EVALUATING THE HYDROGEOLOGIC POTENTIAL FOR AQUIFER STORAGE AND RECOVERY (ASR) IN THE DEEP AQUIFER OF THE FLATHEAD VALLEY, NORTHWEST MONTANA

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Montana Bureau of Mines and Geology

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Cover Photo: Canola in bloom in the Flathead Valley, with the Swan Range in the background. Photo by James Berglund, formerly with the MBMG, currently with the University of Wisconsin-Platteville.

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ABSTRACT

Managed aquifer recharge (MAR) is the purposeful addition of water to aquifers for storage and later use and/or ecological benefit. Aquifer storage and recovery (ASR) is a common MAR method in which water is injected into, and extracted from, an aquifer using wells.

We developed a hydrogeologic ASR screening tool for evaluating the suitability of using ASR in the deep aquifer of the Flathead Valley, northwest Montana. A geographic information system (GIS) and a multi-criteria decision analysis approach were used. Three criteria were rated for the suitability analysis: thickness of the unconsolidated sediments below the confining layers, available drawup, and vertical confinement. Ratings were assigned to each class within the criteria from 0 to 100 based on quantitative and qualitative measures, and professional experience in the area. The criteria were evenly weighted and combined to obtain a maximum suitability score of 100. A sensitivity analysis was conducted on the criteria weights.

Final ASR suitability scores ranged from 0 to 100, and the scores were grouped as "high" (>75), "medium" (50–75), and "low" (<50). High suitability scores covered 26% of the area, 28% was medium, and 45% was low. This evaluation shows that physical hydrogeologic conditions favorable for ASR occur in the area from Kalispell to Whitefish and Columbia Falls, and in an area north of Lake Blaine. The sensitivity analysis showed that equal weighting of the criteria highlighted the high and low suitability areas well, and the medium suitability areas tended to increase or decrease depending on the criterion considered important. A web application (Web App) is provided in addition to this report at https://gis-data-hub-mbmg.hub.arcgis.com/apps/547572190d2b4d7b9ded12687659910d/explore. The Web App guides the reader through the criteria rating, enables browsing at various scales, and provides a platform to explore the final suitability map with other GIS datasets.

This valley-wide evaluation is based on publicly available data, and is intended as a first step to identify areas suitable for ASR based on physical hydrogeologic properties. Additional local investigations and/or pilot studies will be needed to further evaluate potential sites. Other criteria will also need to be evaluated, such as physical and legal availability of recharge water, recharge water quality, recharge water pre-treatment requirements, aquifer geochemistry/mineralogy, native water quality, the potential for geochemical interactions between the recharge water and aquifer materials or native groundwater, land ownership, nearby wells, and economic feasibility.

INTRODUCTION

As Montana's population continues to grow and there are uncertainties about water availability due to drought, there is a growing interest throughout the State in enhancing water supplies by increasing water storage (DNRC, 2015). This could include seasonal or multi-year storage. Managed aquifer recharge (MAR) provides a means to supplement water supplies by intentionally recharging aquifers.

The benefits of MAR are well documented (e.g., Dillon, 2005, Pyne, 2005; Dillon and others, 2019; Parker and others, 2022) and can include:

- improved water supply reliability for agriculture and community systems;
- drought preparedness by increasing water storage in aquifers for use in dry years;
- aquifer replenishment in areas where groundwater is being overdrawn, recharge has been reduced due to changes in land use, or there has been prolonged drought;
- ecosystem enhancement by increasing stream flow during low-flow periods, and improving riparian habitat, wetlands, and fisheries;
- improved water quality by diluting high total dissolved solids and/or other undesirable constituents in native water with recharge water; and
- flood risk reduction by slowing runoff, skimming peak flows, and/or lowering reservoir stage.

The primary approaches to MAR are surface infiltration and aquifer storage and recovery (ASR; Parker and others, 2022). Surface infiltration is typically accomplished by ponding water in percolation basins/pits, running water through unlined leaky canals or ditches, using shallow infiltration galleries, flooding fields during the non-irrigation season, or constructing channel modifications to enhance infiltration and recharge of water into unconfined aquifers. Where land is available, and hydrogeology is suitable, surface infiltration is typically the most cost-effective option for recharging unconfined aquifers (Pyne, 2005). A statewide evaluation of surface infiltration potential in Montana was recently completed by Hanson and others (2024). ASR uses wells to inject water into targeted aquifers that are sufficiently thick and permeable to accept useful water volumes, and to extract water when it is needed (fig. 1; Pyne, 2005; NGWA, 2025). ASR is generally, but not exclusively, used in confined aquifers.

The Montana State Water Plan (DNRC, 2015) recognized that aquifers can provide a means of water storage by retaining high spring flows when the "physical supply exceeds downstream legal demands." In 2011, the Montana Legislature adopted an approach to facilitate reallocating existing water rights for aquifer recharge (MCA 85-2-420). However, DNRC (2015) reports that it has not been widely adopted due to a lack of research "in the area of aquifer recharge."

Purpose and Scope

The purpose of this project is to evaluate the hydrogeologic potential to use ASR wells completed in the deep aquifer in the Flathead Valley of northwest Montana (fig. 2). The focus on the deep aquifer is based on previous work in the area (summarized below) that suggests that this aquifer has the greatest potential for ASR in the Flathead Valley. The analysis of ASR at the valley scale rather than a statewide scale (as was done by Hanson and others, 2024, for surface infiltration) reflects the high variability in geologic settings throughout Montana, the need to tailor the analysis of ASR to the hydrogeologic setting, and the availability of data in the Flathead Valley from previous studies in the area.

This hydrogeologic analysis focuses on identifying areas that show potential to accept, store, and release water through an ASR process. There are many other important considerations that need to be addressed for an ASR project (Pyne, 2005; Brown and others, 2005), such as:

- physical and legal availability of recharge water (e.g., water rights) over time;
- location of ASR site relative to available recharge water;
- recharge water quality and how it changes over time;
- native groundwater quality;
- compatibility of the recharge water with native groundwater and the aquifer materials;
- temporal demand for recovered water;
- ecological considerations, such as effects on stream flows;
- economic considerations, such as the costs for construction, maintenance, and power;
- location relative to other water facilities, such as water treatment plants;
- permitting requirements; and
- site-specific considerations, such as land ownership, existing wells, or the presence of 3-phase power.

A web application (Web App) was designed in coordination with this report and is available at https://gis-data-hub-mbmg.hub.arcgis.com/apps/547572190d2b4d7b9ded12687659910d/explore. This Web App is intended to help the reader understand the process and explore the results with other geographic information system (GIS) datasets.

Hydrogeologic Framework

The Montana Bureau of Mines and Geology (MBMG) has conducted several studies in the Flathead Valley that, along with previous work, inform the hydrogeologic framework. MBMG's Ground Water Assessment Program (GWAP) has 34 long-term monitoring wells in the Flathead Valley, with many having been monitored quarterly since the early 1990s. MBMG's Ground Water Information Center (GWIC; https://mbmggwic.mtech.edu/) includes well logs for about 14,000 wells in the Flathead Valley. MBMG's Ground Water Characterization Program (GWCP), which characterizes groundwater resources on a multi-county scale, conducted fieldwork mostly in the late 1990s, and produced a series of reports on the hydrogeology of the area (LaFave, 2000; Patton and others, 2003; LaFave and others, 2004; Smith and others, 2004; LaFave, 2004a,b; Smith, 2004a–f; McDonald and LaFave, 2004). MBMG's Ground Water Investigations Program (GWIP), which investigates specific groundwater-related questions over smaller areas,

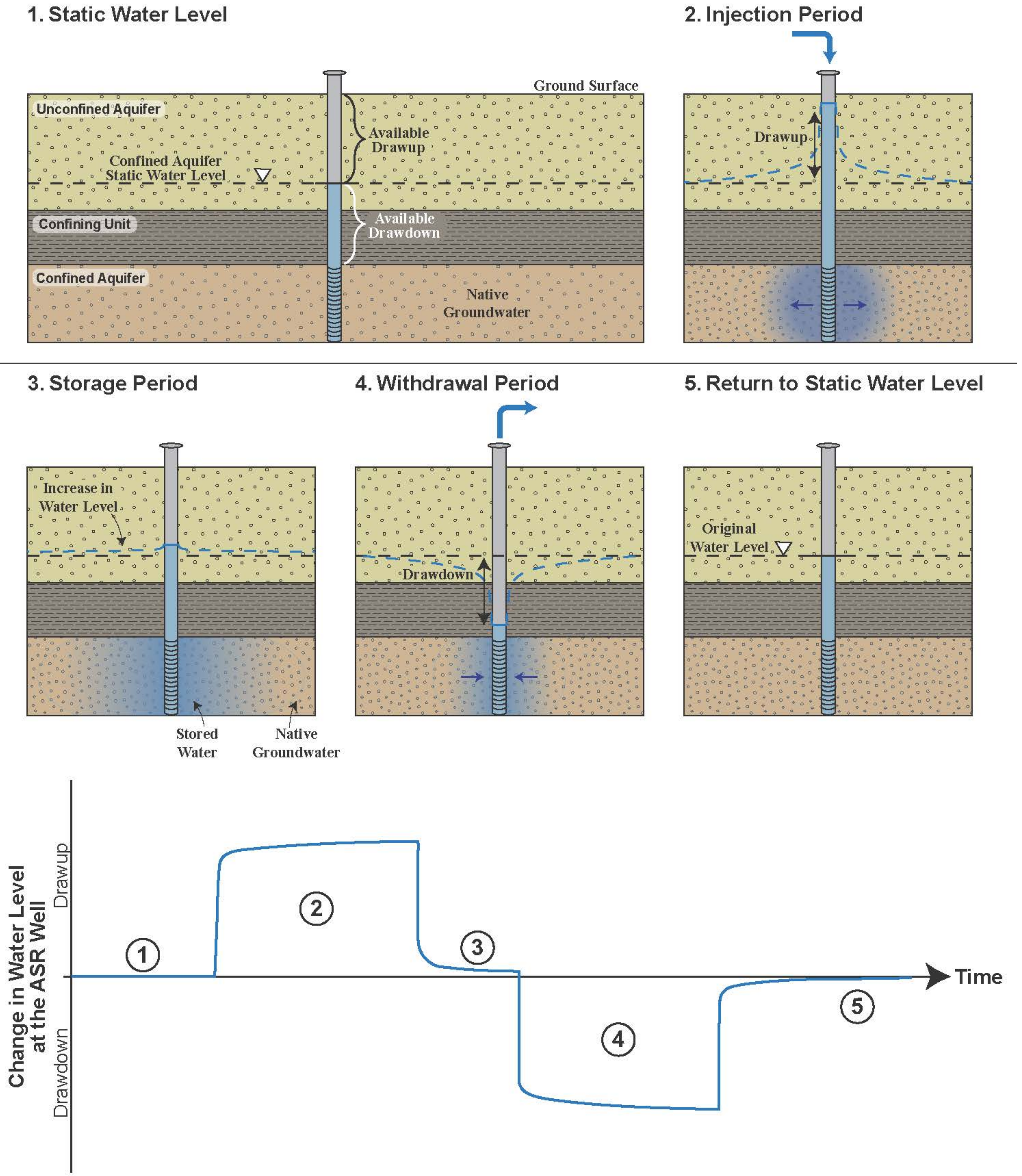


Figure 1. The stages of the injection process are visualized in the diagrams, including: (1) pre-injection artesian static water level in the confined aquifer, (2) injection period where drawup occurs, (3) storage period where stored water dissipates from the ASR well and results in an increased water level, (4) withdrawal period where the stored water is removed and drawdown occurs, and (5) post-withdrawal where the groundwater levels eventually return to the original static water level. Aquifer configuration may vary at different locations. For example, an unconfined aquifer may not be present, the confining unit may be thicker, the target aquifer may not be confined, etc. Conceptual hydrograph of injection and withdrawal at the ASR well is shown at the bottom with the stages labeled.

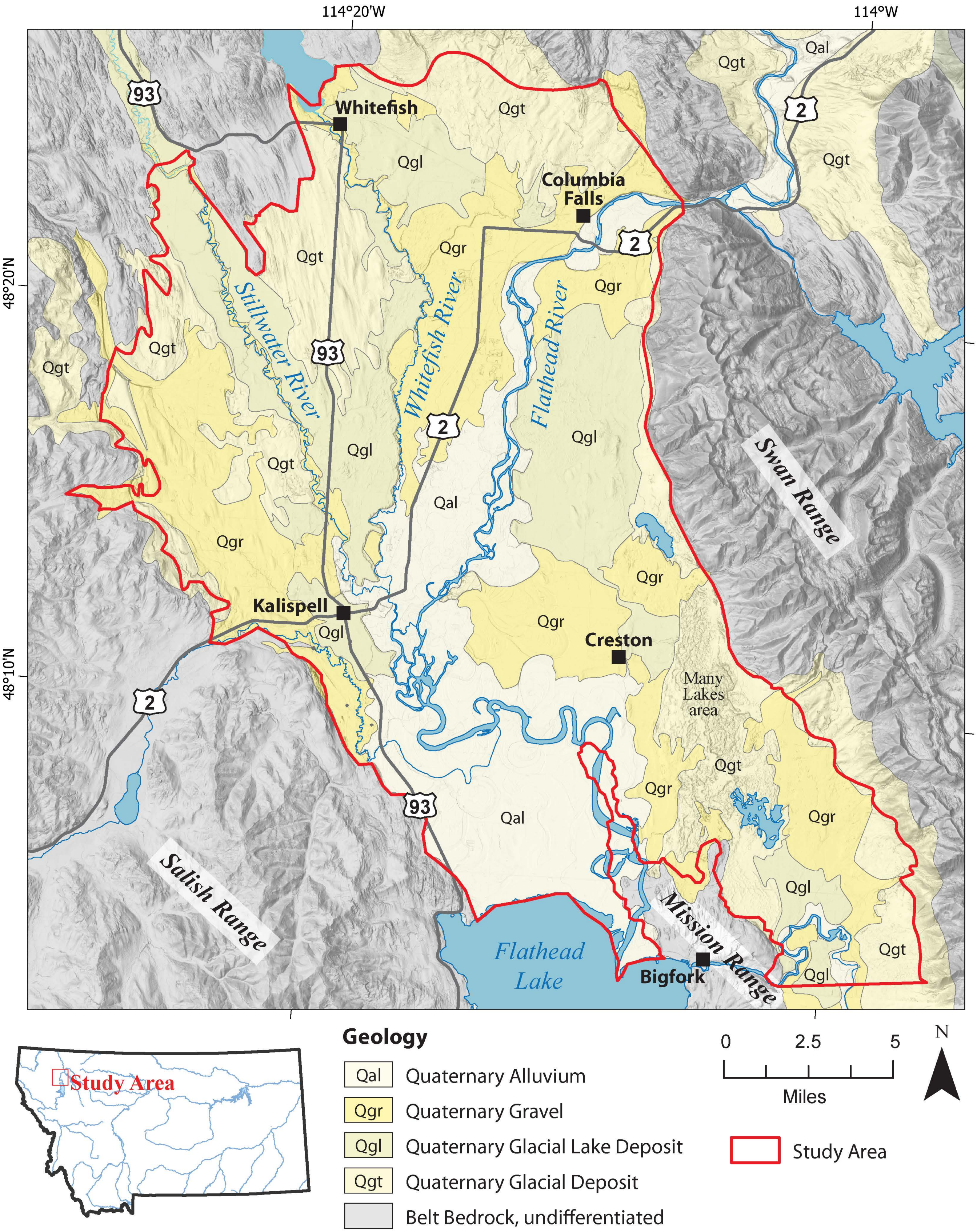


Figure 2. The Flathead Valley, in northwest Montana, contains various sedimentary deposits including alluvial and glacial deposits (modified from Vuke and others, 2007). For a more detailed geologic map of the area see Smith (2004a).

