Managed Aquifer Recharge (MAR):

An Initial Hydrogeologic Screening for Surface Infiltration Suitability in Montana

Ann E.H. Hanson, Andrew L. Bobst, Ginette Abdo, John I. LaFave, and Mary Sutherland

Montana Bureau of Mines and Geology

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Cover photo: Major water use in Montana includes river recreation (top, Big Hole River near Glen), public and domestic water supply (bottom left, public water supply), and irrigated agriculture (bottom right, pivot irrigation field near Melrose). Managed aquifer recharge benefits can include ecosystem enhancement by increasing late-season stream flows; replenishing aquifers that supply residential, commercial, and industrial water use; and improving water-supply reliability for agriculture. Photos by Ann Hanson.

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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. Surface infiltration is a common MAR method in which water infiltrates through the soil profile and unsaturated zone to recharge the aquifer below. An initial screening tool was developed to identify areas in Montana that may be appropriate for the surface infiltration method based on hydrogeologic information. A geographic information system (GIS) and a multi-criteria decision analysis approach were used. This suitability analysis focused on unconfined basin-fill and alluvial surficial aquifers, which includes approximately 16.5 percent of the state (15.5 million acres). The resolution of the analysis was 330 ft x 330 ft (2.5 acre; 1:200,000 resolution).

Four criteria were rated for the suitability analysis: geologic/aquifer properties, depth to groundwater, soil permeability, and topographic slope. Ratings of 1–100 were assigned to each class within the criteria based on quantitative and qualitative measures, and professional experience. The criteria were then weighted as follows: 30 percent geologic/aquifer properties, 30 percent depth to groundwater, 30 percent soil permeability, and 10 percent topographic slope, and linearly combined to obtain a maximum suitability score of 100. A sensitivity analysis was also conducted on the criteria weights.

Final suitability scores ranged from 8 to 100, which were then grouped as “high,” “medium,” and “low.” High suitability areas scored greater than 75, which includes 15 percent of the analyzed area (~2.3 million acres). High suitability areas are common along, but not exclusive to, river terraces. Medium suitability areas scored between 50 and 75, which covers 53 percent of the analyzed area (~8.3 million acres). Low suitability areas scored less than or equal to 50, which includes 32 percent of the analyzed area (~5.0 million acres). Low suitability areas are common where fine-grained glacial or Tertiary sediments are present at the surface. The final statewide MAR surface infiltration suitability map is provided in plate 1 of this report and as a web application (Web App) at https://gis-data-hub-mbmg.hub.arcgis.com/apps/93e50821cc9c494392f238c521ef5576/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.

The Montana statewide MAR surface infiltration suitability map is based on publicly available information and is intended to serve as a first-level screening tool to identify potentially suitable areas; additional local investigations and/or pilot studies will be needed to evaluate the suitability of specific sites.

INTRODUCTION

Given the increased demand for water and uncertainties regarding water availability, there is interest across Montana in developing new ways to augment water supplies. Managed aquifer recharge (MAR) provides a means to supplement water supplies by intentionally recharging aquifers; it is a method to “slow water down” or store water with the intent of recovering water later during times of need or to achieve an ecological benefit (NGWA, 2024; Parker and others, 2022). The two primary approaches to MAR are surface infiltration and aquifer storage and recovery (ASR). Surface infiltration is accomplished by (but not limited to) running water through unlined leaky canals or ditches, ponding water in percolation basins/pits, spreading water across fields, or constructing channel modifications to enhance infiltration and recharge water into aquifers. ASR uses wells to inject and extract water into targeted aquifers; it is generally used in confined aquifers.

The benefits of MAR are well documented (e.g., Dillon, 2005) 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 for aquifers that are being overdrawn, seeing land-use-related decrease in recharge, supplying high-development areas, or have experienced prolonged drought;
- Ecosystem enhancement by increasing late-season stream flows (baseflow) 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 Montana State Water Plan (DNRC, 2015) recognizes that aquifers can provide a means of water storage by retaining high spring flows when the "physical supply exceeds downstream legal demands." Furthermore, many well hydrographs throughout Montana already demonstrate "incidental recharge" due to canal leakage and/or flood irrigation (Patton and others, 2003; Smith, 2006; Waren and LaFave, 2011; Madison, 2023). In 2011, the Montana Legislature adopted an approach to facilitate reallocating existing water rights for aquifer recharge. However, it has not been widely adopted due to a lack of research "in the area of aquifer recharge" (DNRC, 2015).

PURPOSE AND SCOPE

The purpose of this project is to develop a statewide MAR surface infiltration (hereafter MAR will refer to recharge related to surface infiltration) suitability map based on hydrogeologic properties using a geographic information system (GIS) and multi-criteria decision analysis (MCDA) on a 2.5-acre scale. The map is intended to serve as a first-level screening tool to identify areas that merit a more detailed site-specific investigation. The suitability analysis did not consider the potential for ASR because it generally relies on distinctly different hydrogeologic properties and processes.

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/93e50821cc9c494392f238c521ef5576/explore. This Web App is intended to help the reader understand the process and explore the results with other GIS datasets.

The analysis was constrained to areas underlain by unconfined basin-fill or alluvial surficial aquifers because they typically have greater permeability and potential for surface recharge as compared to bedrock aquifers; however, bedrock aquifers may be suitable for surface infiltration in limited areas. The criteria used in the analysis included geologic/aquifer properties, depth to groundwater, soil permeability, and topographic slope. Publicly available information was used to assess each criterion. The final map scores the relative MAR suitability as "high," "medium," and "low" potential.

Other factors that are important to the implementation of a MAR project, such as source water availability, water quality of the source and receiving water, assessment of need, effects to downgradient users, regulatory considerations, and implementation/engineering feasibility were beyond the scope of this project and were not considered.

MONTANA'S GROUNDWATER AND AQUIFERS

Groundwater resources are closely tied to the geology of Montana's two major physiographic provinces, the Northern Rocky Mountains Intermontane Basins and the Northern Great Plains (fig. 1A). The basics of groundwater flow within these physiographic provinces is illustrated in figure 2. Groundwater occurs in aquifers, defined as permeable geologic units that store and transmit usable quantities of groundwater. Aquifers provide two important functions: they transmit water through the subsurface from areas of recharge to areas of discharge, and they provide subsurface water storage.

