or weak to be used as an aggregate resource. However, quartzite of the Deer Trail Group and rock of the Wallace Formation of the Belt Supergroup have passing materials testing data. In the few areas where these rocks crop out in Spokane County, we classify them as Speculative aggregate resources.

ROCKS THAT ARE TYPICALLY NOT A RESOURCE

- Cretaceous and older granitic rock are often very weathered and not durable enough to be used as aggregate. Additionally, these rocks have a high mica content—a group of minerals that are soft and break along a flat plane—which could result in a less durable rock material. We reviewed materials testing results for granitic rocks in neighboring Stevens and Pend Oreille Counties. Granitic rock consistently failed the Los Angeles (LA) abrasion test (Taylor and others, 2009). Our own test results from craggy outcrops of Cretaceous and older granitic rock in Spokane County aligned with the failing results reported in Stevens and Pend Oreille Counties. Four samples of granite and pegmatite rock from the Mount Spokane area collected for this study failed LA abrasion tests and narrowly passed Washington Degradation tests. For these reasons, we classify Cretaceous and older granitic rock as Not a Resource.
- Gneissic units in the study area also have consistently failed materials testing. For this reason, the following geologic units were classified as Not a Resource: Newman Lake gneiss, Hauser Lake gneiss, gneiss of Mica Peak, gneiss of Cable peak, Striped Mountain gneiss, and gneiss near Table Mountain.
- The Latah Formation (Joseph, 1990) includes claystone, siltstone, and sandstone interpreted as Miocene lacustrine and fluvial deposits. This formation underlies and is interbedded with Columbia River Basalt. Because these rocks are easily eroded and often overlain by colluvium, talus, and soils, we classify the Latah Formation as Not a Resource.

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 data, current and historical mining activity, and lidar. We classified potential aggregate resources based on the quality, quantity, and certainty of the resource, and then performed proximity and developed-lands 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 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 other relevant 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. Where 1:24,000-scale geologic maps are not available, we used less detailed 1:100,000-scale geologic maps.

For this project, we compiled the surface geology from all published geologic maps within Spokane County with scales greater than or equal to 1:100,000 (see geologic data sources on the Map Sheet). There are thirteen 1:24,000-scale geologic maps in Spokane County covering about 40 percent of the county. Three 1:100,000-scale geologic maps were used for the remaining 60 percent of the county.

SUBSURFACE DATA

Two main data sources provide direct information about materials found underground, and both require drilling. The first data source 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 second data source is 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, bedrock beneath a thin layer of loess).

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, 620 subsurface records were used for this project.

AGGREGATE TESTING DATA

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 2024 standards for Hot Mix Asphalt (HMA) (WSDOT, 2024a). Current and historical test data are available from the WSDOT Aggregate Source Approval (ASA) database (WSDOT, 2024b). Per our request, WSDOT provided us with spatial data for testing sites that are viewable on their ASA Web Mapping Application. We digitized all available test results from WSDOT's ASA reports for test sites in Spokane County (220 test sites and 229 test reports). Sometimes WSDOT ASA reports only include one test result from either the LA abrasion or the Degradation tests. Prior to around 1970, the Degradation test was not a standard part of aggregate testing in Washington State. For this reason, we consider many of the older testing reports incomplete and we interpret these types of results as Incomplete Pass or Incomplete Fail, depending on the result of the available test.

To supplement the WSDOT data, in May 2024 we collected ten bedrock samples from various sites located on land managed by Spokane County and the Washington State Department of Natural Resources (DNR) or from rock outcrops adjacent to roads. These samples were tested by WSDOT's Materials Lab and the results are reported in Appendix A. Our sampling effort focused on rock units that were not represented in the WSDOT ASA database.

SURFACE MINE LOCATION DATA

We used the locations of active, inactive, and historical 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 mines with inactive permits, historical mines, 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 (WGS, 2024). We were provided access to SMRP records of inactive (canceled or terminated) permitted mines, permit boundaries, and reclaimed boundaries (Nicole Damer, WGS, written commun., 2024). As of July 2024, there were 63 active permitted aggregate mines and 97 inactive (canceled or terminated) permitted mines in Spokane County. In addition, we received information from SMRP's regional surface mine specialists on active permitted sites that have transitioned from resource extraction to site reclamation (Kelsay Stanton and Ben Stanton, WGS, written commun., 2023 and 2024). Each SMRP permit corresponds to a single mining commodity. For this project we only include SMRP sites permitted for sand-and-gravel and rock-and-stone commodities and leave out sites permitted for other commodities such as dolomite and clay. In Spokane County, six sites permitted for sand and gravel also mine rock and stone, and one site permitted for rock and stone also mines sand and gravel resources. For these seven unique sites, we have noted these mining commodity nuances in the 'surface mine site' feature class within the GIS data that accompany this report (these data can be accessed through the WGS Geologic Information Portal). We also included prospect- and mine-related point features (points that were not included in the SMRP database) from digitized versions of USGS topographic maps from 1949–1981 (Horton and San Juan, 2016). These data represent historic and (or) small mining operations including 271 gravel, borrow, or sand pits and 19 open pit mines or quarries in Spokane County.