conducted investigations focused on the deep aquifer (Rose, 2018; Rose and others, 2022), the thickness of the deep aquifer and the composition of the underlying unconsolidated Tertiary sediments (Bobst and others, 2022), and the hydrogeology of the east side of the Flathead Valley (Myse and others, 2023; Berglund and others, 2024; Smith and Bobst, 2025; Bobst and others, 2025).

Physiography

The Flathead Valley has low relief, with elevations ranging from about 2,900 ft above mean sea level (ft-amsl) near Flathead Lake to about 3,100 ft-amsl near Whitefish and Columbia Falls. The surrounding mountains reach elevations above 7,000 ft-amsl. The elevation of Flathead Lake depends on the operations of Seli'š Ksanka Qlispe' Dam, approximately 5 mi west of Polson, on the south side of Flathead Lake. The lake covers about 200 mi^2 at full pool, and the elevation is typically held between 2,885 and 2,892 ft-amsl.

Structure

The Flathead Valley is the southernmost expression of the Rocky Mountain Trench, which extends over 1,000 mi north into the Yukon Territory, Canada (Garland and others, 1961; Harrison and others, 1992). The Rocky Mountain Trench formed by extension where the bedrock beneath the valleys dropped relative to the surrounding terrane along normal faults, such as along the west flank of the Swan Range (figs. 2, 3). Gravity and seismic surveys (Konizeski and others, 1968; LaPoint, 1971; Stickney, 1980; Wold, 1982) along with well logs indicate that the bedrock surface beneath the valley is asymmetrical, with greater downdropping along the east side of the valley (Smith, 2004b). A thick layer of unconsolidated basin-fill sediments overlies the downdropped bedrock within the valley (figs. 2, 3). These unconsolidated Tertiary to Quaternary basin-fill sediments are up to ~3,000 ft thick (Smith, 2004b).

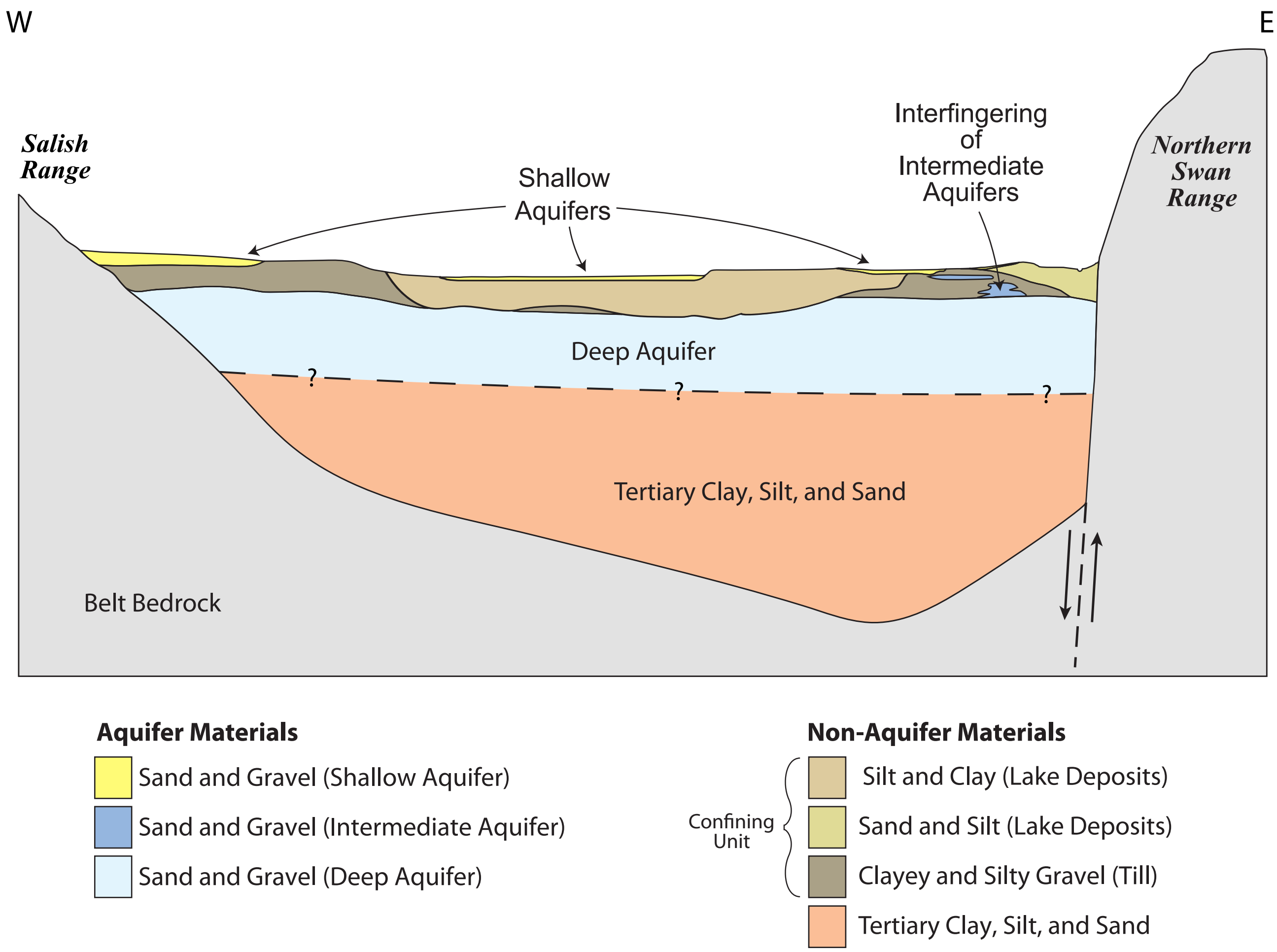


Figure 3. Generalized cross-section across the Flathead Valley. The deep aquifer overlies Tertiary sediments and is overlain by confining units that may include an intermediate aquifer(s) and the shallow aquifers (adapted from LaFave and others, 2004).

Hydrostratigraphy

The stratigraphy of the Flathead Valley is complicated due to multiple periods of glacial advances and retreats that resulted in changing depositional systems (e.g., glacial outwash, till, fluvial deposits, and lake deposits) and partial erosion of previously deposited sediments. This results in aquifers and aquitards that are heterogeneous, and not necessarily continuous, even over short distances.

Belt Bedrock

Bedrock in this area is composed of the Piegan and Ravalli Groups of the Belt Supergroup, which are primarily siltite, metacarbonates, quartzite, and mafic sills (Harrison and others, 1992; Smith, 2004a; Lonn and others, 2020). These units, referred to as Belt bedrock in this report, underlie the unconsolidated to poorly consolidated Tertiary and Quaternary basin-fill deposits in the valley, and are exposed in the mountain ranges that surround the valley (fig. 2). Belt bedrock is also exposed in the southern Flathead Valley, north of Bigfork, where the northern end of the Mission Range extends into the valley (fig. 2). This northern extension of the Mission Range bisects the deep aquifer in the southeastern portion of the valley. The primary porosity and permeability of the Belt bedrock are low; however, secondary porosity (fracturing) allows these units to store and transmit groundwater.

Tertiary Sediments

Tertiary sediments occur above the Belt bedrock in some areas (fig. 3), and are interpreted to be the Kishenehn Formation (LaFave and others, 2004; Bobst and others, 2022), which is dominated by mudstone, but contains some lenses of sand and gravel. These Tertiary sediments function as a basal aquitard in the Flathead Valley (LaFave and others, 2004; Bobst and others, 2022). Only one water well is known to have penetrated the Tertiary sediments in the Flathead Valley (Bobst and others, 2022), and at that site, about 1.5 mi north of Flathead Lake, the top of the Tertiary sediments were encountered at about 1,200 ft below ground surface (1,700 ft amsl), beneath about 800 ft of deep aquifer sediments.

Deep Aquifer

The Quaternary deep aquifer of the Flathead Valley overlies the Tertiary sediments (fig. 3; LaFave and others, 2004; Rose, 2018; Berglund and others, 2024) and is interpreted to be glacial outwash composed of silt, sand, gravel, and cobbles. The top of the deep aquifer is about 200 ft below the ground surface throughout much of the study area, but it is variable, with it being less than 100 ft in some areas and over 700 ft in others (Smith, 2004c; Rose and others, 2022). The clasts in these sediments are dominantly composed of siltite, which is consistent with a Belt bedrock source. Groundwater elevations, water-quality data, and groundwater modeling also suggest that the deep aquifer receives substantial recharge along the east side of the Flathead Valley (LaFave and others, 2004; Berglund and others, 2024; Bobst and others, 2025).

Results from 96 aquifer tests performed on the deep aquifer within the Flathead Valley (summarized in appendix B of Rose and others, 2022) reflect the variability in sediment types and well completions. Transmissivity values (*T*) ranged from 36 to 98,172 ft^2/d, with an interquartile range (IQR) from 1,479 to 17,050 ft^2/d, a median of 6,800 ft^2/d, and a geometric mean of 4,549 ft^2/d. This large range of transmissivity values suggests a high degree of heterogeneity in the aquifer based on the depositional and erosional history of the unit. The *T* values do not show apparent spatial or vertical trends (appendix A, fig. A1).

This aquifer is a primary source of water, and is used for municipal water supplies, irrigation wells, and domestic wells. Maximum well yields of 3,000 gpm have been reported for the deep aquifer. The deep aquifer appears to be the most promising target for ASR in the Flathead Valley based on it being thick, laterally extensive, permeable, and often confined.

Mountain Front Deposits

Mountain front deposits occur near the edges of the valley and include coarse-grained sediments eroded from the mountain blocks mixed with till and other glacial deposits. Holocene alluvial fans and landslides near the land surface were deposited across the till (Smith, 2004a), and they are expected to also occur at depth.

While the mountain front deposits are heterogeneous, they are generally permeable, with reported well yields ranging from 3 to 20 gpm (Bobst and others, 2025). Also, the Swan Range to the east of the Flathead Valley receives up to 70 in of precipitation per year, but most of the mountain creeks draining that area cease to flow at the mountain front. This shows that the mountain front deposits are sufficiently permeable to allow infiltration of streamflow along the Swan Range front, which provides recharge to both the shallow and deep aquifers on the east side of the valley.

Confining Layers and Intermediate Aquifer(s)

The deep aquifer away from the mountain fronts is generally overlain by ice-proximal glacial sediments and glacial lake sediments (fig. 3). In some studies, these units have been grouped together as the confining layers (LaFave and others, 2004; Smith, 2004d; Rose, 2018; Rose and others, 2022). However, data from more recent studies indicate that heterogeneity within the confining layers can be important for providing hydrologic connections between the deep aquifer and shallow aquifers in some areas (Berglund and others, 2024; Smith and Bobst, 2025; Bobst and others, 2025). Smith (2004d) indicates that the combined thickness of the confining layers is from less than 100 ft to over 600 ft.

The ice-proximal deposits include basal till, ablation till, and glacial–fluvial deposits. Basal till is extremely poorly sorted and functions as an aquitard. Ablation till is somewhat sorted due to reworking by meltwater, and is typically productive for domestic water wells (Smith, 2004a). The glacial–fluvial sand and gravel layers are more well sorted and form intermediate aquifers. In some areas the intermediate aquifers are interfingered with the deep aquifer, resulting in communication between these zones (Smith, 2004d), and potentially a connection between the deep aquifer and shallow aquifers.

Glacial lake sediments were deposited during and after glacial retreat (Smith 2004a,g). Glacial lake deposits in the Flathead Valley have been mapped as both fine-grained and sandy (Smith, 2004a). Fine-grained glacial lake sediments were deposited in low-energy environments, generally further from the glacier and the lake shore, in deeper water. The fine-grained glacial lake deposits function as an aquitard. In shallower water, near the lake shore and/or the glacier, sandy glacial lake sediments were deposited. Aquifer testing has shown communication through the sandy glacial lake sediments (Myse and others, 2023), and they are locally productive to domestic water wells (Smith, 2004a). The sandy glacial lake sediments function as a low-productivity aquifer, and can provide a conduit for flow between the deep aquifer and shallow aquifers.