The characteristics of an aquifer—productivity, storage capacity, and baseline water quality—are primarily controlled by geology. Understanding Montana's geology is critical to understanding the State's groundwater resources. The geologic units and aquifers described in this report are based on the Geologic Map of Montana (Vuke and others, 2007; 1:500,000 scale) and the Principal Aquifers of Montana map (Crowley and others, 2017; 1:1,000,000 scale). Additional detail on Montana's aquifers can be found in LaFave (2020).

In general, groundwater occurs under unconfined (water table) or confined conditions (figs. 2A, 2B). In unconfined aquifers, the water table represents the upper boundary of the aquifer and pore spaces are fully saturated below the water table. In the unsaturated area above the water table, pore spaces are filled with air and water. The water table moves upward or downward in response to changes in storage as water recharges or discharges from the aquifer. Most unconfined aquifers along streams are in direct hydraulic connection with surface water (figs. 2A, 2B).

Deeper sediments and bedrock are likely to contain confined or semi-confined aquifers. Confined or semi-confined aquifers are permeable geologic units that are completely saturated and overlain or "capped" by aquitards (confining layers). Aquitards are relatively low-permeability layers such as clay, silt, or shale that restrict groundwater flow. Groundwater in confined aquifers occurs under pressure, and the water level in a well completed in a confined aquifer will typically be

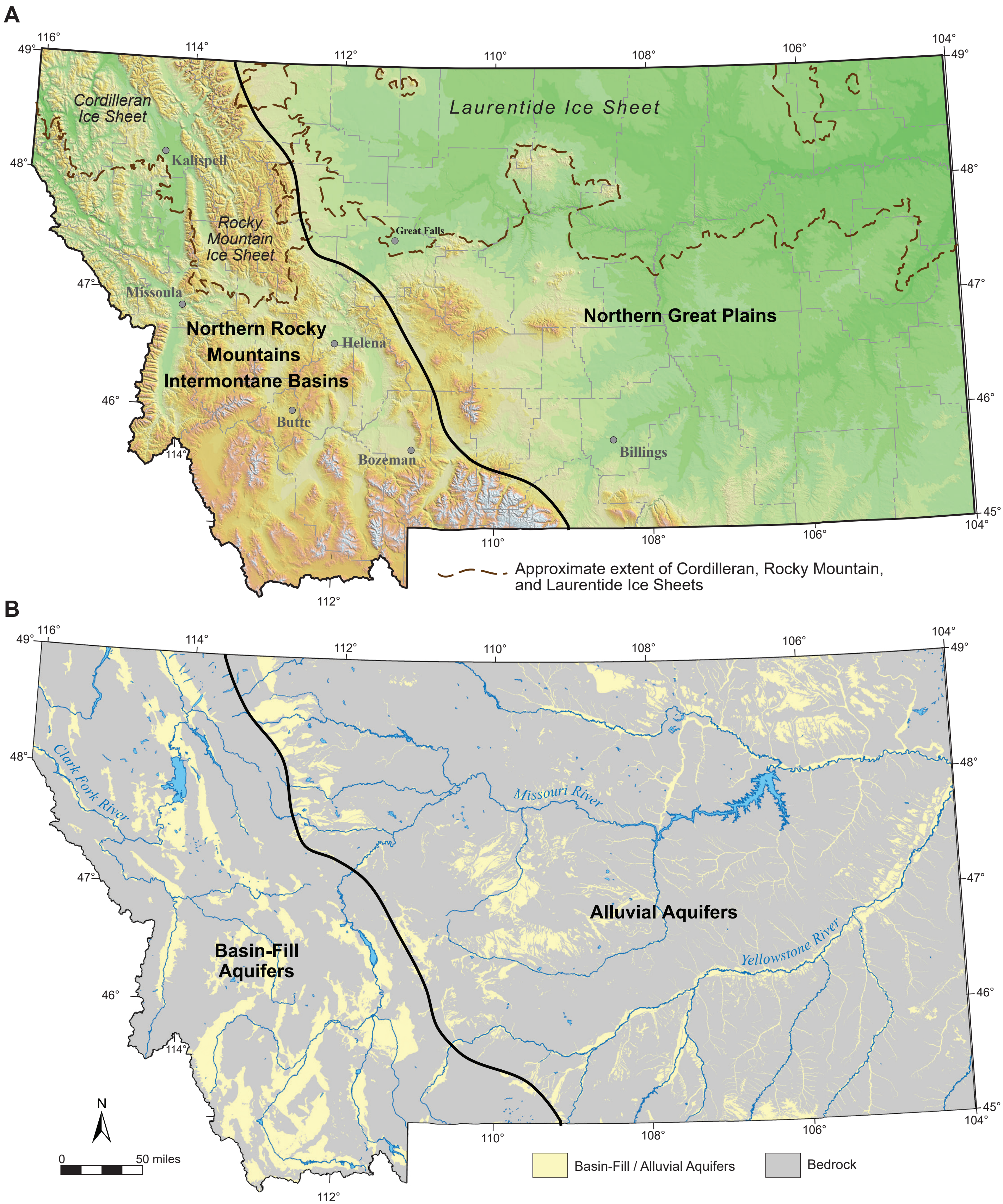
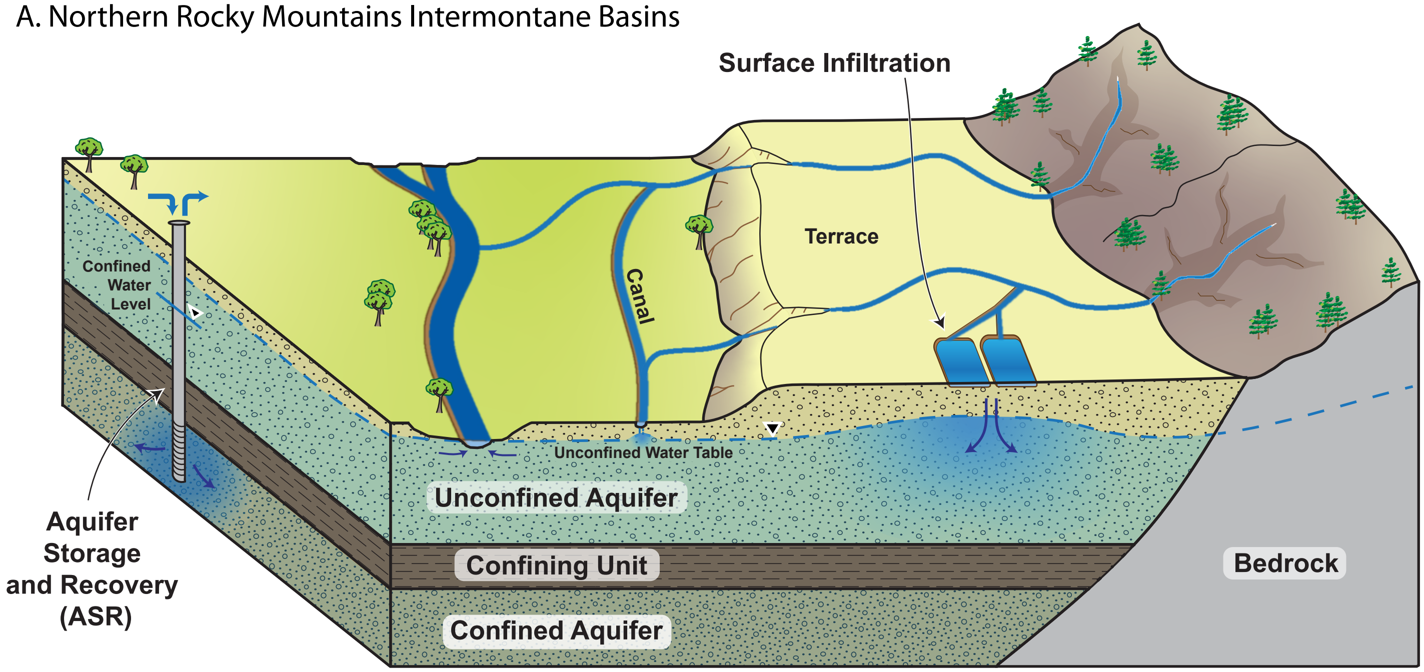