LIDAR

Airborne lidar is a detailed topographic dataset collected by airplane, typically with a horizontal resolution of 3 ft and a vertical accuracy of <1 ft. Lidar 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 where the geologic mapping was either insufficiently detailed or where there was a mismatch in adjacent published maps. In areas that had been mined, we used 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 used lidar elevation data to estimate resource thickness. We used lidar data collected between 2005 and 2020 from eight different lidar projects that cover about 76 percent of Spokane County (Washington Geological Survey, 2005, 2007, 2013, 2015, 2016, 2019a, 2019b, 2021).

LANDSLIDE DATA

Landslide areas and deposits are generally not good sources of aggregate because landslide deposits are poorly sorted. For this reason, we chose to exclude areas that intersect with the best available landslide mapping for Spokane County, which is WGS's

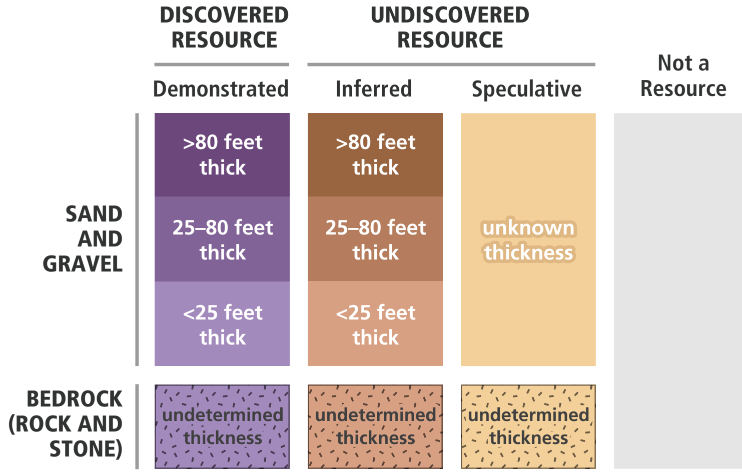

Figure 3. Generalized aggregate resource classification scheme used in this study. In general, the level of knowledge and certainty decreases from Demonstrated resources to Speculative resources; regions classified as Not a Resource may or may not have a high level of knowledge and certainty. Note that bedrock resources are mined for rock and stone commodities and we use the terms 'bedrock' and 'rock and stone' interchangeably.

Washington State Landslide Inventory Database (Washington Geological Survey, 2023b). This dataset shows landslides compiled from a variety of sources mapped over the past few decades. In some places there are landslide polygons mapped at different times that overlap each other. Rather than pick and choose which landslide polygon is the 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 legibility at 1:24,000 scale. Additionally, where landslides have been mapped over water, we chose to preserve the water boundary in our data. Note that at the time of our analysis, there was no lidar-informed landslide inventory for Spokane 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 detailed investigation of potential slope instability by a qualified practitioner.

Resource Classification Scheme

OVERVIEW

Our classification scheme (Fig. 3) provides a framework for making consistent decisions and interpretations about aggregate resources from available data. Like 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 divided resources by their quality and available thickness and imposed 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 accommodate 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 chose one of the most common uses—Hot Mix Asphalt—and assessed quality based on the requirements of this product, as detailed by the 2024 Standard Specifications of the Washington State Department of Transportation (WSDOT, 2024a). 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. 3). 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 present, 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 subdivided Demonstrated and Inferred resources into three bins according to their estimated thickness: <25 ft thick, 25–80 ft thick, and >80 ft thick (Fig. 3). 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 these resources economically viable in the future. Because the thickness of bedrock resources is difficult 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.

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 the data described earlier in *Sources of Data* while excluding land that falls outside the scope of our work. For Spokane County, we excluded areas that intersect with the WGS landslide database (WGS, 2023b) and land within the boundaries of Turnbull National Wildlife Refuge (Konzek, 2024). In general, water boundaries represented on 1:100,000-scale geologic maps were used. More detailed water boundaries were used wherever 1:24,000-scale geologic maps were available. The water boundaries at these two scales do not always align where they meet at map boundaries.

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. In some cases, areas surrounding an active surface mine were classified as Speculative or Inferred based on our classification scheme (Table 1). Any areas within active permitted mine sites we knew to be undergoing reclamation (or which 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 resources depending on the availability of site-specific data in their vicinity (Table 1).

We used subsurface data (in conjunction with geologic unit descriptions and cross sections) to estimate the thickness of some geologic deposits and to modify the boundaries of the geologic unit polygons that form the initial basis of our inventory. Subsurface records were classified as Good, Bad, Thin, or Other. 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 ft thick may not be economically viable to extract. We interpreted subsurface records that record primarily bedrock as 'Other' and recorded the depth to bedrock in feet. Because the inventory does not attempt to calculate volume of bedrock sources, thickness of bedrock was not recorded. For all analyzed records, the actual thicknesses of aggregate material and overburden (if present) were 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 exists 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 only once in Spokane County where available subsurface records indicate a thin loess deposit— Not a Resource—is underlain by Columbia River Basalt rock—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 nonglacial alluvial deposits as aggregate resources depends on the size of the river system and the geology and geometry of the drainage basin. Deposits from major alluvial systems could be sources of aggregate because they typically produce well sorted, thick, and extensive sand and gravel deposits. Our workflow included reviewing all alluvial geologic deposits 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 or <1 acre) were trimmed, extended, or merged to achieve legibility at 1:24,000 scale.