Shallow Aquifers

The shallow aquifers (fig. 3) are composed of a variety of sediment types including silt, sand, and fine gravel. These lithologic types are grouped into a single hydrogeologic unit due to them having a common stratigraphic location above the confining layers, typically being unconfined, having a direct hydraulic connection to surface waters, and often being able to supply sufficient water for domestic wells (Konizeski and others, 1968; Noble and Stanford, 1986; Smith, 2004a; LaFave and others, 2004; Rose, 2018; Berglund and others, 2024).

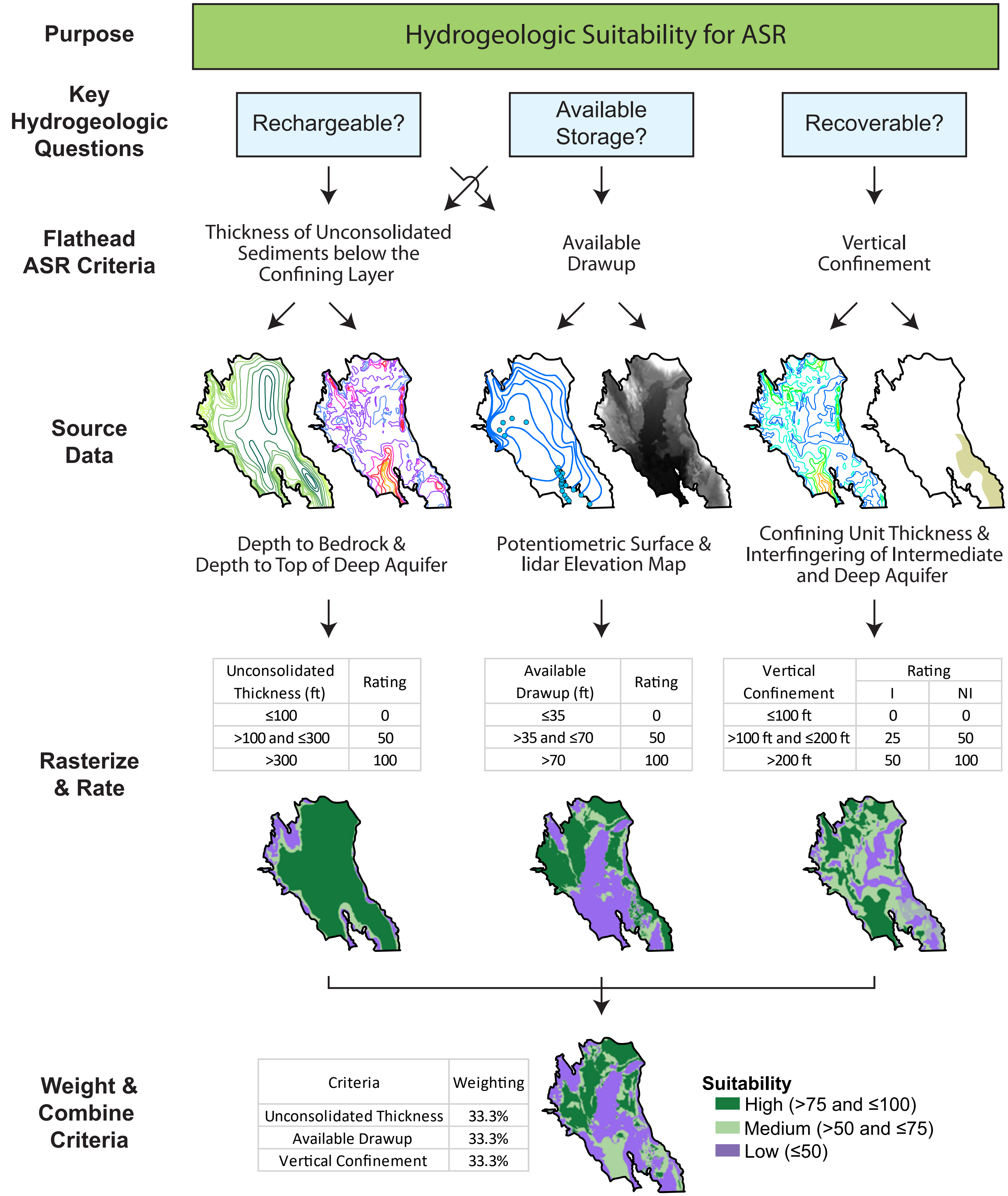
METHODS

The results of this evaluation are presented as a suitability map based on physical hydrogeologic properties. The map was developed using GIS and multi-criteria decision analysis (MCDA; Malczewski and Rinner, 2015) on a 2.5-acre scale similar to Hanson and others (2024). The map is intended to serve as a first-level screening tool to identify areas that merit more detailed site-specific investigations for potential ASR projects.

The suitability of an area for ASR depends on several hydrogeologic properties. These properties vary spatially across the Flathead Valley; consequently, the suitability for ASR also varies spatially. To develop an ASR suitability map, we evaluated and combined publicly available geospatial data that represent relevant hydrogeologic properties.

Multi-Criteria Decision Analysis

The MCDA approach (fig. 4) involves choosing criteria important for ASR, creating/rasterizing the datasets, assigning ratings within criteria, assigning weights to the criteria, and then combining them. The geospatial datasets chosen for each criterion (see Criteria and Rating within Criteria section below) were converted to raster datasets and then quantitatively combined. Raster datasets break spatial data into equally sized cells that form rows and columns. Each cell has a geographic location and the raster value represents the hydrogeologic property at that location. If the dataset consisted of contoured data, values between the contours were estimated (interpolated)



Unconsolidated Thickness (ft)	Rating
≤100	0
>100 and ≤300	50
>300	100

Available Drawup (ft)	Rating
≤35	0
>35 and ≤70	50
>70	100

Vertical Confinement	Rating	
	I	NI
≤100 ft	0	0
>100 ft and ≤200 ft	25	50
>200 ft	50	100

Criteria	Weighting
Unconsolidated Thickness	33.3%
Available Drawup	33.3%
Vertical Confinement	33.3%

Figure 4. Flowchart of the multi-criteria decision analysis approach for ASR suitability in the Flathead Valley. The key hydrogeologic questions and available data guide the selection of criteria for the suitability analysis. Classification and rating can be found in table 1. I, interfingered; NI, not interfingered. Refer to Methods and appendix A for discussion of rating and weighting decision process.

in order to rasterize the data. Input data were rasterized to 330 ft x 330 ft cells (2.5 acres per cell). This produces an approximate map scale of 1:200,000. The original data used to derive the criteria datasets ranged in scale from 1:63,500 to 1:100,000 (discussed below). The 1:200,000 resolution balances the uncertainties in the known datasets (see Limitations section) while increasing the raster size to a 2.5-acre cell size that is appropriate for preliminary site screening for ASR.

Criteria and Rating within Criteria

The MCDA approach requires the criteria to be complete, non-redundant, and minimal while adhering to the scope of the work (Malczewski and Rinner, 2015; Sallwey and others, 2019). For this analysis, complete criteria refer to hydrogeologic datasets relevant to the potential success or failure of ASR. Nonredundant criteria require independent datasets so a hydrogeologic property isn't "counted" multiple times when the datasets are combined. Minimal criteria simplify the datasets to only those directly affecting ASR suitability.

Hydrogeologic properties necessary for ASR include a sufficiently thick aquifer that can adequately store and transmit water in useful quantities while retaining the injected water in the storage zone so it is available for extraction when needed. The criteria below reflect the rechargeability of the aquifer, the amount of storage, and the recoverability of the injected water (fig. 4):

- thickness of the unconsolidated sediments below the confining layers (rechargeability and available storage),
- available drawup (rechargeability and available storage), and
- vertical confinement (recoverability).

Choosing, classifying, and rating criteria are all inherently subjective; however, the following discussion provides information on the decision process. Criteria were rated from 0 (low suitability) to 100 (high suitability). Maps of the criteria data and their ratings are in appendix A.

<u>Thickness of the Unconsolidated Sediments below the Confining Layers</u>

The deep aquifer was chosen as the target aquifer because of its typically adequate transmissivity and storativity for ASR. Since aquifer test results do not show clear spatial trends (Rose and others, 2022; appendix A), transmissivity and storativity were not assessed directly as criteria. Instead, the assessment was based on having sufficient thickness of unconsolidated sediments to provide adequate transmissivity and storage. In this way areas near the basin margin and bedrock highs receive a lower rating, while areas where the unconsolidated sediments are sufficiently thick receive a uniformly high rating.

The thickness of unconsolidated sediments was evaluated using contour maps of the depth to bedrock (based on well logs, seismic data, and gravity data; Smith, 2004b) and the depth to the top of the deep aquifer (based on approximately 3,400 well logs; Smith, 2004c). The contours from each map were digitized and interpolated. The depth to the top of the deep aquifer was subtracted from the depth to bedrock to create a thickness of the unconsolidated sediments below the confining layers coverage (appendix A, fig. A2). The thickness criterion was divided into three classes (table 1) based on Shaw and others (2020). Ratings increased with increased thickness. Thicknesses ≤100 ft were considered inadequate for ASR (rated 0) while thicknesses >300 ft were expected to have at least portions of unconsolidated package that are suitable for ASR (rated 100). Thicknesses between 100 and 300 ft were rated as 50 (appendix A, fig. A3).

Tertiary sediments, which are less permeable than the deep aquifer (Bobst and others, 2022), underlie the deep aquifer in the deeper portions of the basin (fig. 3), but the Tertiary sediments have only been encountered in one well. Therefore, it was not possible to exclude the Tertiary sediments from the thickness criterion. This is acceptable because the criterion gives low ratings to areas near the basin margins or bedrock highs where the deep aquifer is thin, and while the calculated thickness may be biased high in the deeper portion of the basin, those areas will receive the highest rating because the thickness is over 300 ft. For example, at the one site where the top of the Tertiary sediments has been encountered (Bobst and others, 2022), the deep aquifer was approximately 800 ft thick and would receive the maximum rating on its own. Another approximately 800 ft of Tertiary sediments (based on drilling and geophysical data) underlie the deep aquifer, making the thickness of unconsolidated sediments below the confining layers 1,600 ft, but it still just gets the maximum score.

Table 1. Summary of the hydrogeologic criteria ratings for ASR in the Flathead Valley deep aquifer.

ASR Key Questions	Flathead ASR Criteria	Ratings				
Rechargeable & Available Storage	Thickness of Sediments below the Confining Layers	Depth (ft bgs)	≤100	>100 and ≤300	>300	
		Rating	0	50	100	
	Available Drawup	Drawup (ft)	≤35	>35 and ≤70	>70	
		Rating	0	50	100	
Recoverable	Vertical Confinement	Confining Layer Thickness (ft)	≤100	>100 ft to ≤200, Interfingered	>100 to ≤200 ft, Not Inter-fingered OR Confining Layer >200, Interfingered	>100 and Not Interfingered
		Rating	0	25	50	100

Available Drawup

Available drawup refers to the depth below ground surface to the potentiometric surface for the deep aquifer at a location (fig. 1). Available drawup is an important control on how easily water can be injected into the aquifer, and if the injection must be under pressure or can be gravity fed. Injection under pressure is relatively common for ASR projects, but it increases project complexity (Pyne, 2005). Greater available drawup also allows for a greater rise in groundwater level during injection without increasing the potential for adverse impacts to nearby wells, such as causing neighboring wells to become flowing artesian. We recognize that in many cases raising the groundwater level in a well can be beneficial, but that is not always the case. The effects to nearby wells are an important consideration in the deep aquifer since there are many domestic wells completed in this aquifer (see Additional Considerations section).

Available drawup was calculated by subtracting the elevation of the potentiometric surface from the land surface. The potentiometric surface for the deep aquifer from Rose and others (2022) was used as a starting point, but was extended using potentiometric contours from LaFave (2004a) to cover the entire valley. This potentiometric surface was interpolated and rasterized. The 1 m lidar elevation map (USGS, 2025) was bilinearly resampled to match the 330 ft raster cell size. The potentiometric surface raster was subtracted from the land surface raster to give available drawup (appendix A, fig. A4).

To better understand the potential increase in groundwater level during injection, theoretical drawup was calculated for a range of transmissivities and storativities (fig. 5A), different injection rates, durations of injection, and distances from the injection well (tables 2, 3). The aquifer properties were based on reported values from aquifer tests in the deep aquifer (see appendix B of Rose and others, 2022). Injection rates were based on published values for sand and gravel aquifers (<100 to 4,300 gpm per well; table 4). For a range of transmissivities and storativities (fig. 5A), a 100% efficient well that fully penetrates the aquifer had a theoretical drawup of approximately 1 to 26 ft at a distance of 1 ft from the well after injecting 100 gpm for 100 days (fig. 5B). To test the effects of varying injection rates we used the geometric mean transmissivity (4,549 ft^2/d) and mean storativity (1.52×10^{-3}). These values were selected since transmissivity is typically log normally distributed, and storativity is typically normally distributed (Freeze, 1975; Helsel and others, 2020). Injection rates from 100 to 1,000 gpm for 100 days resulted in drawup at 1 ft from the well from approximately 7 to 70 ft (fig. 5C).