Figure 1. (A) Montana can be divided into two physiographic provinces: the Northern Rocky Mountains Intermontane Basins and the Northern Great Plains. The approximate extent of the Cordilleran, Rocky Mountain, and Laurentide ice sheets are shown. (B) Distribution of basin-fill aquifers (western intermontane basins) and alluvial aquifers (east-central river valleys). Adapted from Crowley and others (2017).

A. Northern Rocky Mountains Intermontane Basins



B. Northern Great Plains

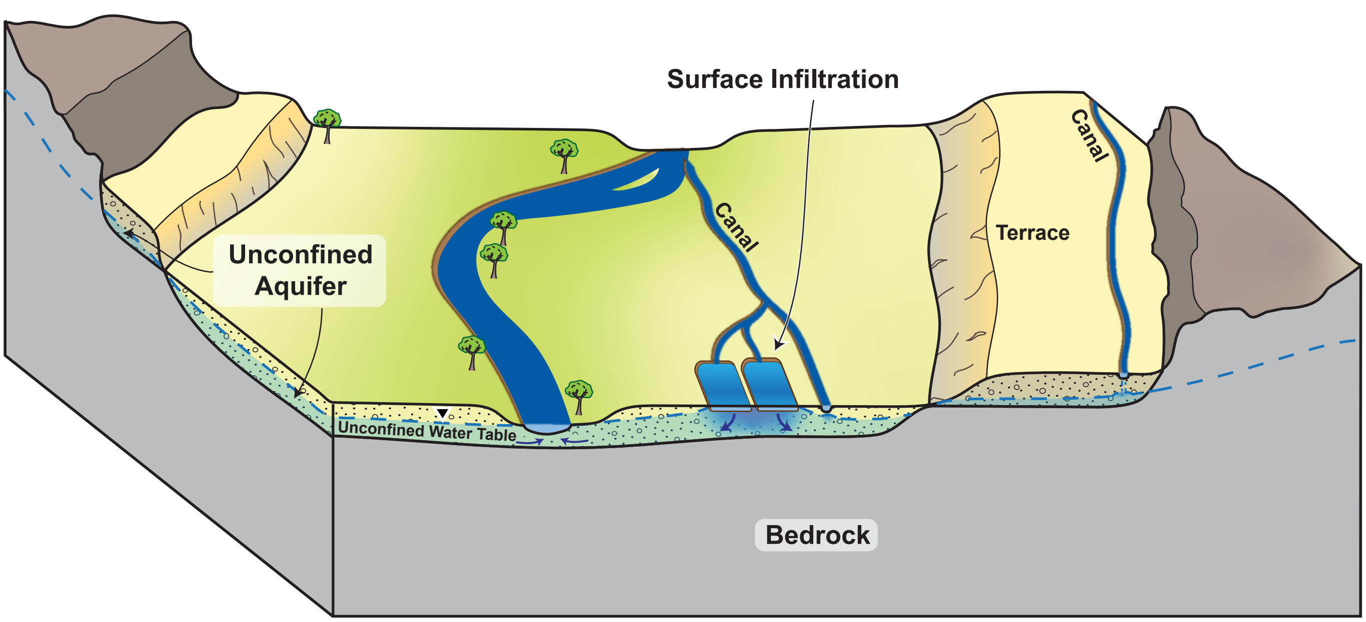


Figure 2. Schematic block diagram of MAR surface infiltration and aquifer storage and recovery (ASR) methods. (A) In the Northern Rocky Mountains Intermontane Basins, surface infiltration is possible for unconfined aquifers while ASR is more suited for confined aquifers. (B) In the Northern Great Plains where bedrock is shallow, unconfined alluvial aquifers are more suited for surface infiltration.

above the top of the aquifer (fig. 2B). Water levels in confined aquifers will rise and fall with recharge and discharge, respectively, as changes in storage cause pressure changes within the aquifer.