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 high 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 (canceled or terminated permit) aggregate mines or quarries, or historical mining activity.	Sometimes intersects with or adjacent to small mining operations, inactive (canceled or terminated permit) aggregate mines or quarries, or historical mining activity.	Sometimes intersects with or adjacent to small mining operations, inactive or reclaimed (canceled 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.
Consistency of evidence *Lower priority 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%.

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 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). 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.

Table 2. Recoverability values used in this study.

Variable	Conditions	Recoverability
Geologic recoverability (R_{gl} and R_{gh})	Glacial flood deposits	80–90%
	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%
	Deeply and pervasively incised surface	70%

ESTIMATING VOLUME AND TONNAGE

We modeled the three-dimensional shape of each aggregate resource as its mapped polygon extruded to its thickness (Fig. 4). 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. 4).

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

Equation 1. $$V_{low} = A \times D_{low} \times R_{gl} \times R_t \times R_w \times C - V_{mined}$$

Equation 2. $$V_{high} = A \times D_{high} \times R_{gh} \times R_t \times R_w \times C - V_{mined}$$

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 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 for Spokane County), or by consulting the most recent mine operators report for estimated mine depth (Fig. 4). V_{mined} was calculated with:

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

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

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

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

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

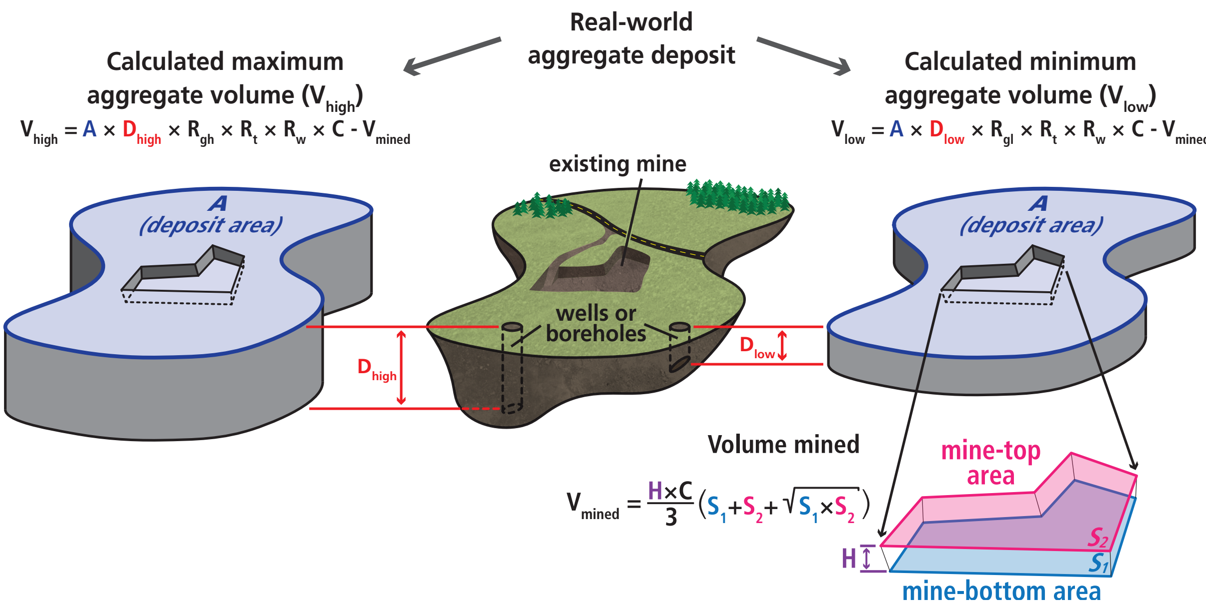

Figure 4. Method used to calculate the volume of a resource polygon. If a surface mine was present, we subtracted the volume of material that had already been removed from the volume of the whole aggregate deposit. Variables are explained in Table 3.

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 ranges. 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.

The estimated thicknesses of sand and gravel deposits are highly variable in subsurface data from Spokane County, usually due to the variability in the depth of geotechnical boreholes and water wells, which can range from tens to hundreds of feet deep. Therefore, our volume and tonnage estimates have larger ranges than those for other counties, reflecting a greater uncertainty around the true thickness of many resource deposits in Spokane County.

Developed Land Classification

Aggregate resources located on land that has already been developed are generally unavailable for extraction. Our inventory workflow method did not consider current land use in deciding the quantity and quality of a resource. This results in an inventory that overestimates the amount of available resource where land has been built on. 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 (98-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 June 2024. 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.