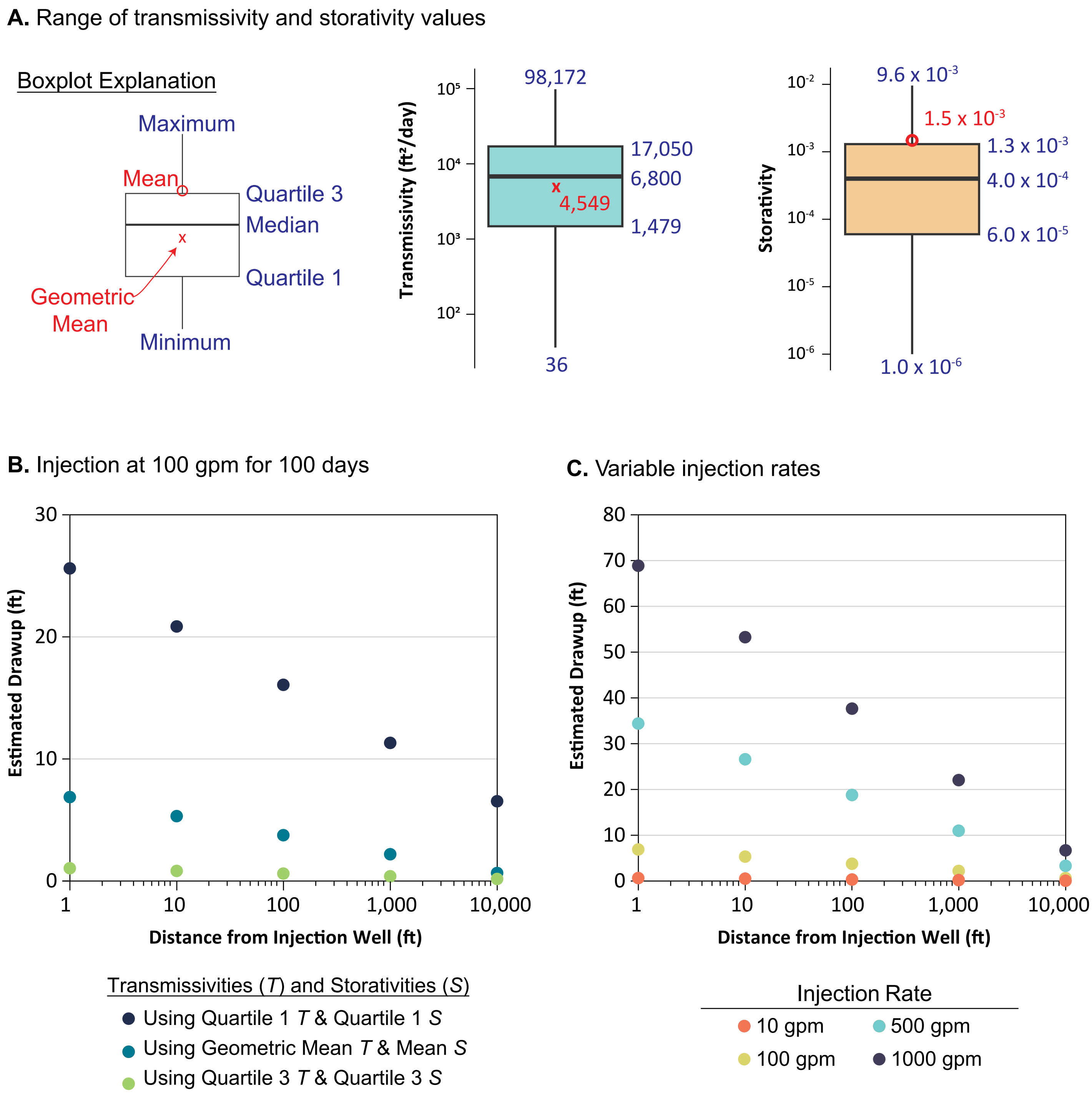


Figure 5. Boxplots demonstrating range of transmissivity (*T*) and storativity (*S*) values for the deep aquifer (A) from aquifer tests collated in Rose and others (2022). Quartiles, geometric means, and means from (A) were used to estimate theoretical drawup for a well that is injecting at 100 gpm for 100 days (B; table 2). Using the geometric mean *T* and mean *S*, theoretical drawup was estimated for injecting for 100 days at 10, 100, 500, and 1,000 gpm (C; table 3). Note that the x-axes on B and C are logarithmic. These theoretical drawup estimates were used to rate the available drawup criterion.

Table 2. Summary of estimated drawup for a well that is injecting at 100 gallons per minute (gpm) for 100 days using range of values for transmissivity (*T*) and storativity (*S*).

Transmissivities and Storativities in Drawup Estimate	*T* (ft²/d)	*S*	Estimated Drawup at Distances from Injection Well (ft)				
			1	10	100	1,000	10,000
Geometric mean T & mean S	4,549	1.52×10^{-3}	6.9	5.3	3.8	2.2	0.67
Median T & median S	6,800	4.00×10^{-4}	4.7	3.7	2.8	1.8	0.79
Quartile 1 T & quartile 1 S	1,479	6.00×10^{-5}	26	21	16	11.3	6.5
Quartile 1 T & quartile 3 S	1,479	1.30×10^{-3}	20	15	11	5.7	1.19
Quartile 3 T & quartile 1 S	17,050	6.00×10^{-5}	1.1	0.84	0.62	0.40	0.19
Quartile 3 T & quartile 3 S	17,050	1.30×10^{-3}	1.2	0.98	0.76	0.55	0.33

Note. See figure 5A for boxplots of *T* and *S* values, and 5B for a graphical summary of these results.

Table 3. Summary of estimated drawup for variable injection rates using the geometric mean transmissivity (4,549 ft²/d) and mean storativity (1.52×10^{-3}).

Injection Rate (gpm)	Days	Estimated Drawup at Distances from Injection Well (ft)				
		1	10	100	1,000	10,000
10	1	0.53	0.38	0.22	0.07	0.00
	10	0.61	0.45	0.30	0.14	0.01
	100	0.69	0.53	0.38	0.22	0.07
	1,000	0.77	0.61	0.45	0.30	0.14
100	1	5.3	3.8	2.2	0.7	0.0
	10	6.1	4.5	3.0	1.4	0.1
	100	6.9	5.3	3.8	2.2	0.7
	1,000	7.7	6.1	4.5	3.0	1.4
500	1	27	19	11	3.4	0.0
	10	31	23	15	7.1	0.5
	100	34	27	19	11	3.4
	1,000	38	31	23	15	7.1
1,000	1	53	38	22	6.7	0.0
	10	61	45	30	14	1.0
	100	69	53	38	22	6.7
	1,000	77	61	45	30	14

Note. See figure 5A for boxplots of *T* and *S* values, and figure 5C for a graphical summary of these results. gpm, gallons per minute.

The available drawup criterion was classified based on the drawup calculations at a distance of 1 ft from the injection well, after injecting at 500 and 1,000 gpm for 100 days. Greater drawup availability was rated higher because it suggests a higher injection rate can be used at that location during ASR (table 1). Locations with ≤35 ft available drawup suggests a maximum injection rate of less than 500 gpm and was rated less suitable (0) for ASR. Locations with >35 ft of available drawup but ≤70 ft suggests maximum injection rates of about 500 to 1,000 gpm and was rated a 50. Finally, locations with >70 ft available drawup suggests a maximum injection rate of >1,000 gpm and was rated 100 (appendix A, fig. A5). The reader is cautioned that these drawup values are based on the geometric mean transmissivity and mean storativity of the deep aquifer, and on a well that is 100% efficient and fully penetrating. The result should be used only as a relative qualitative guide of drawup suitability (see Limitations section).

Vertical Confinement

Sufficient confinement is needed to minimize groundwater flow away from the storage zone, and maintain water availability for later extraction. As described in the hydrogeologic framework, there are sediments of the intermediate aquifers that interfinger

Table 4. Summary of selected published ASR injection rates and aquifer properties.

	Injection Rates (gpm/well)		Injection Zone Properties			
ASR Project	Minimum	Maximum	Aquifer Thickness (ft)	Transmissivity (ft^2/d)	Hydraulic Conductivity (ft/d)	Lithology
General ASR dicussion (Burt and Barry, 2011)	100	3,500	NR	NR	NR	NR
General ASR discussion (Pyne, 2005)	70	3,500	NR	NR	NR	NR
Wichita ASR webinar (GWPC, 2025)	200	800	NR	NR	NR	NR
Madison and McCarty ranches (Burt and Barry, 2011)	700	1,400	NR	NR	NR	Basalt flows
Peace River, FL (Pyne, 2005)	350	700	100–330	4,900–6,000	18–49	Limestone
Cocoa, FL (Pyne, 2005)	550	850	70-90	4,800–13,500	70–150	Limestone
Marathon, FL (Pyne, 2005)	235	350	40	2,300	58	Sand
Port Malabar/Palm Bay, FL (Pyne, 2005)	700		72	2,300	32	Limestone
Boynton Beach, FL (Pyne, 2005)	1,000		100	9,400	94	Sandy limestone
Okeechobee, FL (Pyne, 2005)	3,500	6,900	500	600,000	1,200	Limestone
Chesapeake, VA (Pyne, 2005)	1,800	3,200	120	9,800–12,400	11–14	Clayey sand
Swimming River, NJ (Pyne, 2005)	400	1,200	80	5,500–7,100	69–89	Silty sand
Wildwood, NJ (Pyne, 2005)	650	1,000	120	11,600	97	Sand
Kerrville, TX (Pyne, 2005)	700	1,000	75	940	12	Sandstone
Highlands Ranch, CO (Pyne, 2005)	198	263	467	1,100	2	Sandstone
Las Vegas, NV (Pyne, 2005)	700	4,300	~400	130–40,100	~1–100	Sandy gravel
Calleguas, CA (Pyne, 2005)	600	1,350	450	19,400	43	Sand and gravel
Goleta, CA (Pyne, 2005)	<100	800	NR	13,000–20,000	NR	Alluvial
Pasadena, CA (Pyne, 2005)	NR		<800	100–25,000	2–60	Sand and gravel
Seattle, WA (Pyne, 2005)	2,300		NR	20,000–47,000	NR	Sand and gravel
Kuwait (Pyne, 2005)	100	1,080	420–500	400–43,000	0.8–100	Limestone
Windhoek, Namibia (Pyne, 2005)	273	950	~250	650–850	~3	Quartzite
Adelaide, Australia (Pyne, 2005)	NR		200	1,900	10	Limestone and sand
Adelaide (Bolivar), Australia (Le Gal La Salle and others, 2005)	180		220	NR	3.3–330	Limestone and sand

Note. NR, value was not reported. When only one value is given for injection rates, it is the only value reported. Note that some transmissivity and hydraulic conductivity values are estimated based on other reported information.

with the deep aquifer sediments in some areas. This may provide a conduit for flow from the storage zone to the shallow aquifers. Therefore, two criteria were used to address vertical confinement: the thickness of the confining layers and the presence of interfingering between the deep aquifer and intermediate aquifers (both per Smith, 2004d; appendix A, figs. A6, A7).

The datasets were created by digitizing the thickness of the confining layers isopach map (Smith, 2004d) and interpolating the contours, and by digitizing the “interfingering” polygons. The minimum contour on the Smith (2004d) confining layers thickness map was 100 ft, so the available data do not allow for finer resolution criteria below this value. Based on recent work in the valley (Smith and Bobst, 2025; Bobst and others, 2025), the Smith (2004d) delineation of the interfingering between the deep aquifer and intermediate aquifers was adapted to only include the polygon near the Many Lakes area where there has been confirmed hydraulic communication between the shallow and deep aquifers; all other interfingering polygons were removed since in some of those areas the deep aquifer appears to be well confined (Bobst and others, 2025; L. Smith, oral commun., 2025). The other areas identified as interfingered (Smith, 2004d) should receive additional scrutiny during site-specific evaluations. The ratings for vertical confinement were divided into four classes (table 1). Higher ratings were assigned for increasing thickness of the confining layers with 0 for ≤100 ft, 50 for >100 ft to ≤200 ft, and 100 for >200 ft. Then if the location was within the interfingered polygon, the rating was reduced by half (table 1; appendix A, fig. A6).

Weighting Criteria

The suitability criteria were weighted based on their perceived importance to ASR. Different weighting combinations were evaluated in a sensitivity analysis (see Sensitivity Analysis section below). The final weighting was based on evaluating the results in select areas where the authors had previously conducted hydrogeologic studies and were considered to have high and low ASR suitability. Each of the three criteria were given equal weight (33.3%) in the final suitability map.

The datasets were combined using the weighted linear combination (WLC) method, chosen for its simplicity and widespread use (Sallwey and others, 2019). For each raster cell, a WLC equation (e.g., Eastman and others, 1993) was used to calculate the ASR suitability:

$$\text{ASR Suitability} = \sum \text{criteria weight} \times \text{rating within criterion.}$$

RESULTS

The MCDA analysis provides a screening-level identification of locations in the Flathead Valley that may have appropriate hydrogeologic characteristics for ASR based on the datasets used (the thickness of the unconsolidated sediments below the confining layer, available drawup, and vertical confinement). However, a low suitability score does not mean ASR is impossible nor does a high suitability score mean ASR success is guaranteed (see Limitations section). Site-specific information will be needed to refine this analysis (see Additional Considerations section below).

The ASR suitability analysis area included approximately 222,000 acres (fig. 6A). Suitability scores ranged from 0 to 100 and were grouped as “high” (>75), “medium” (>50 and ≤75), and “low” (≤50) suitability. Approximately 26% of the area (58,800 acres) is scored high, 28% (~62,800 acres) is scored medium, and 45% (~101,000 acres) is scored low (fig. 6B).

High suitability areas are present between Kalispell, Whitefish, and Columbia Falls, and north of Lake Blaine (fig. 6A). These areas show high suitability because they: (1) are far enough away from the mountain fronts that the deep aquifer is anticipated to be thick (appendix A, fig. A2), (2) are away from the center of the valley that has low available drawup (appendix A, fig. A4), and (3) have a moderate to thick confining unit (appendix A, fig. A6). Conversely, locations of low suitability occur along the mountain range fronts and in the center of the valley. Along the mountain fronts, the thickness of unconsolidated sediments below the confining unit is not sufficiently thick. In the center of the valley, available drawup is low due to groundwater levels being near or above ground surface. Therefore, these areas would need to inject under pressure and assess potential implications for neighboring wells.