Physiographic Provinces

The Northern Rocky Mountains Intermontane Basins and the Northern Great Plains physiographic provinces manifest broad differences in geology, geologic history, topography, and climate, creating different hydrogeologic settings.

Northern Rocky Mountains Intermontane Basins

The Northern Rocky Mountains Intermontane Basin region covers the western third of Montana and is characterized by mountain ranges separated by valleys (intermontane basins; figs. 1A, 2A). The intermontane basins are topographic and geologic features that are structurally downdropped relative to the surrounding mountains and contain basin-fill sediments consisting of unconsolidated to consolidated Tertiary and Quaternary deposits that are up to several thousand feet thick (Tuck and others, 1996; fig. 2A).

The Intermontane Basin region contains the headwaters of the Missouri and Columbia Rivers systems and is characterized by perennial and ephemeral streams and their associated floodplains. In most basins, modern floodplains are adjacent to older, higher river terraces. These features grade to pediments, alluvial fans, or glacial deposits that meet mountain fronts with an abrupt change in slope (fig. 2A).

Within the intermontane basins, groundwater occurs in the shallow, unconfined alluvial (sand and gravel) aquifers, and in many basins deeper confined to semi-confined aquifers also exist (fig. 2A). Both aquifer types can store large amounts of groundwater and are commonly highly productive. Unconfined alluvial aquifers are mostly within 200 ft of the land surface and occur adjacent to the major streams. Confined aquifers generally occur at depths greater than 100 ft.

The mountain ranges separating the basins in western Montana are composed of relatively impermeable bedrock that consists mostly of the Precambrian Belt Supergroup, Paleozoic to Mesozoic sedimentary rocks, and Cretaceous and Tertiary igneous and volcanic rocks. Although relatively impermeable, there is sufficient fracture permeability in many places for the bedrock to provide water to low-yield wells for domestic or stock use.

Northern Great Plains

The eastern two-thirds of Montana is in the Northern Great Plains physiographic province (fig. 1A). This region is characterized by gently rolling to highly dissected topography, but also includes several isolated mountain ranges of the Rocky Mountains.

The alluvial aquifers in the Great Plains consist of shallow Quaternary and Tertiary sand and gravel deposits interbedded with silt and clay. These aquifers are generally less than 100 ft thick (Zelt and others, 1999) and are restricted to the width of the river valley (figs. 1B, 2B). The alluvium is thickest along the Missouri and Yellowstone Rivers and their major tributaries. Alluvial deposition and therefore aquifer thickness generally increase in the downstream direction. Additionally, discontinuous terrace gravels flank the rivers in some areas. Well-formed terraces also occur along the Rocky Mountain Front (approximately demarked by the black line in fig. 1A) and off the Beartooth Mountains southwest of Billings (plate 1). North of the Missouri River alluvial aquifers frequently occur in glacial sediments (fig. 1B); the major aquifers in the glacial sediments are outwash and buried-valley deposits.

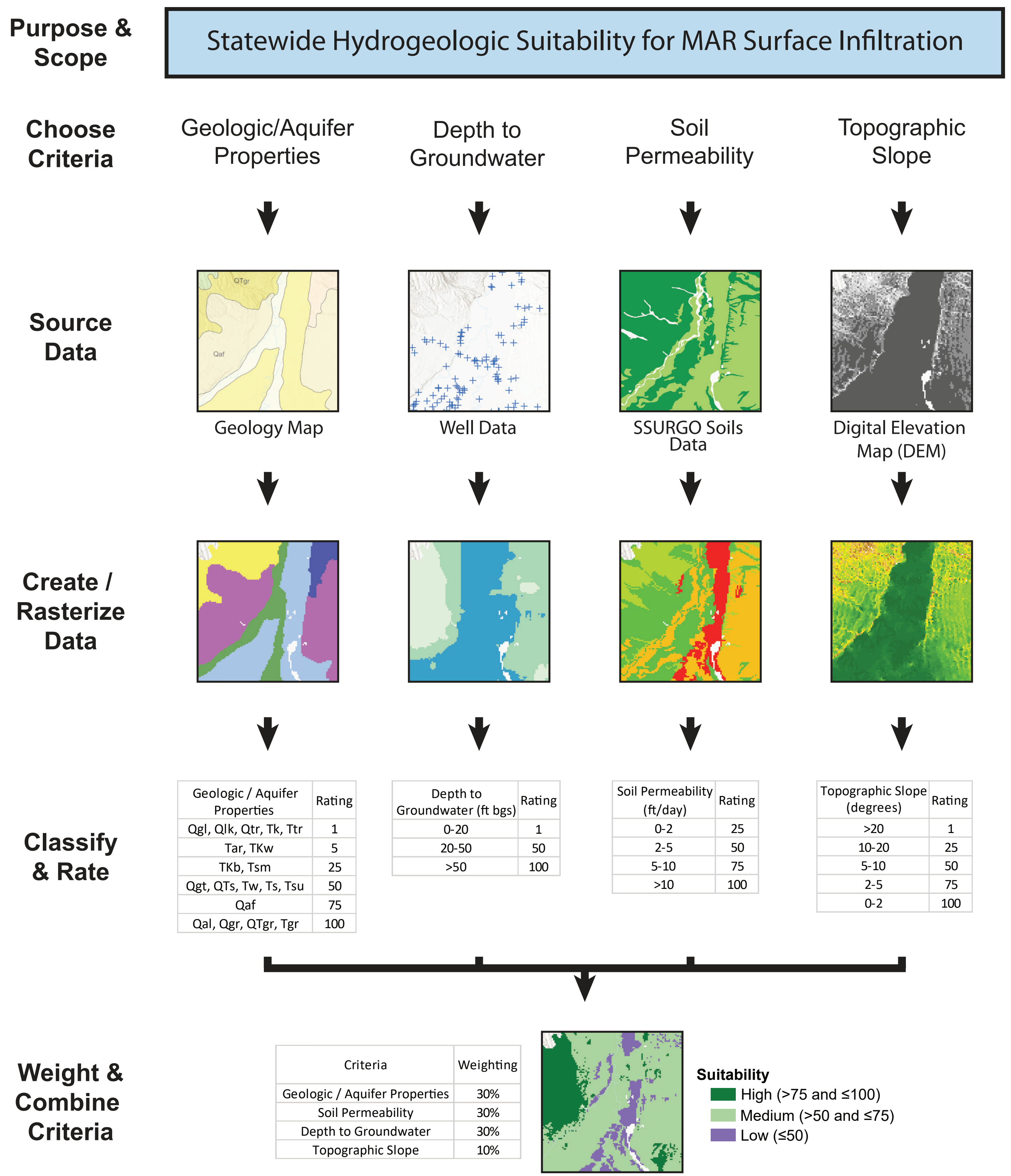
The shallow alluvial aquifers in the Northern Great Plains are underlain by a thick sequence of Paleozoic to Tertiary sedimentary bedrock aquifers composed of sandstone, coal, and limestone. These bedrock aquifers are mostly confined, with limited surface exposures, and have less favorable permeability and storage characteristics than the alluvial aquifers.