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)

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 where it is sourced to 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 Spokane County, we performed two analyses. The first calculates aggregate transportation distances along roads from active mines in Spokane County. This analysis reveals areas in the county that have limited road 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 Spokane County actively extracting material and calculated a 10-mile service area from each of these sources of aggregate along the public road transportation network. Our analysis used 53 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 (Kelsay Stanton and Ben Stanton, Washington Geological Survey, written commun., 2023, 2024). 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 Spokane County, we did not include any permitted mines from neighboring counties or states 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 11 aggregate demand points in Spokane County. Aggregate demand points are locations that use aggregate resources. 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 this analysis, our 11 aggregate demand points represent eight cities and three large, future transportation projects. We included the cities of Spokane, Spokane Valley, Cheney, Liberty Lake, Airway Heights, Medical Lake, Deer Park, and Millwood (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. We placed the aggregate demand points for these eight cities at major road intersections near the centroid of the city boundary, so they may not align with the traditional mapped city centers. From Spokane County's 2024–2029 Transportation Improvement Program, we selected the locations of three upcoming projects that require aggregate resources (Spokane County, 2024). 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 11 aggregate demand points.

For both proximity analysis scenarios, we used the 'Service Area Solver' tool within the Network Analyst extension using the 'asyncServiceArea' service in ArcGIS Pro 2.9.11. The Service Area solver tool uses road data from ArcGIS Online's network dataset. 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 the transportation network, the travel mode settings, and the driving distances used in our analyses are representative of actual aggregate transportation in the study area, but acknowledge that our analyses may not reflect the needs of all users.

AGGREGATE RESOURCE INVENTORY RESULTS

Resource Estimates

Our results identify Demonstrated, Inferred, and Speculative sand-and-gravel and bedrock aggregate resources in Spokane County (see Map Sheet). In total, we identify 574,681 acres of land as having the potential for aggregate resources, about 51 percent of the county's land area (Table 4). This total is divided into 328,976 acres of sand and gravel aggregate resources and 245,705 acres of bedrock resources (Fig. 5). For sand and gravel resources mapped as Inferred and Demonstrated (our two highest-certainty classifications), we estimate 7.4 to 26.4 billion cubic yards of sand and gravel aggregate—approximately 11.8 to 47.5 billion tons (Fig. 6). For comparison, Washington State produced approximately 40 million tons of sand and gravel aggregate in 2022 (National Minerals Information Center, 2024). Note that the ranges for volume and tonnage estimates in this inventory are larger than those in other counties we have mapped due to variability in subsurface records in Spokane County. Because of the difficulty of quantifying the thickness of bedrock aggregate resources, we did not estimate their volume or tonnage.

DEMONSTRATED RESOURCES

Within Spokane County, there are a total of 3,389 acres of Demonstrated resources (Table 4), which include 2,725 acres of sand and gravel resources and 664 acres of bedrock resources. We estimate between 270 million and 307 million cubic yards of sand and gravel within this category (Fig. 6). Based on NLCD data, about 10 percent of the Demonstrated sand and gravel resources are located on developed land; about 16 percent of Demonstrated bedrock resources are on developed land.

INFERRED RESOURCES

Within Spokane County, there are a total of 372,035 acres of Inferred resources (Table 4), which include 149,220 acres of sand and gravel resources and 222,815 acres of bedrock resources. We estimate Inferred resources contain between

Table 4. Area, volume, and tonnage estimates for potential aggregate resources in Spokane 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	**2,725** *(2,441)*	**270** *(242)*	**308** *(276)*	**432** *(387)*	**554** *(496)*
Inferred	**149,220** *(86,958)*	**7,156** *(3,451)*	**26,097** *(12,875)*	**11,450** *(5,521)*	**46,974** *(23,175)*
Speculative	**177,031** *(156,513)*				
Subtotal	**328,976** *(245,912)*	**7,426** *(3,693)*	**26,405** *(13,151)*	**11,882** *(5,908)*	**47,528** *(23,671)*
Bedrock/rock and stone					
Demonstrated	**664** *(555)*				
Inferred	**222,815** *(209,572)*				
Speculative	**22,226** *(21,559)*				
Subtotal	**245,705** *(231,686)*				
Total area of all aggregate resources					
Total	**574,681** *(477,598)*				