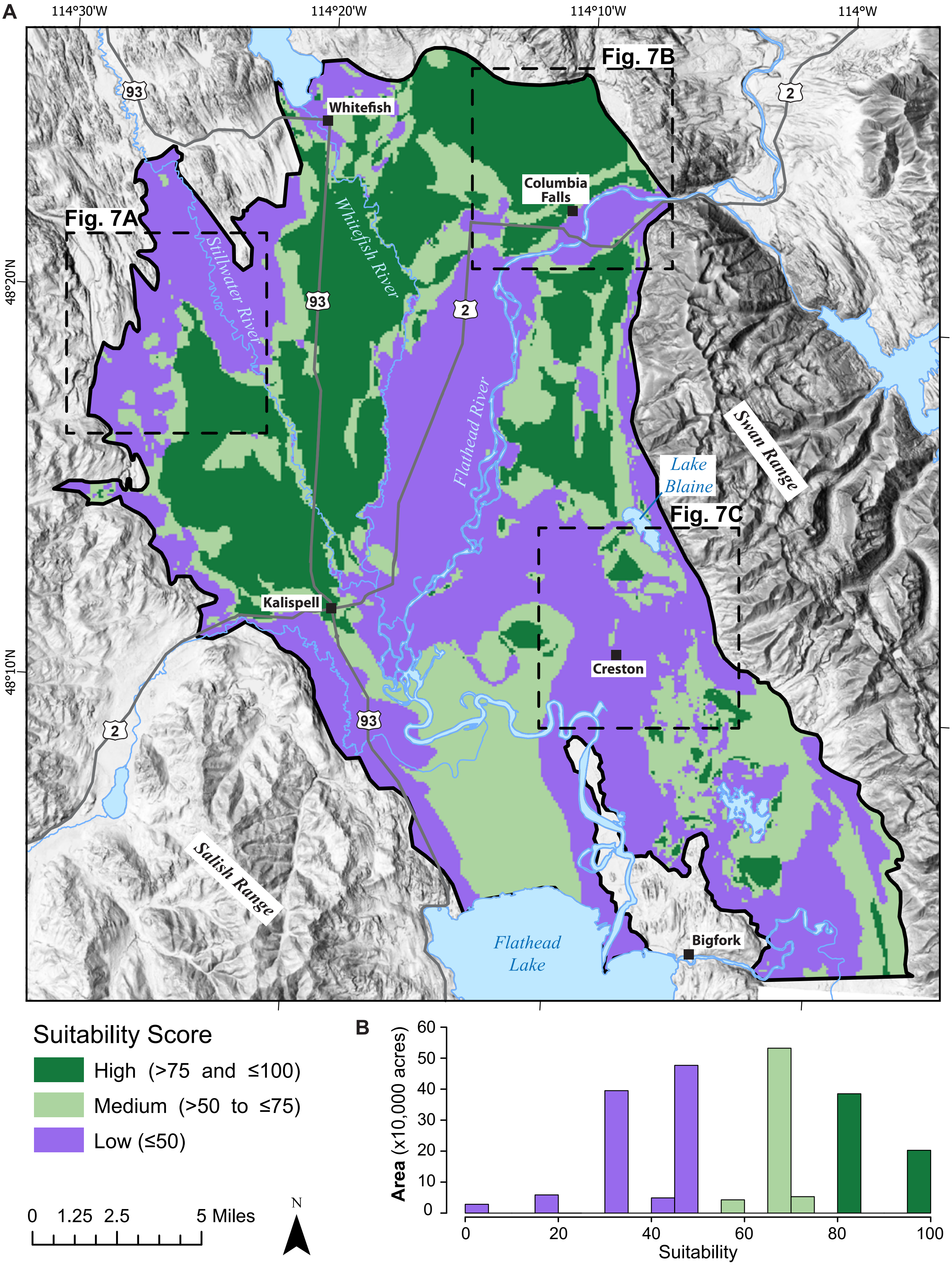


Figure 6. Final suitability of hydrogeologic potential for aquifer storage and recovery in the deep aquifer of the Flathead Valley (A). High suitability occurs between Kalispell, Whitefish, and Columbia Falls, and north of Lake Blaine. The distribution of the ASR suitability for Flathead Valley is shown in (B). Dashed boxes show focus areas (fig. 7).

Evaluations in Focus Areas

To assess the suitability analysis, three locations are used as examples to compare to known field or monitoring data. Other locations can be similarly understood by looking at the criteria data and ratings (appendix A).

Lost Creek Fan Area

The Lost Creek Fan is an accumulation of sediments deposited by glacial meltwater (LaFave and others, 2004) that overlie the confining layer and deep aquifer in the northwest part of the study area (figs. 6A, 7A). ASR suitability varies throughout this area—it is low near the mountain front and along the Stillwater River and high in the southeast. Along the mountain front, bedrock is within 300 ft of the ground surface, and the shallow alluvium is thick (LaFave and others, 2004; Smith, 2004b), resulting in the thickness of unconsolidated sediments beneath the confining layer being thin (fig. 7A). Near the Stillwater River wells completed in the deep aquifer show artesian conditions similar to those of the long-term monitoring well (GWIC ID 148194) that is completed in the underlying bedrock (fig. 7A). Away from the mountain front and the Stillwater River, the thickness of unconsolidated sediments below the confining layer, available drawup, and vertical confinement become adequate for ASR. However, additional site-specific investigations are needed to evaluate the potential for the shallow and intermediate aquifers of the Lost Creek Fan area to be interfingered with the deep aquifer (LaFave and others, 2004).

Columbia Falls Area

The Columbia Falls area is in the northeastern part of the analyzed area (fig. 6A). Glacial deposits overlie the deep aquifer northwest of the Flathead River while ≲100 ft of gravels and alluvium of the shallow aquifers overlie the confining layers near the river (Smith, 2004a,e). ASR suitability is mostly medium to high throughout this area except near the Flathead River (figs. 6A, 7B). Depth to bedrock increases quickly away from the northeastern mountain front while the depth to the deep aquifer is generally between 100 and 200 ft (Smith, 2004b,c), suggesting the deep aquifer is likely sufficiently thick. Both available drawup and the vertical confinement is rated low near the Flathead River. Two long-term monitoring wells (fig. 7B) completed in the deep aquifer show different annual hydrographs. Near the mountain front (GWIC ID 87873), recharge during snowmelt can cause groundwater-level fluctuations >70 ft, while further from the mountain front (GWIC ID 85274), groundwater-level fluctuations are less pronounced (<10 ft) and show climatic and irrigation-related effects. Near the mountain front, there is a connection between the deep aquifer and shallower alluvium; however, this connection decreases away from the mountain front, similar to conditions along the Swan Range Front to the south (Smith and Bobst, 2025; Bobst and others, 2025).

Creston Area

The area east of Creston (fig. 6A) shows hummocky topography that was formed when stagnant glacial ice melted on the land surface and locally produced depressions (Smith, 2004a). ASR suitability in this area is generally low to medium (fig. 7C). Although there is sufficient thickness of the unconsolidated sediments below the confining layer away from the mountain front, the available drawup and vertical confinement are rated low in many places. Both springs and flowing artesian wells are present near Jessup Mill Pond. Recent drilling in the area showed dominantly sandy glaciolacustrine sediments above the deep aquifer that allow for communication between the shallow and deep aquifers (Smith and Bobst, 2025; Bobst and others, 2025). Heterogeneous sediments above the deep aquifer in this area make the suitability analysis appear "patchy" southeast of Jessup Mill Pond (fig. 7C); the lack of consistent hydrogeologic characteristics in this area makes it less suitable for ASR.

Sensitivity Analysis

A sensitivity analysis was performed to assess the spatial and quantitative impact of the criteria weights. This consisted of three analyses where one of the criteria was emphasized by increasing its weight to 50 percent, and the other two criteria weights were reduced to 25 percent. To evaluate the changes in suitability, the raster values of the final suitability map (fig. 6A) were subtracted from the reweighted raster values. The geographic distribution and magnitude of the changes were used to evaluate the sensitivity of ASR suitability to each criterion. Emphasizing any one of the criteria increased or decreased the suitability score for individual raster cells by up to 17 (fig. 8).

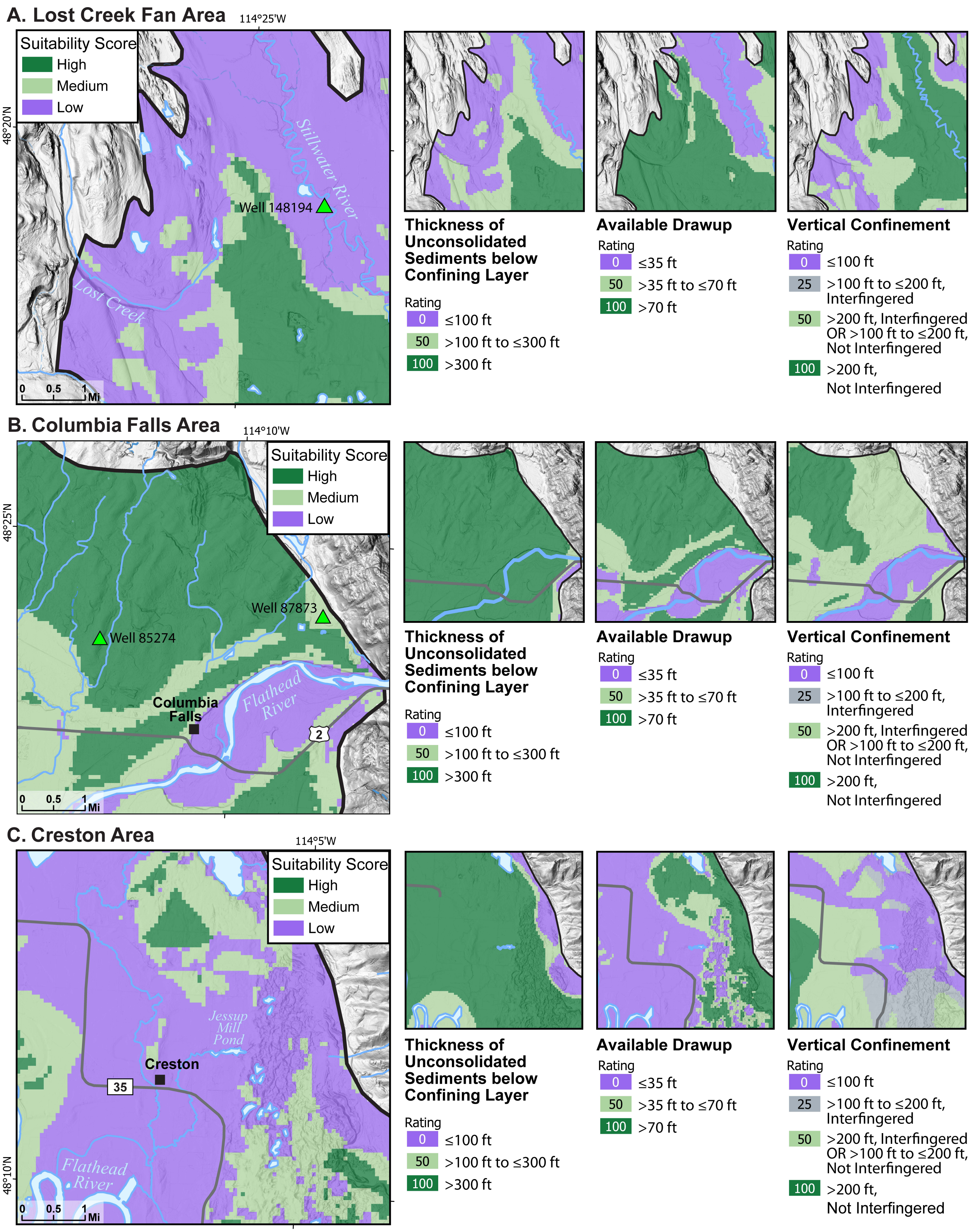


Figure 7. The final aquifer storage and recovery suitability is the combination of the three criteria: thickness of the unconsolidated sediments below the confining layer, available drawup, and vertical confinement. Close-up examples of the analysis are provided for Lost Creek Fan (A), Columbia Falls (B), and Creston (C) areas.

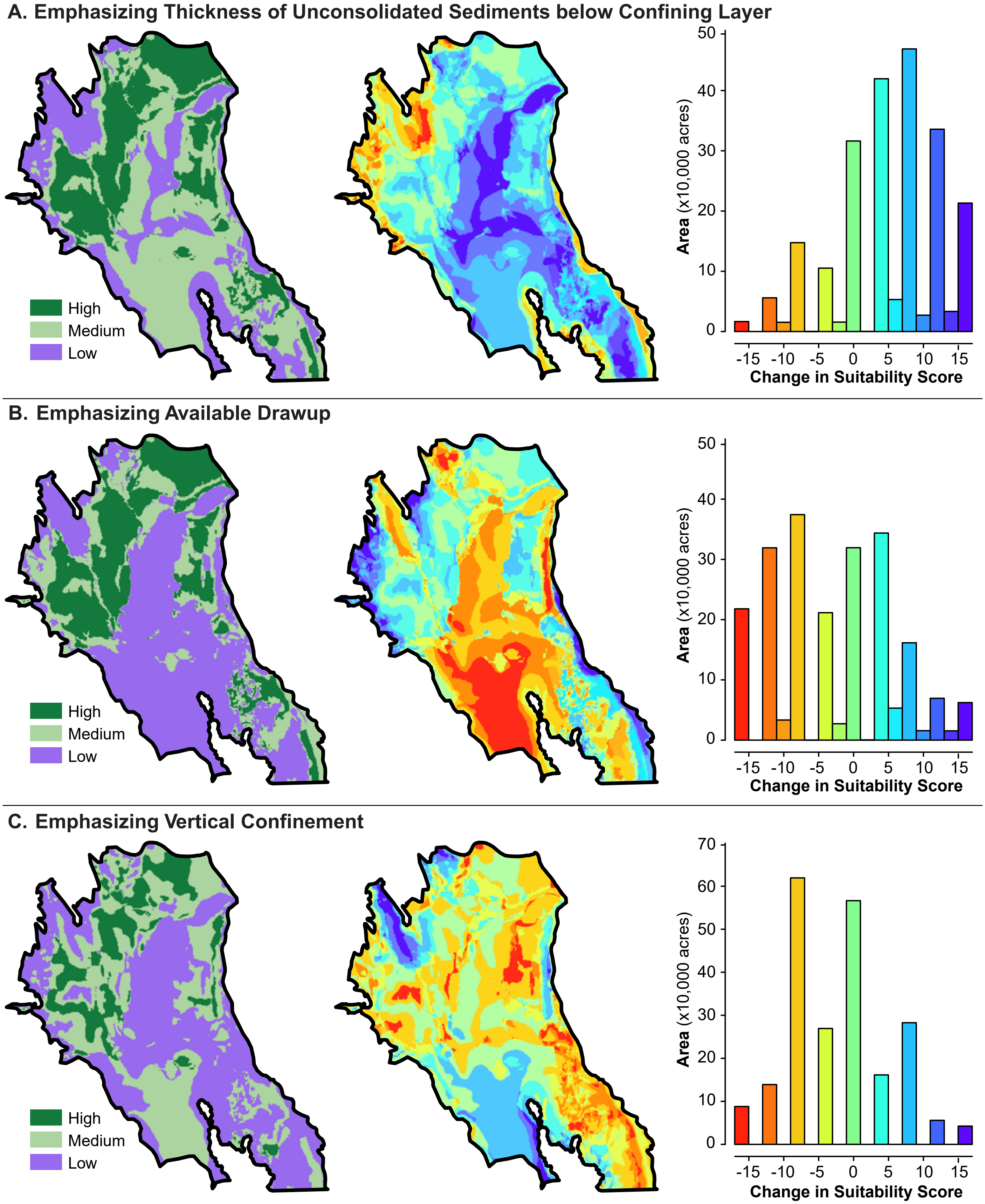


Figure 8. Sensitivity analysis showing the change in ASR suitability scores when emphasizing (A) thickness of the unconsolidated sediments below the confining layers, (B) available drawup, or (C) vertical confinement. The emphasized criteria's weight changed from 33% to 50% while the other two criteria weights changed from 33% to 25%. Suitability scores mostly increased when emphasizing the thickness of the unconsolidated sediments below the confining layer, and mostly decreased when emphasizing available drawup and vertical confinement.