METHODS

The suitability for surface infiltration depends on several hydrogeologic properties. These hydrogeologic properties vary spatially across Montana, and consequently, the suitability for surface infiltration also varies spatially. To develop a MAR suitability map, publicly available geospatial data that represent relevant hydrogeologic properties were evaluated with regards to surface infiltration.

Multi-Criteria Decision Analysis (MCDA)

To obtain a suitability score, MCDA (Malczewski and Rinner, 2015) and ESRI's ArcGIS Pro program were used to evaluate and combine the geospatial data. The MCDA approach (fig. 3) involves choosing criteria important for MAR methods, creating/rasterizing the datasets, assigning ratings within criteria, assign-



Geologic / Aquifer Properties	Rating
Qgl, Qlk, Qtr, Tk, Ttr	1
Tar, TKw	5
TKb, Tsm	25
Qgt, QTs, Tw, Ts, Tsu	50
Qaf	75
Qal, Qgr, QTgr, Tgr	100

Depth to Groundwater (ft bgs)	Rating
0-20	1
20-50	50
>50	100

Soil Permeability (ft/day)	Rating
0-2	25
2-5	50
5-10	75
>10	100

Topographic Slope (degrees)	Rating
>20	1
10-20	25
5-10	50
2-5	75
0-2	100

Criteria	Weighting
Geologic / Aquifer Properties	30%
Soil Permeability	30%
Depth to Groundwater	30%
Topographic Slope	10%

Figure 3. Flow chart of the multi-criteria decision analysis (MCDA) approach for statewide MAR surface infiltration suitability. Complete tables of the criteria classification and rating can be found in tables 1–4. Refer to Methods and appendix A for discussion of rating and weighting decision process.

ing weightings of the criteria, and then combining the criteria.

The geospatial datasets chosen for each criterion (see Criteria and Rating Within Criteria section below) were converted to raster datasets to quantitatively combine them. Raster datasets break spatial data into equally sized cells that form rows and columns. Each cell represents a geographic location and the value of the hydrogeologic property at that location. Input data were rasterized to 330 ft x 330 ft cells, which is 2.5 acres per cell. This produces an approximate map scale of 1:200,000. It should be recognized that the original data used to derive the criteria datasets ranged in scale from 1:12,000 to 1:500,000 (discussed below), and the 1:200,000 resolution was chosen to be a balance among the different dataset resolutions.

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 surface infiltration augmenting recharge in an area. Non-redundant 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 the MAR suitability.

Hydrogeologic properties necessary for surface infiltration and groundwater recharge include a geologic unit/aquifer that can adequately store and transmit water in usable quantities, sufficient available unsaturated storage above the aquifer, soils that are sufficiently permeable to allow water to infiltrate below the land surface, and relatively flat land-surface slopes that can retain water and promote infiltration. The criteria chosen to represent these hydrogeologic characteristics for the surface infiltration suitability analysis were:

- geologic/aquifer properties,
- depth to groundwater (DTW),
- soil permeability, and
- topographic slope.

Classification of the criteria is subjective; however, the following discussion provides information on the decision process for classifying and rating. Additional discussions, maps, and figures regarding the ratings can be found on the Web App "Analysis" tab and in appendix A.

Geologic/Aquifer Properties

A geologic unit is the host material for an aquifer. The lithology of an aquifer controls its ability to store and transmit water. The Montana Bureau of Mines and Geology's (MBMG) 1:500,000 Geologic Map of Montana (Vuke and others, 2007) was the basis for the geologic unit/aquifer properties dataset. The basin-fill and alluvial surficial geologic units from the geologic map are shown in table 1 and range in age from Tertiary–Cretaceous to Quaternary. The surficial geologic unit polygons were rasterized using ArcGIS maximum combined area cell assignment and can be viewed in the Web App "Analysis" and "Explore" tabs.

For each geologic unit, the lithology was used to estimate hydraulic conductivity (K) and specific yield (S_y) from literature-based values (appendix A; Freeze and Cherry, 1979; Heath, 1983; Fetter, 1994, 2001). High K values allow water to move more quickly through the aquifer, requiring less time for recharge and limiting groundwater mounding. High S_y values allow for a greater volume of water to be stored in the aquifer per unit change in groundwater level, limiting groundwater mounding. The K and S_y values were used to guide ratings of the units between 1 and 100 (table 1; Web App "Analysis" tab).

Younger and coarser-grained units typically have higher K and S_y values and were rated as more suitable (closer to 100). Older sediments are generally more compacted and/or cemented with lower K and S_y (appendix table A1); older and finer-grained sediments were rated least suitable (closer to 1). Fine-grained sediments deposited by recent glaciers can mantle the surficial geology in northern Montana (fig. 1A, extent of Cordilleran, Rocky Mountain, and Laurentide ice sheets). In these areas, the geologic unit was still used for the geologic/aquifer properties criteria (see appendix A for further reasoning).