Bold = entire inventory
(Italics) = undeveloped areas only

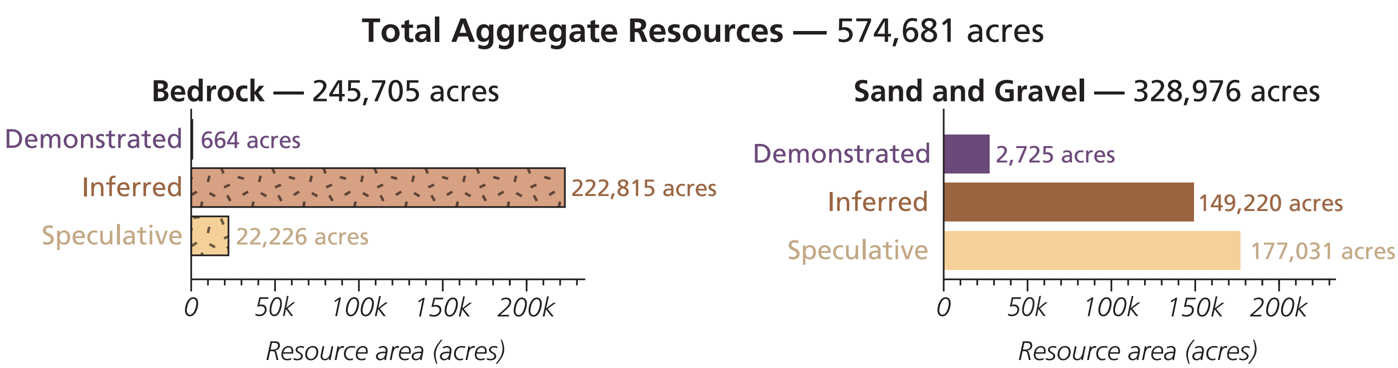

Figure 5. Distribution of material types and quality classifications of inventoried aggregate resources in Spokane County.

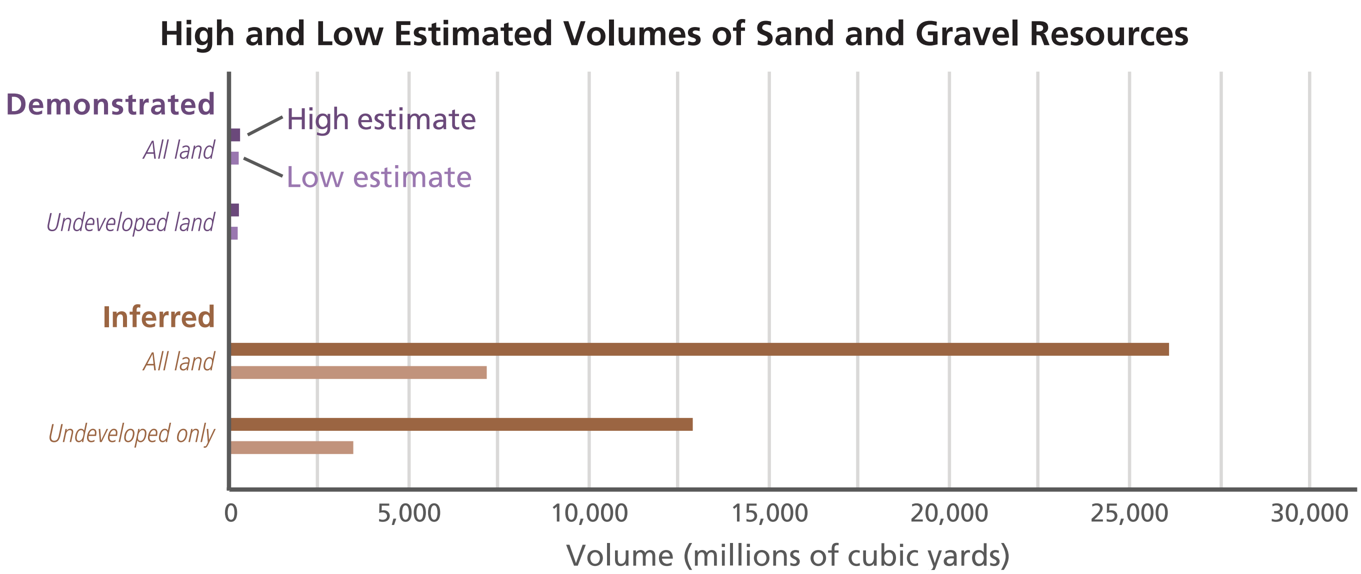

Figure 6. Volume estimates of Demonstrated and Inferred sand and gravel aggregate resources. 'All land' denotes volumes for the full inventory without consideration of land use, while 'Undeveloped land' filters the inventory to only areas classified as undeveloped by the NLCD.

7.2 and 26.1 billion cubic yards of sand and gravel (Fig. 6). Note that the ranges for volume and tonnage estimates in this inventory are larger than those in other counties we have mapped due to variability in subsurface records in Spokane County. According to NLCD data, about 42 percent of Inferred sand and gravel resource areas are located on developed land; about 6 percent of Inferred bedrock resource areas are on developed land. Taking into consideration the large percentage of Inferred resource areas impacted by developed lands according to the NLCD, we estimate undeveloped Inferred sand and gravel resources contain between 3.5 and 12.9 billion cubic yards of sand and gravel (Table 4).

SPECULATIVE RESOURCES

Within Spokane County, there are a total of 199,257 acres of Speculative resources (Table 4), which include 177,031 acres of sand and gravel resources and 22,226 acres of bedrock resources. Because we lack thickness information for Speculative resources, we do not estimate their volume or tonnage. According to NLCD data, about 12 percent of Speculative sand and gravel resources and about 3 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 not be accessible due to development. Overall, about 17 percent of the total area we classified as potential aggregate resources—about 97,084 acres—is classified as developed according to data from the NLCD and is likely to be inaccessible for resource extraction. Total areas of potential aggregate resources in undeveloped areas are provided in Table 4. Inferred sand and gravel resources were the most impacted by the NLCD analysis. In our inventory, 42 percent of Inferred sand and gravel resource areas are located on developed lands. Taking developed lands into consideration, we estimate undeveloped Inferred sand and gravel resources contain between 3.5 and 12.9 billion cubic yards of sand and gravel (Table 4), a reduction in our total Inferred sand and gravel volume by about 50 percent.