By emphasizing the thickness of the unconsolidated sediments below the confining layer, the suitability scores decreased near the mountain range fronts and along the southern boundary where bedrock is near the surface (fig. 8A). The shallower depth to bedrock results in a thinner package of sediments that form the deep aquifer and less suitability for ASR. Conversely, suitability scores increased towards the center of the Flathead Valley. The valley center has the thickest unconsolidated sediments below the confining layer and receives the highest rating. The valley center also has the lowest available drawup, so emphasizing the thickness of the unconsolidated sediments below the confining layer de-emphasizes the available drawup criteria, causing an additional increase to the suitability score. Overall, emphasizing the thickness of the unconsolidated sediments below the confining layer increases the suitability of 83 percent of the analyzed area: 28 percent was now considered high suitability (up from 26 percent), 43 percent was considered medium suitability (up from 28 percent), and 29 percent was considered low suitability (down from 45 percent).

By emphasizing available drawup, approximately half the raster cells decreased and half increased in suitability (53 percent and 46 percent, respectively; 1 percent remained the same). Suitability scores decreased near the center of the valley (fig. 8B) where available drawup is ≤35 ft and receives a rating of 0. Near the valley margins, available drawup is greater and receives the highest rating. Overall, the percentage of high, medium, and low suitability did not change significantly (≤6 percent): 26 percent was considered high suitability (same as final suitability map), 23 percent was considered medium suitability (down from 28 percent), and 51 percent was considered low suitability (up from 45 percent).

Emphasizing vertical confinement (fig. 8C) had the greatest impact on the areas that had a high suitability score (fig. 6A). The thickness of the confining layer ranges from 0 to >600 ft (Smith, 2004d). However, the confining layer thickness is only >300 ft in the center of the valley, near Flathead Lake. The area between Kalispell, Whitefish, and Columbia Falls generally has a confining layer that is 100 to 200 ft (appendix A, fig. A6) that is rated 50. Therefore, by emphasizing vertical confinement, the highly rated thickness of unconsolidated sediments below the confining layer and available drawup are weighted less, while the medium-rated vertical confinement is weighted more. This reduced the high suitability to medium suitability in many areas. In total, 50 percent of the analyzed area decreased suitability, and 49 percent increased suitability (1 percent remained the same). Thirteen percent was considered high suitability (down from 26 percent), 38 percent was considered medium suitability (up from 28 percent), and 49 percent was considered low suitability (up from 45 percent).

Overall, the sensitivity analysis showed that the high suitability area between Kalispell, Whitefish, and Columbia Falls, and north of Lake Blaine (fig. 6A) still shows areas of high suitability no matter which criteria are emphasized (fig. 8). Similarly, the low suitability area in the center of the valley along the Flathead River (fig. 6A) still shows low suitability when each criterion is emphasized (fig. 8). Therefore, the equal weighting of the criteria highlights the high and low suitability areas well, and the medium suitability areas tend to increase or decrease depending on the criterion considered important.

LIMITATIONS

The results presented here are intended as an initial screening for ASR suitability in the Flathead Valley to help identify locations of interest for further investigation. The scope of this analysis only included hydrogeologic properties relevant to ASR; some additional considerations that need to be addressed in future studies are discussed below (See Additional Considerations section). There are also limitations to the suitability analysis that include the simplifying assumptions made when assessing the criteria and the resolution of the criteria data.

The focus of this analysis was on the deep aquifer based on its wide spatial coverage throughout the valley and previous studies that demonstrated sufficient transmissivity (LaFave and others, 2004; Rose and others, 2022; Myse and others, 2023). Transmissivity values are dependent on hydraulic conductivity and aquifer thickness by:

$$T = Kb,$$

where T is transmissivity (L^2/t; ft^2/d), K is hydraulic conductivity (L/t; ft/d), and b is aquifer thickness (L; ft). In this analysis, transmissivity was assessed solely on aquifer thickness (b) represented by the thickness of the unconsolidated sediments below the confining layer (which included the Tertiary sediments below the deep aquifer in some areas). While it is assumed that the *K* value for the deep aquifer will be sufficient given that it is typically composed of sand and gravel, there are areas/intervals where it is finer grained and less permeable, and areas/intervals where it is coarser grained and more permeable. Neither hydraulic conductivity values nor spatial variability in lithology are demarcated well enough across the study area to incorporate into this analysis (appendix A). The depth to the Tertiary sediments is also unknown (with the exception of one location from Bobst and others, 2022), which could cause an overestimation of the thickness of the deep aquifer in some areas.

The calculations for assessing available drawup were based on transmissivity values from previous aquifer tests. All known wells in the deep aquifer are completed with a partial penetration, and the median screen length from the aquifer tests in Rose and others (2022) is 20 ft. The transmissivities of partially penetrating wells are consequently calculated with a smaller contributing aquifer thickness (*b*). Transmissivities for an ASR well that penetrates a larger portion of the aquifer (e.g., >200 ft) could have a transmissivity greater than 10 times the geometric mean transmissivity used for tables 2 and 3. A higher transmissivity would cause the estimated drawup in tables 2 and 3 to be substantially less and change how the available drawup ratings were classified (fig. 5). On the other hand, the values in tables 2 and 3 also assume that the ASR well is 100% efficient. Lower efficiency will increase the amount of drawup (or pressure) necessary in the ASR injection well. Therefore, while the specific values calculated in tables 2 and 3 may not reflect the actual effects of a particular ASR well, the ratings derived from them still provide useful classifications for identifying areas with more or less suitable available drawup.

The potentiometric surface used in the available drawup criteria was created from two studies (LaFave and others, 2004a; Rose and others, 2022). The potentiometric surface was contoured using 20-ft intervals, which are considered accurate at the 1:200,000 resolution of the analysis. Locally, water levels from long-term monitoring wells can vary 8–75 ft seasonally and/or among years (e.g., GWIC IDs 81636 and 87873; MBMG, 2025; also see the Web App for this project at https://gis-data-hub-mbmg.hub.arcgis.com/apps/547572190d2b4d7b9ded12687659910d/explore, which includes links to MBMG's long-term monitoring wells). Further investigations should be aware of the seasonality of groundwater elevations in the deep aquifer when assessing ASR.

Recoverability of injected water was assumed to depend mainly on the vertical thickness of the confining layer. The thickness of the confining unit was coarsely contoured at 100-ft intervals (Smith, 2004d) and could be refined in future studies or during local investigations. Locations with coarser-grained sediments in the confining layers interval may be less confined (e.g., leaky-confined conditions) than areas with finer-grained sediments even if the thickness of the layer (and the rating) is similar. The heterogeneity of the confining layers was incorporated into the analysis where previous studies confidently interpret interfingering of the intermediate and deep aquifers to allow hydrologic communication (Smith, 2004d; Smith and Bobst, 2025; Bobst and others, 2025). However, other locations of interfingering shown in Smith (2004d) need additional investigation (L. Smith, oral commun., 2025). Furthermore, the confinement criteria assumed the water injected does not necessarily need to be the same water recovered. However, if water quality and/or drift rates are a concern, the hydraulic gradient would need to be assessed as part of recoverability.

Finally, all three suitability criteria were assumed to be equally important (see Methods and Sensitivity Analysis). However, one of the potential advantages of ASR is the ability to inject under pressure rather than relying on gravity-dependent recharge as required by surface infiltration. If injecting under pressure is anticipated, the available drawup criteria may be less important than other criteria. More detailed analysis on the effect of injecting under pressure on nearby wells would be necessary before adjusting this assumption on criteria weight.

ADDITIONAL CONSIDERATIONS

This suitability analysis allows stakeholders to identify sites with the greatest potential for ASR in the deep aquifer of the Flathead Valley. The analysis did not address non-hydrogeologic criteria such as permitting considerations, physical and legal availability of recharge water, need for the recovered water, water quality, site-specific land considerations, or economic considerations. Additionally, there are many uncertainties with ASR projects that can only be addressed by detailed site-specific analysis and data collection.

This section is not exhaustive but is intended to highlight additional information that may affect ASR in the Flathead Valley. We recommend that ASR proponents follow a phased investigation that allows for plans to be modified as new information is acquired. This would likely be similar to that described in Pyne (2005), which includes feasibility assessment, conceptual design, field investigations, a testing program, and then full-scale operations.

Consultation and coordination with the applicable agencies early in the ASR process are advised since several types of permits will be required.

1. Injection into the deep aquifer of the Flathead Valley would require a Class V underground injection control (UIC) permit, which in Montana is regulated by the U.S. Environmental Protection Agency (EPA) under the Safe Drinking Water Act.
2. Recovery of the water for a public water supply would require permitting from the Public Water Supply Bureau of the Montana Department of Environmental Quality (DEQ).
3. Water rights for the diversion of recharge waters, and the extraction of water, would need to be permitted through the Montana Department of Natural Resources and Conservation (DNRC).
4. Other development permits and building permits will likely be required.

The water quality in the deep aquifer is generally good; however, there are some parameters that may be of concern to ASR operations. The deep aquifer typically contains calcium–magnesium–bicarbonate type water, with total dissolved solids concentrations less than the secondary maximum contaminant limit (MCL) of 500 mg/L (LaFave and others, 2004; LaFave, 2004b; Rose and others, 2022; Bobst and others, 2025). There have been exceedances of the primary MCLs for arsenic (10 mg/L) and nitrate (10 mg/L), the secondary MCL for iron (0.3 mg/L), the human health guideline for manganese (0.1 mg/L), and the health advisory for radon (300 pCi/L; Bobst and others, 2025). Water quality would need to be evaluated as part of a feasibility assessment, field investigations, and/or a testing program. Specifically, the evaluation would also need to address how the proposed recharge water would interact with the native water and the aquifer materials. One concern, for example, would be injecting oxygenated surface waters into aquifers, which can change redox conditions and cause the mobilization of metals (e.g., arsenic; Fakhreddine and others, 2021). Pre- and/or post-treatment of the water may need to be addressed as part of the conceptual design.

Further feasibility analysis should also consider sources of recharge water. A detailed investigation is needed on the amount of water available for diversion from different sources, how water availability varies over time, the distance from the source water to a potential ASR site(s), and the quality of the diverted water and how it varies over time. One quality consideration specific to surface-water sources is total suspended solids and how they vary over time. High total suspended solids may require treatment to reduce the total load to a level that would not rapidly plug ASR wells.

Groundwater elevation trend analyses from Rose and others (2022) showed areas of statistically significant groundwater levels declines north and west of Kalispell. Groundwater levels decreased by 1–27 ft over 14–23 years. The declines in groundwater levels were attributed to pumping rather than changes in precipitation. This area may represent a potential “need” for aquifer recharge that overlaps with high ASR suitability from this analysis (fig. 6A). Further investigation of the spatial extent of declining groundwater levels could be assessed to quantify the volume of water needed to offset pumping.

The population of Flathead Valley is rapidly increasing (U.S. Census Bureau, 2025), and the deep aquifer is widely used for domestic wells. ASR proponents will need to consider effects from/to neighboring wells including drift/withdrawal of the injected water, water-elevation changes, and water-quality changes. Therefore, the density of wells (see Web App “Explore Tab”) within the deep aquifer may become an important consideration.

CONCLUSIONS

This evaluation shows that physical hydrogeologic conditions favorable for ASR occur in the area from Kalispell to Whitefish and Columbia Falls, and in an area north of Lake Blaine (fig. 6A). Overall, 26% of the valley was rated as having high potential for ASR into the deep aquifer, while 28% was rated medium and 45% rated low. The thickness of unconsolidated sediments was adequate except for near the valley edges or bedrock highs. Areas with little available drawup (high groundwater levels), particularly near the Flathead River in the center of the valley, caused suitability scores to be reduced. Scores were also reduced where the confining layers were thin or interfingered with intermediate aquifers.

A high suitability score does not necessarily mean ASR will be successful, nor does a medium to low suitability score suggest that ASR is unfeasible. This suitability map provides a first step in identifying locations for further evaluation of potential ASR projects in the Flathead Valley. Natural systems are heterogeneous and must be evaluated with site-specific data. Considerations for an ASR project include defining the project purpose, establishing physical and legal water availability, conducting field investigations to define hydrogeologic information and potential geochemical effects, and evaluating the project's economic feasibility.