Depth to Groundwater (DTW)

The depth to groundwater is a measure of the unsaturated zone thickness. The available storage volume per unit area is the product of the unsaturated zone thickness and S_y. The DTW dataset was compiled from water-well records in the Ground Water Information Center (GWIC; MBMG, 2024) database. MBMG's GWIC database is the central information repository for Montana's groundwater resources. The

Table 1. Lithologic description of the basin-fill and alluvial surficial geologic units and the suitability ratings from least suitable (1) to most suitable (100) for MAR surface infiltration.

1:500K Geologic Unit	Unit Age	Geologic Label	Lithology Description (from Vuke and others, 2007)	Geologic Unit Area to Total Analyzed (%)	Rating (1-100)[1]
Lacustrine deposits	Quaternary	Qlk	Light brown to brown, well-sorted, unconsolidated, laminated sand, silt, and clay.	0.5	1
Glacial lake deposits	Quaternary	Qgl	Light brown laminated silt, fine-grained sand, and clay.	1.3	1
Travertine	Quaternary–Tertiary	Qtr, Ttr	White to light grayish pink travertine, typically vuggy and finely crystalline, locally banded limestone.	<0.1	1
Kishenehn Formation	Tertiary	Tk	Light to dark bluish gray, locally sandy clay with interbeds of light gray, nodular sandstone, conglomerate, and coal.	0.7	1
Willow Creek Formation	Tertiary–Cretaceous	TKw	Reddish gray, olive gray, and purple mudstone, and gray, greenish gray, and yellow sandstone.	0.7	5
Arikaree Formation	Tertiary	Tar	Greenish gray, fine-grained sandstone with interbedded light gray volcanic ash.	0.2	5
Sediment or sedimentary rock	Middle Tertiary	Tsm	Tuffaceous siltstone, sandstone, bentonitic mudstone, conglomerate, limestone, and equivalent sediment and ash beds.	3.3	25
Beaverhead Group	Tertiary–Cretaceous	TKb	Reddish gray conglomerate with limestone and quartzite clasts, gray limestone, and grayish brown sandstone.	1.5	25
Sediment or sedimentary rock	Tertiary	Ts	Conglomerate, tuffaceous sandstone and siltstone, marlstone, and equivalent sediment and ash beds.	7.2	50
Sediment or sedimentary rock	Upper Tertiary	Tsu	Conglomerate, tuffaceous sandstone and siltstone, marlstone, and equivalent sediment and ash beds.	3.9	50
Wasatch Formation	Tertiary	Tw	*Southeastern Montana:* orangish brown, arkosic sandstone, lenticular conglomerate and siltstone, dark gray carbonaceous shale, coal, and varicolored claystone. *Bears Paw Mountains:* variegated red, pink, lavender, light green, yellow, gray, and very light gray shale, bentonitic claystone, and siltstone; light gray, brown, and green cross-bedded sandstone; and lenses of boulder conglomerate.	1.5	50
Sediments and basin-fill	Quaternary–Tertiary	QTs	Yellowish gray to very pale orange, angular silt and clay-size sediment with lenses of angular and subangular locally derived rock ranging to very large boulder size but generally cobble size and smaller. In some areas granules and pebbles float in the silty matrix. Locally cemented.	0.2	50
Glacial deposits	Quaternary	Qgt	Dominantly till, outwash, and local glacial lake deposits.	10.8	50
Alluvial fan deposits	Quaternary	Qaf	Variable deposits with fan-shaped morphology developed where slope gradient changes abruptly.	2.0	75
Gravel	Tertiary	Tgr	Variable deposits that range from pebble to boulder size and include sand, silt, and clay. Dominantly alluvial terrace, abandoned channel and floodplain, remnant alluvial fan, and local glacial outwash.	7.6	100
Gravel	Quaternary–Tertiary	QTgr	Variable deposits that range from pebble to boulder size and include sand, silt, and clay. Dominantly alluvial terrace, abandoned channel and floodplain, remnant alluvial fan, and local glacial outwash.	13.6	100
Alluvium	Quaternary	Qal	Gravel, sand, silt, and clay deposits of stream and river channels, and floodplains.	25.1	100
Gravel	Quaternary	Qgr	Variable deposits that range from pebble to boulder size and include sand, silt, and clay. Dominantly alluvial terrace, abandoned channel and floodplain, remnant alluvial fan, and local glacial outwash.	20.0	100

[1]See appendix A for additional hydrogeologic information used to inform rating.

data include well-completion reports from drillers and water-level measurements. Wells less than 200 ft deep with a driller-reported static water-level measurement or a water level measured as part of an MBMG site visit were selected for analysis. Wells that have a reported bedrock aquifer code or are located on bedrock units were removed from the dataset. The number of documented water-level measurements per well varied from one (e.g., when driller-reported) to thousands of measurements (e.g., when part of the long-term groundwater monitoring network). Therefore, an average water level was used for wells with more than one measurement. Inverse distance weighting (IDW) was used to interpolate the DTW at a 330 ft x 330 ft resolution (1:200,000); the interpolations were then clipped to the basin-fill and alluvial surficial geologic units.

In general, the potential storage, and hence DTW suitability, should increase with increasing DTW. However, the most suitable DTW values for surface infiltration reported in the literature vary: i.e. >30 ft (Jasrotia and others, 2007; Kazakis, 2018; Fuentes and Vervoort, 2020), to >50 ft (Duraiswami and others, 2009; Hammouri and others, 2014), or even >100 ft (Malekmohammadi and others, 2012). However, some studies indicate that a large DTW may be unsuitable for surface infiltration because there can be increased unrecoverable water through a thicker unsaturated zone and/or longer recharge times (Steinel and others, 2016; Shaw and others, 2020).

This study divided DTW into three classes, and the ratings increased with greater DTW (table 2; Web App "Analysis" tab). The three DTW classes were based on known data uncertainties: more divisions would be misleading regarding the precision of the dataset and fewer divisions would overstate the suitability of locations with shallow DTW that were biased deeper in the statewide interpolation (see Limitations section). A DTW ≤20 ft was considered an insufficient amount of storage for surface infiltration and increases the potential for unintended consequences such as formation of seeps or surface flooding due to mounding and/or consumptive use by phreatophytes; therefore, it was rated as a 1. In many cases, these areas correspond to known wetlands. The second DTW class is consistent with the literature: DTW >20 and ≤50 ft is suitable for recharge but provides a buffer for the error in the interpolated DTW; this class was rated 50. The highest rating was given to DTW >50 ft and rated 100. Long-term monitoring wells with DTW >50 ft often show annual water-level changes in response to spring runoff or irrigation onset, suggesting seasonal recharge. Therefore, greater DTW does not have apparent disadvantages (e.g., increased recharge time) at depths up to 200 ft but has the advantage of more storage availability.