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 10-mile service area around actively extracting mines in Spokane County (Fig. 7). We interpret the areas outside of the 10-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 29 percent of the county could be interpreted as a 10-mile aggregate desert. Some of these areas may be outside the 10-mile service area because they lack roads or because a mine site is located adjacent to a one-way road which impacts its service area. This analysis reveals that the distribution of mines in Spokane County at the time of this study is serving most of the county area.

The second proximity analysis models a 10- and 20-mile transportation distance outward from 11 points of aggregate demand: 8 cities (Spokane, Spokane Valley, Cheney, Liberty Lake, Airway Heights, Medical Lake, Deer Park, and Millwood); and 3 large, future transportation projects, showing which potential resources are close to areas that use aggregate (Fig. 8). About 51 percent of potential aggregate resources are within 10 mi of the aggregate demand points, and about 89 percent are within 20 mi. Only 11 percent of the potential aggregate resources are more than 20 mi from the selected aggregate demand points. Potential resource areas close to populated areas and construction project

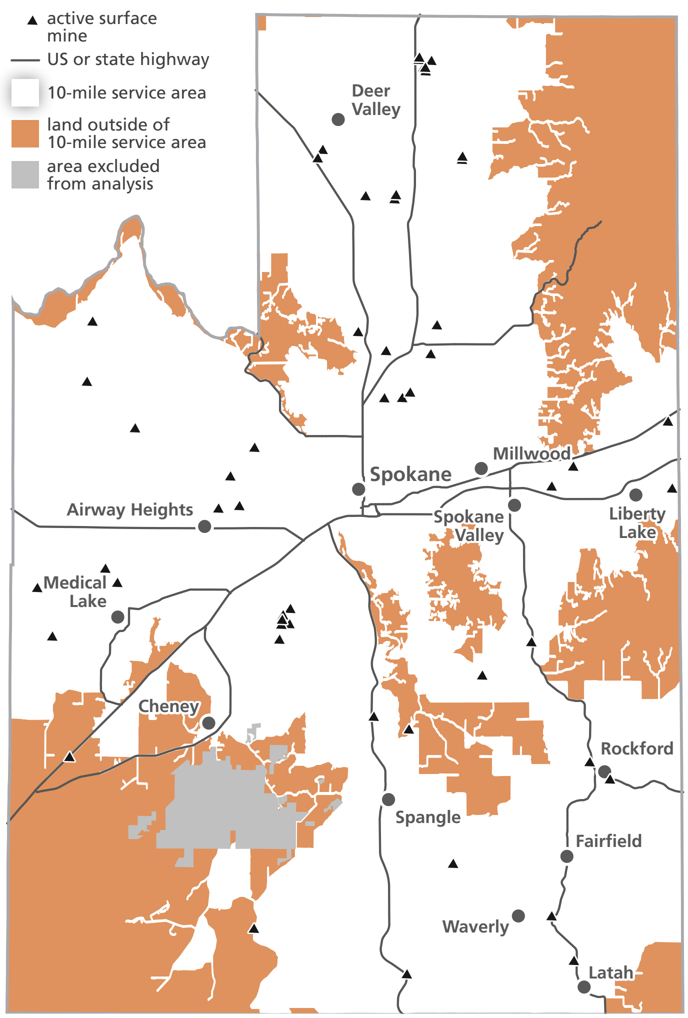

Figure 7. Proximity analysis using currently active aggregate mines in Spokane County and a 10-mile service area. Gray shading shows areas excluded from the analysis; orange shading highlights areas that fall outside of the service area and may experience higher aggregate transportation costs.

areas present an opportunity to source aggregate closer to where it is needed and to reduce transportation costs. Resource polygons that fall outside of these transportation zones may represent future aggregate sources that could serve future populations or different transportation projects 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. Key takeaways from the report are:

- Our inventory identifies 574,681 acres—about 51 percent of Spokane County's land area—as having the potential for aggregate resources.
- The approximately 21,000-acre Turnbull National Wildlife Refuge was not analyzed for this inventory because of federal protections that restrict the development of new mines.
- The inventory identifies 328,976 acres as sand and gravel resources and 245,705 acres as rock and stone resources.
- For sand and gravel resources mapped as Demonstrated and Inferred, we estimate 7.4 billion to 26.4 billion cubic yards of aggregate (11.9 billion to 47.5 billion tons).
- An analysis of the proximity of areas to currently active mines reveals an accessible distribution of active mine sites with only 29 percent of the county falling outside of a 10-mile aggregate transportation distance.
- An analysis of the proximity of resources to areas of aggregate demand reveals that approximately 89 percent of our inventory falls within a 20-mile drive from 11 assumed points of high aggregate demand. With only 11 percent of the inventory falling outside of a 20-mile driving distance, the potential resources in the inventory are very accessible to current areas of aggregate demand.
- We also find that approximately 97,084 acres—or 17 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.