Additional exploration of the data and results from this study are available at https://gis-data-hub-mbmg.hub.arcgis.com/apps/547572190d2b4d7b9ded12687659910d/explore. This includes long-term monitoring wells, irrigation infrastructure, land cover, land ownership, geology, and other coverages.

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APPENDIX A

ADDITIONAL DATA

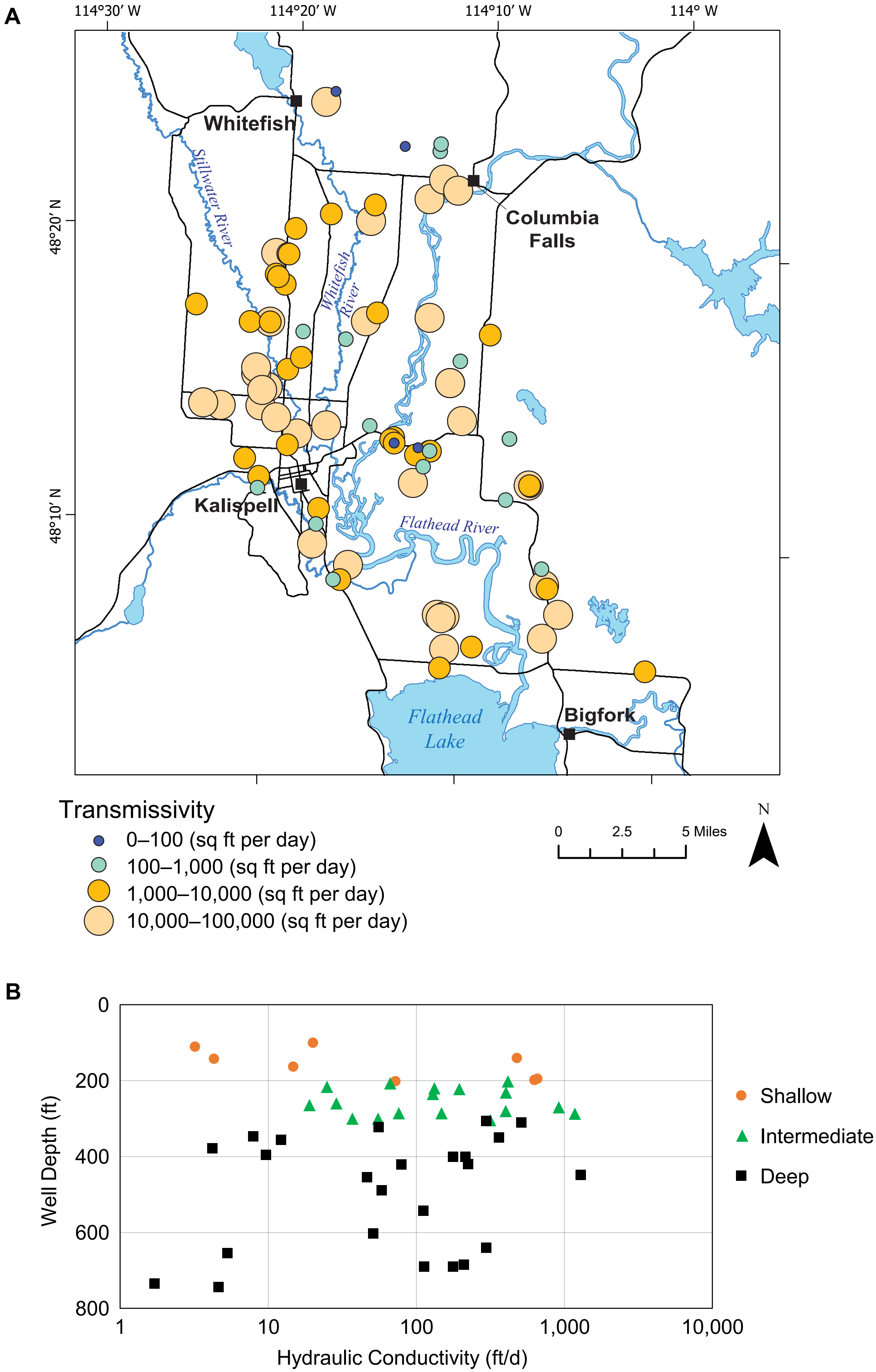

Figure A1. Spatial variability of transmissivity in the Flathead Valley (A; minimally adapted from Rose and others, 2022, fig. 10). Transmissivity also varies vertically with no systematic relationship with well depth (B; as shown by Berglund and others, 2024, appendix figure D2).

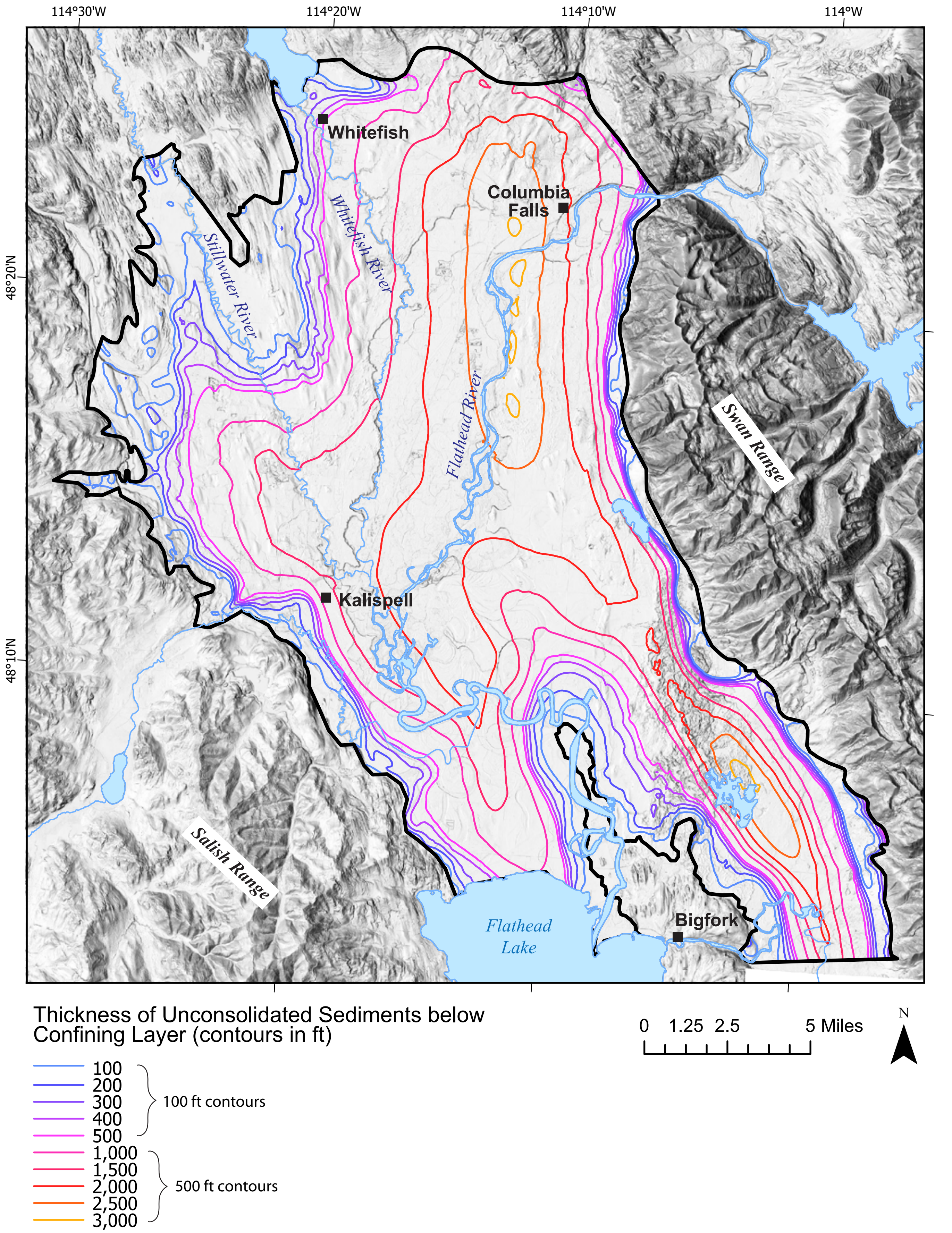

Figure A2. Contours of criteria 1: thickness of unconsolidated sediments below the confining layer. Dataset was created by subtracting the depth to the bedrock (Smith, 2004b) from the depth to the top of the deep aquifer (Smith, 2004c). The unconsolidated sediments include the Tertiary sediments that underlie the deep aquifer in much of the study area.

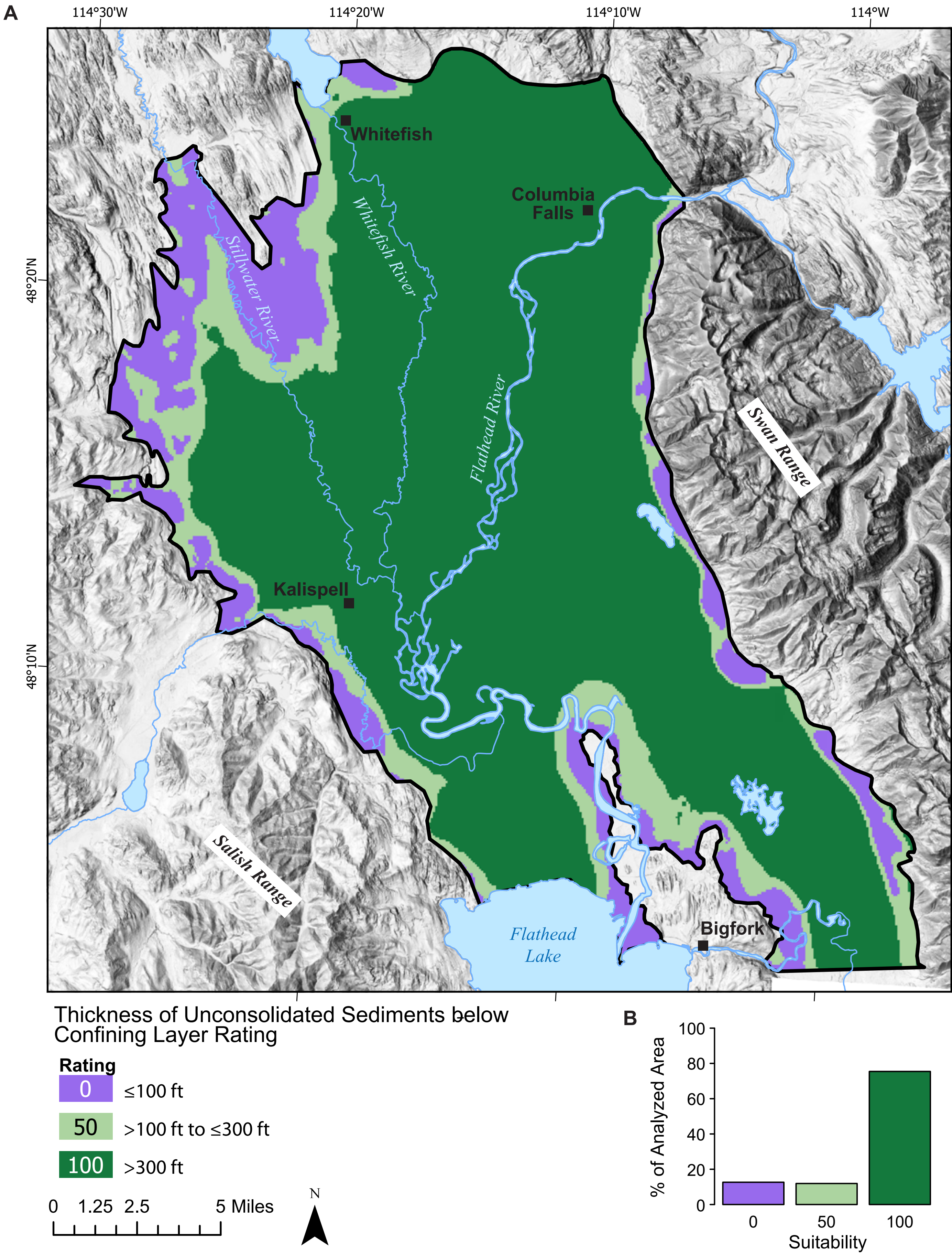

Figure A3. (A) Ratings given to criteria 1: thickness of unconsolidated sediments below the confining layer. (B) Percentage of analyzed area in each of the rating classifications.