Soil Permeability

Successful surface infiltration requires permeable soil. The Soil Survey Geographic Database (SSURGO; USDA, 2024) provides statewide soil information at a 1:12,000 scale to depths of 200 cm (~6.5 ft). Each SSURGO map unit (mukey ID) has one or more components (cokey ID) and each component has one or more soil horizons. One of the attributes of the SSURGO soil horizons is the representative saturated hydraulic conductivity (ksat_r). To obtain representative saturated hydraulic conductivity for a SSURGO map unit, a depth-weighted harmonic average was calculated from the soil horizon ksat_r values within each component. Then, an area-weighted average was calculated from the components of each SSURGO map unit. The averaged saturated hydraulic conductivity values were converted from µm/s to ft/d and termed "soil permeability" for this study. The soil permeability data were clipped to the basin-fill and alluvial surficial geologic units and rasterized using bilinear interpolation. Collinearity between geologic/aquifer properties and soil permeability was assessed but was not present between the two criteria (Pearson correlation coefficient = 0.01).

Higher soil permeability values indicate faster infiltration rates. Classification of soil permeability varies in literature and is commonly based on an author's experience (e.g., Shaw and others, 2020). For this study, soil permeability values were divided into four classes (rated 25, 50, 75, and 100)—ratings were increased with increasing soil permeability values (table 3; Web App "Analysis" tab). The division at 2 ft/d division is similar to a soil permeability class in both Ghayoumian and others (2007) and Russo and others (2015). The 5 ft/d division is based on Shaw and others (2020). Finally, the 10 ft/d division was subjectively chosen to better refine the most permeable units.

Table 2. Suitability ratings assigned to the depth to groundwater (DTW) from least suitable (1) to most suitable (100) for MAR surface infiltration in the basin-fill and alluvial surficial geologic units.

Depth to Groundwater (ft bgs[1])	Area to Total Analyzed (%)	Rating (1–100)
≤20	32%	1
>20 and ≤50	52%	50
>50 and <200	16%	100

[1]bgs, below ground surface.
Note. DTW is representative of the aquifer's storage availability.

Table 3. Suitability ratings assigned to the soil permeability from least suitable (25) to most suitable (100) for MAR surface infiltration in the basin-fill and alluvial surficial geologic units.

Soil Permeability (ft/day)	Area to Total Analyzed (%)	Rating (1-100)
≤2	41%	25
>2 and ≤5	36%	50
>5 and ≤10	15%	75
>10	8%	100

Note. Soil permeability is representative of the rate the recharge water can infiltrate past the soil profile.

Topographic Slope

Flat or gently sloped land enables ponding and infiltration of recharge water, whereas more steeply sloped land may enhance runoff rather than infiltration. The topographic slope dataset was generated from the USGS 10-m digital elevation model (DEM; 1:24,000; USGS, 2024). The raster was clipped to the basin-fill and alluvial surficial geologic units and resampled using bilinear interpolation.

Topographic slope was divided into five classes rated 1, 25, 50, 75, and 100, with higher ratings given to lower slopes (table 4; Web App "Analysis" tab). The ≤2 degrees and >2 to ≤5 degrees classes were based on literature (Shaw and others, 2020). The >5 to ≤10 degrees and >10 to ≤20 degrees classes were added because Montana's western basins have steeper slopes, especially along valley margins, that are suitable for some MAR methods (e.g., transecting canals, in-stream channel modifications, reverse tile drains). Therefore, higher slopes were given a lower rating than low slope areas, but not such a low rating that they would be excluded.

Table 4. Suitability ratings assigned to the topographic slope from least suitable (1) to most suitable (100) for MAR surface infiltration in the basin-fill and alluvial surficial geologic units.

Slope (degrees)	Area to Total Analyzed (%)	Rating (1–100)
≤2	53%	100
>2 and ≤5	22%	75
>5 and ≤10	14%	50
>10 and ≤20	9%	25
>20	2%	1

Note. Topographic slope is representative of the terrain's ability to promote infiltration.

Percent Weighting of Criteria

The suitability criteria were weighted based on their perceived importance to surface infiltration. Different weighting combinations were also 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 surface infiltration suitability. Geologic/aquifer properties, DTW, and soil permeability were given equal weightings; topographic slope was weighted lower because some surface infiltration methods can be implemented on higher slopes. The relative weightings used in this study are:

- Geologic/aquifer properties: 30%
- DTW: 30%
- Soil Permeability: 30%
- Topographic Slope: 10%

Weighted Linear Combination (WLC)

The datasets were combined using the 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 MAR suitability:

$$\textit{MAR Surface Infiltration Suitability} = \sum \textit{criteria weight} \times \textit{rating within criterion.}$$

RESULTS

The MCDA analysis provides a statewide MAR suitability map, shown in plate 1 and the Web App. This analysis provides a screening-level identification of locations that may have appropriate hydrogeologic characteristics based on the datasets used (geologic/aquifer properties, DTW, soil permeability, and topographic slope). However, a low suitability score does not mean surface infiltration is impossible nor does a high suitability score mean surface infiltration success is guaranteed (see Limitations section below). Site-specific information will be needed to refine this analysis for specific locations (see Additional Considerations section below).

The surface infiltration suitability scores vary throughout Montana. Approximately 16.5 percent of the state (~15.5 million acres) is underlain by basin-fill or alluvial surficial geologic units and were included in this analysis. Suitability scores ranged from 8 to 100 (fig. 4A). The scores were grouped as "high" (>75), "medium" (>50 and ≤75), and "low" (≤50) suitability. Fifteen percent of the analyzed area (~2.3 million acres) is scored high. Fifty-three percent of the analyzed area (~8.3 million acres) is scored medium. Thirty-two percent of the analyzed area (~5.0 million acres) is scored low.