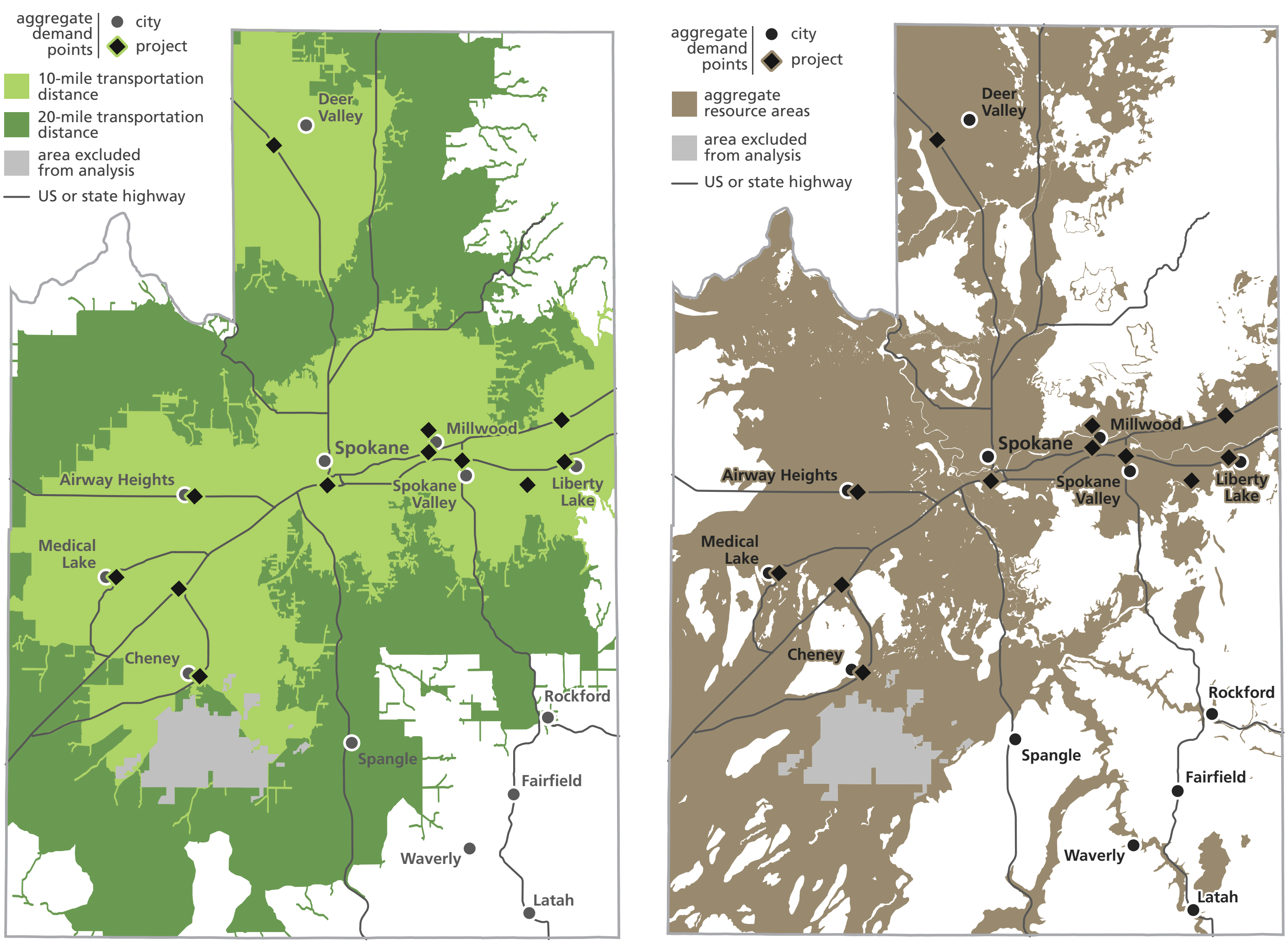

Figure 8. *Left:* Proximity analysis showing a 10-mile and 20-mile outward service area from fifteen points of aggregate demand: eight cities (Spokane, Spokane Valley, Millwood, Liberty Lake, Airway Heights, Medical Lake, Cheney, and Deer Valley), and three upcoming projects that require aggregate resources. Right: Distribution of aggregate resource areas in Spokane County (see Map Sheet).

AUTHOR CONTRIBUTIONS

A. Rudko and A. Steely developed the methods used in this report. A. Rudko completed the aggregate resource classification workflow, calculated the area, volume, and tonnage estimates, completed the developed lands and proximity to markets analyses, and led field work. A. Steely reviewed the GIS data and provided comments and minor additions to the pamphlet.