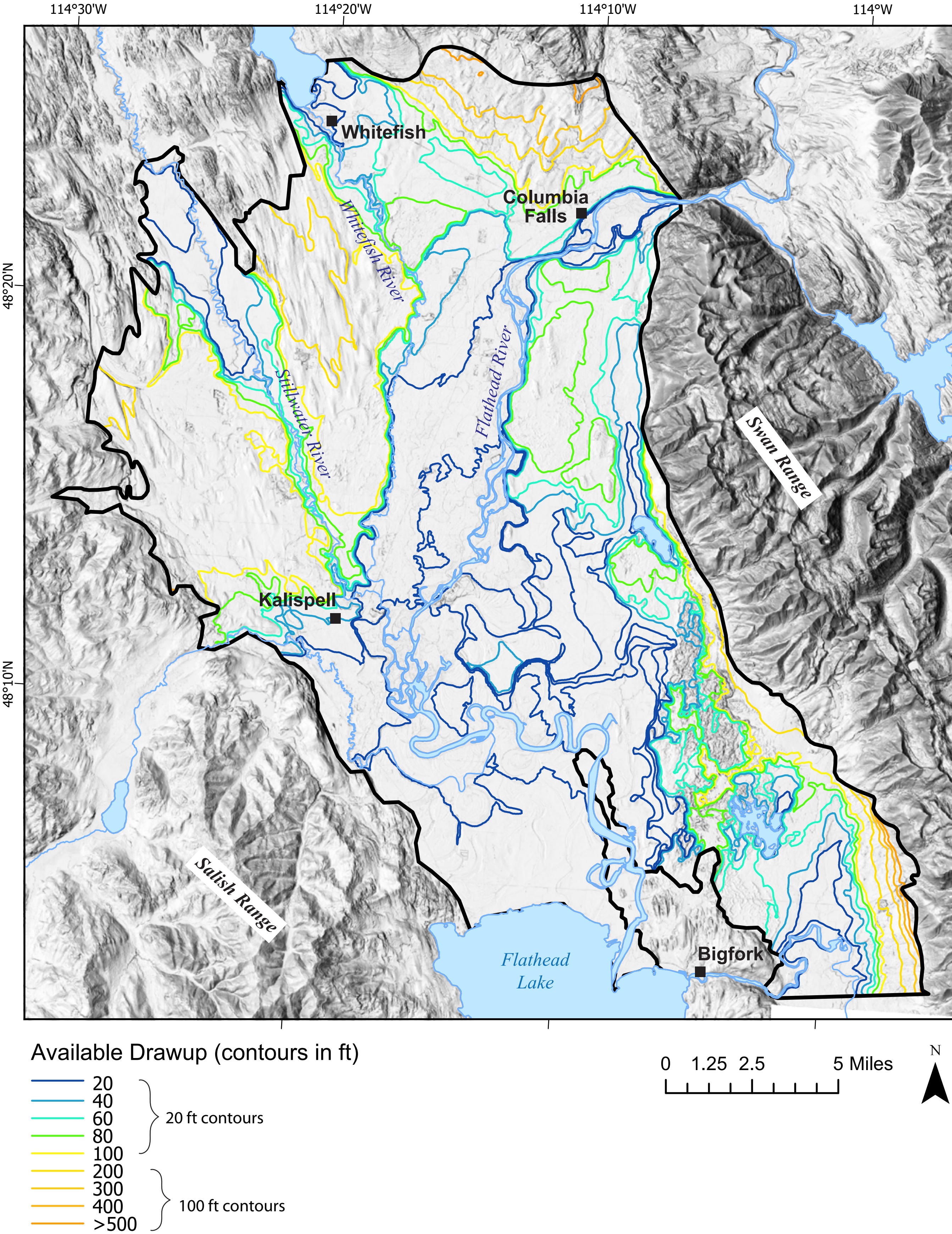

Figure A4. Contours of criteria 2: available drawup. Dataset was created by subtracting the potentiometric surface (Rose and others, 2022, extended with Smith, 2004b) from the 1 m lidar elevation map (USGS, 2025).

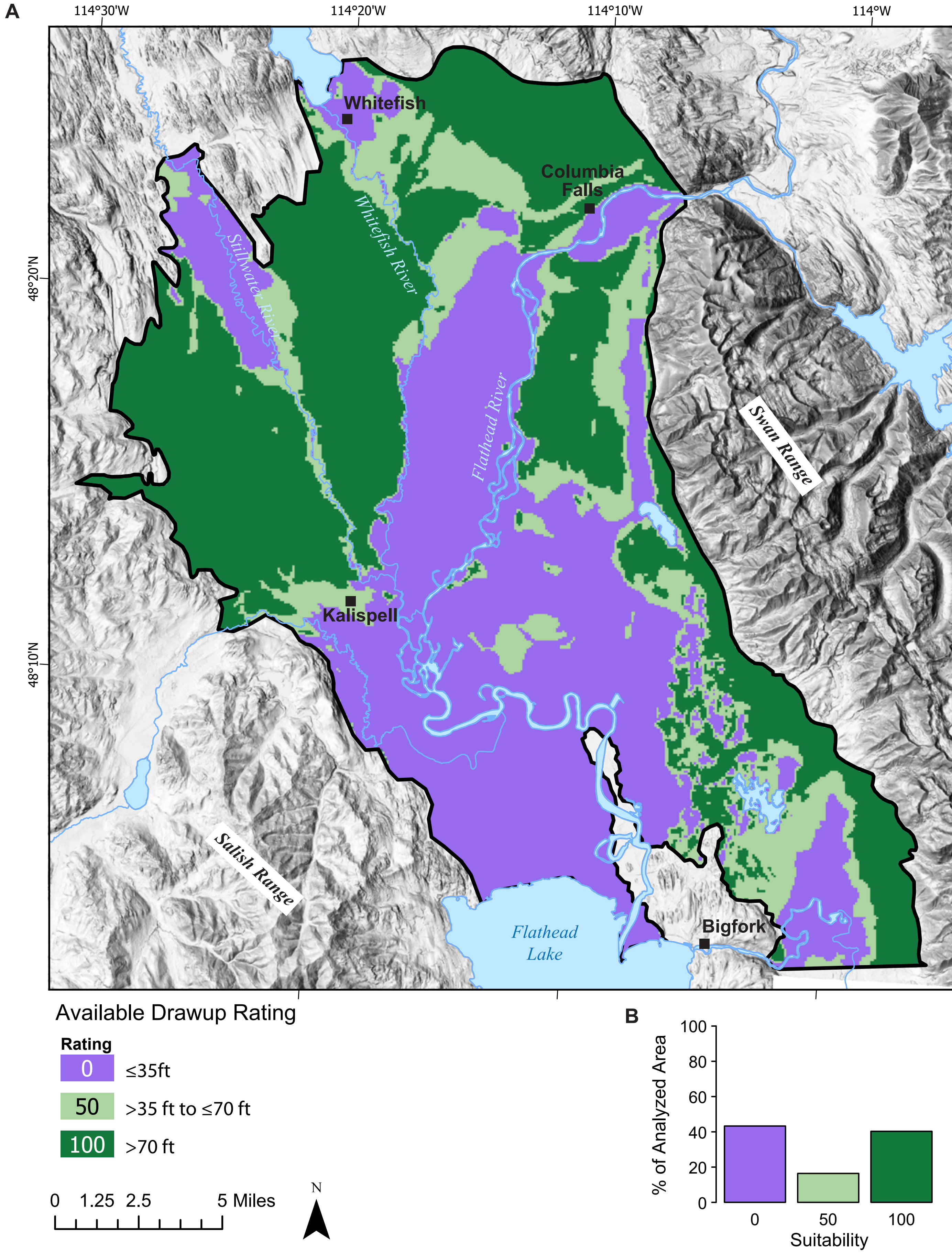

Figure A5. (A) Ratings given to criteria 2: available drawup. (B) Percentage of analyzed area in each of the rating classifications.

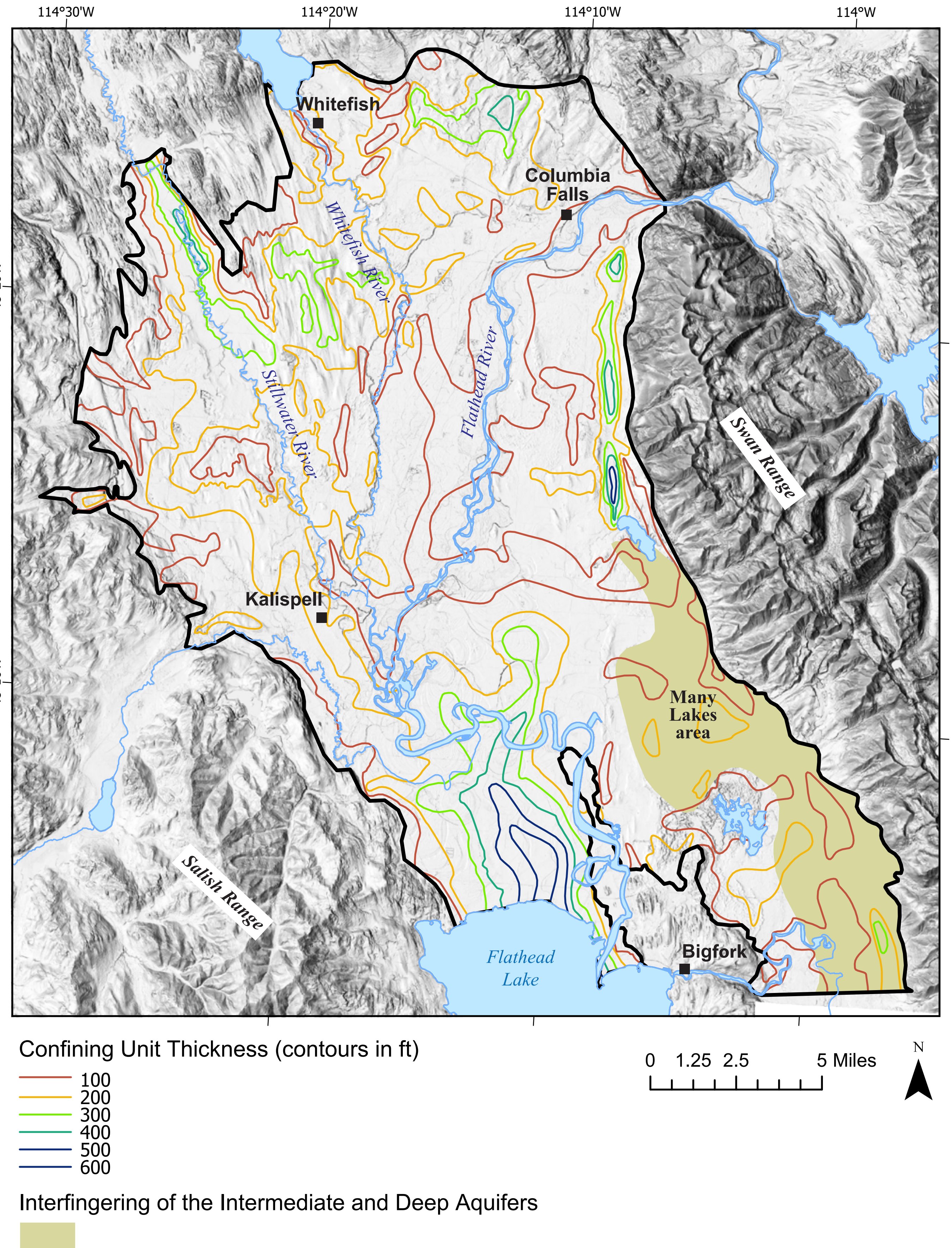

Figure A6. Datasets for criteria 3: vertical confinement. Confining unit thickness was digitized from Smith (2004d) and the interfingering of the intermediate and deep aquifers was adapted from Smith (2004d).

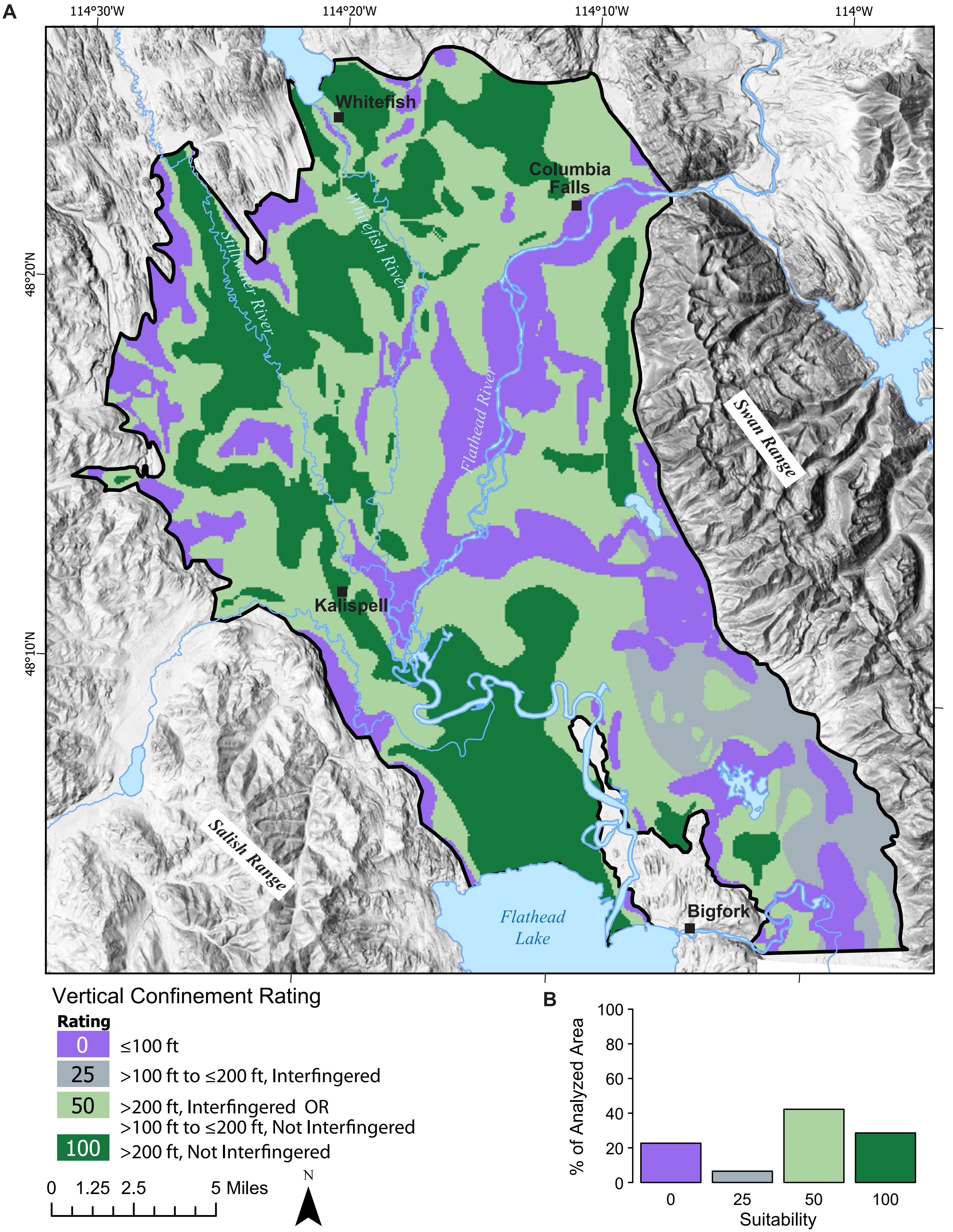

Figure A7. (A) Ratings given to criteria 3: vertical confinement. (B) Percentage of analyzed area in each of the rating classifications.