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Appendix A. New Aggregate Testing Data

We collected and tested ten 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-owned land or Spokane County parcels in coordination with DNR region engineers and county staff. We collected 10 gallons of rock at each site. No additional processing was needed prior to laboratory analysis. In May 2024, all the samples were sent to WSDOT Materials Laboratory for testing according to standard methods described in the Washington Department of Transportation Materials Manual (WSDOT, 2024c). 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-SE-1	7/23/2024	28	67	Pass
Latitude	47.55348	Sampling Notes: Sampled from unit Ymsw (Hamilton and others, 2004a). Sampled from rock pieces at base of the outcrop adjacent to road. Used rock hammer to break rock into a more appropriate size for sample. Some pieces were too hard to break with a rock hammer. Most rocks had planar bedding visible, some had more gneissic fabric, and some had abundant micas.		
Longitude	-117.62167			
Generalized Aggregate Unit	Metamorphic bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-SE-2	7/23/2024	55	60	Partial Fail
Latitude	47.98501	Sampling Notes: Sampled from unit $Kiat_s$ (Joseph, 1990) Sampled directly from outcrop and larger float near outcrop. Used sledgehammer to break pieces into sample size. Lots of grus (weathered granite) at the base of the outcrop. Highly variable sample including pieces with large micas, aplite, and medium to coarse grained granodiorite.		
Longitude	-117.18370			
Generalized Aggregate Unit	Intrusive bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-SE-3	7/29/2024	60	32	Partial Fail
Latitude	47.97829	Sampling Notes: Sampled from unit Tkiaa (Joseph, 1990) from roadcut. Easily broken with sledgehammer or by simply dropping rock pieces on the ground. Outcrop was highly weathered with large micas and goethite (weathered iron oxide).		
Longitude	-117.17107			
Generalized Aggregate Unit	Intrusive bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-SE-4	7/23/2024	66	30	Partial Fail
Latitude	48.00576	Sampling Notes: Sampled from unit Kog_{ms} (Waggoner, 1990a). Used sledgehammer and rock hammer to pry off pieces from the roadcut. This sample had many similarities to sample WGS-SE-2.		
Longitude	-117.12628			
Generalized Aggregate Unit	Intrusive bedrock			
Commodity	Rock and stone			

Table A1. Continued.

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-SE-5	7/29/2024	45	43	Partial Fail
Latitude	47.96675	Sampling Notes: Sampled from unit Kg (Hamiliton and Derkey, 2005). Sampled from a small DNR ‘pit’ that was used to repair a forestry road. Collected small pieces and used sledgehammer to break fresh pieces to an appropriate sample size.		
Longitude	-117.32654			
Generalized Aggregate Unit	Intrusive bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-SE-6	8/1/2024	71	30	Partial Fail
Latitude	47.79763	Sampling Notes: Sampled from unit Knl (Derkey and others, 2004d). Used sledgehammer to break off chunks from outcrop into sample-sized pieces. Strongly weathered.		
Longitude	-117.05905			
Generalized Aggregate Unit	Metamorphic bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-SE-7	8/1/2024	35	70	Partial Fail
Latitude	47.72144	Sampling Notes: Sampled from unit Ki (Derkey and others, 1999). Collected sample from active road construction site. Area was freshly blasted and we collected rock sample from base of rock wall. Rock texture ranged from porphyritic to massive. Mylonitic foliation at lower outcrop.		
Longitude	-117.32593			
Generalized Aggregate Unit	Intrusive bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-SE-8	8/1/2024	31	51	Partial Fail
Latitude	47.64905	Sampling Notes: Sampled from unit pTog (Derkey and others, 1999). Sampled at quarried rock face adjacent to parking lot of a permitted mine site that has undergone extensive reclamation work. We speculate that while this unit was mined at this site, the primary commodity was basalt.		
Longitude	-117.34435			
Generalized Aggregate Unit	Metamorphic bedrock			
Commodity	Rock and stone			

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-SE-9	8/1/2024	72	7	Fail
Latitude	47.37839	Sampling Notes: Sampled from unit Yms_{sr} (Waggoner, 1990b). Sampled from county pit wall that was blasted about 15 years ago. Sampled a variety of the formation including meta sandstone and siltite. County stated that road made using this pit weathered quickly and would likely not be used again for road gravel for this reason.		
Longitude	-117.05502			
Generalized Aggregate Unit	Metamorphic bedrock			
Commodity	Rock and stone			

Table A1. Continued.

Sample ID	Test Date	LA Abrasion Value	Degradation Value	Overall Test Result
WGS-SE-10	8/1/2024	51	50	Partial Fail
Latitude	47.70073	Sampling Notes: Sampled from unit p€bgh (Joseph, 1990). Used sledgehammer to break larger pieces off of outcrop and into an appropriate size for sampling. Collected from an area that was mapped as having both Hauser Lake and Newman Lake Gneiss. I sampled the more weathered and schistose rock here rather than the darker gray rock I interpreted to be Newman Lake Gneiss (unit Knl).		
Longitude	-117.16028			
Generalized Aggregate Unit	Metamorphic bedrock			
Commodity	Rock and stone			