Locations of high suitability are prevalent along gently sloping river terraces that consist mainly of gravel and have a depth to groundwater >50 ft. Pediments that flank mountain ranges also show high suitability scores if the surficial geology is coarse-

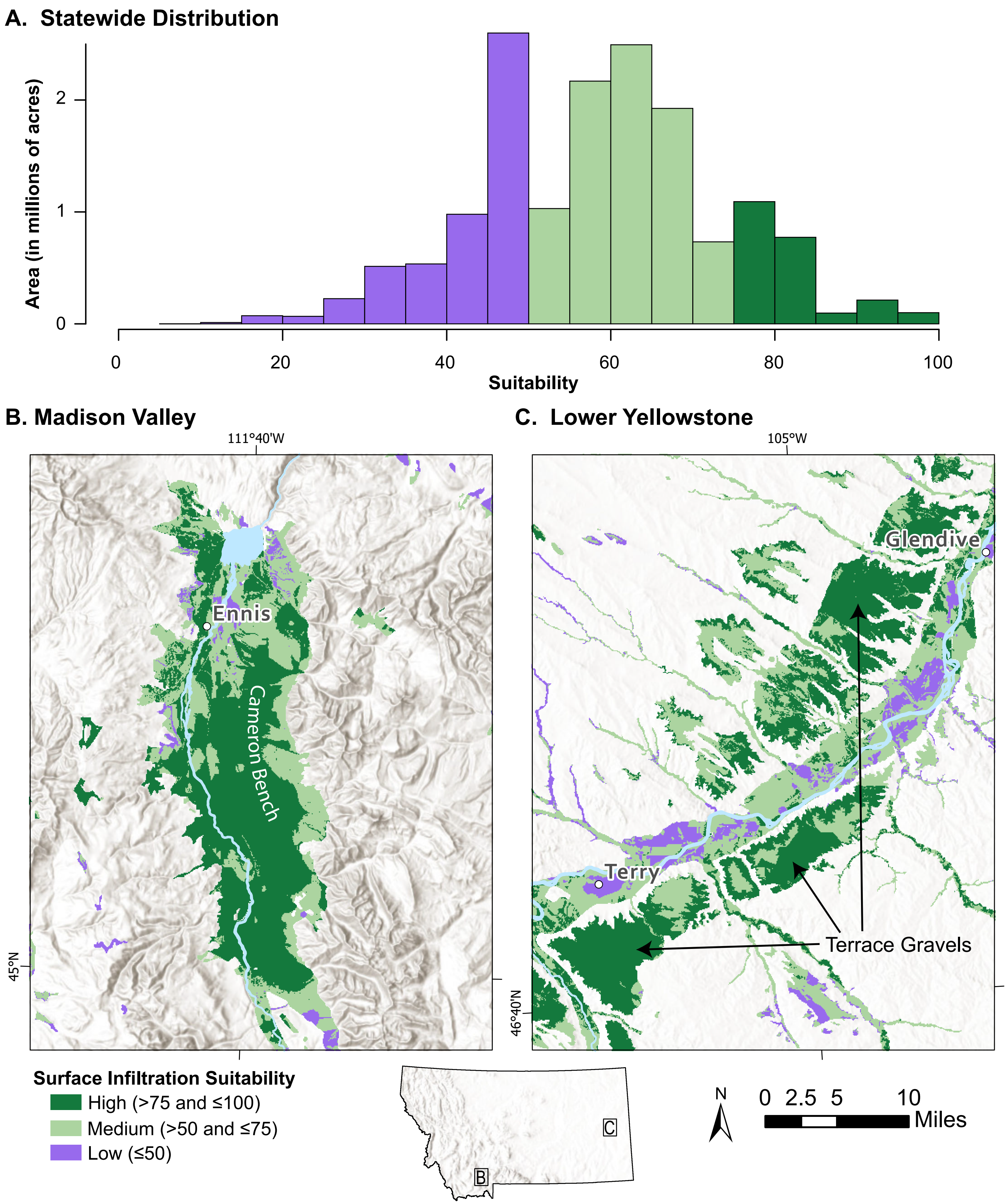


Figure 4. MAR surface infiltration suitability results provides a screening-level identification of locations with a high (>75), medium (>50 and ≤75), and low (≤50) suitability for MAR surface infiltration based on hydrogeologic characteristics. (A) Distribution of the surface infiltration suitability for the State. Histogram bars are colored based on high (dark green), medium (light green), and low (purple) suitability. The statewide map can be found in plate 1. Examples of MAR surface infiltration suitability for the (B) Madison Valley near Ennis and (C) Lower Yellowstone River Valley near Glendive and Terry.

grained and geologically young (Quaternary to late Tertiary). Conversely, locations of low suitability are most common where fine-grained sediments are present within the soil profile and/or aquifer. For example, low suitability scores are seen in the Mission Valley south of Flathead Lake, where clay-rich, Glacial Lake Missoula sediments are present (Smith, 2004), and between the Snowcrest and Ruby Mountain Ranges (plate 1), where middle Tertiary sediments crop out at the surface (Vuke and others, 2007).

The statewide distribution of suitability scores is shown in figure 4A. Two locations with widespread high suitability scores in the western (near Ennis; fig. 4B) and eastern (near Glendive and Terry; fig. 4C) parts of the State provide examples to compare the suitability analysis with regard to known field data.

The first example is the Cameron Bench in the Madison Valley near Ennis (fig. 4B); it is topographically the highest terrace in the valley and relatively flat. The terrace deposits consist of Quaternary sands and gravels (Kellogg and Williams, 2006); lithology logs from two monitoring wells (GWIC wells 149530 and 256853) record sands and gravels greater than 300 ft and reported yields of 99 gallons per minute (MBMG, 2024). Kellogg and Williams (2006) state there is less than 6 ft of loess (windblown sediment) on top of the terrace gravels; the SSURGO data (USDA, 2024) show a sand-dominated (>60%) soil profile. With sand dominating the soil profile, water should infiltrate the aquifer quickly, consistent with the >5 ft/day soil permeability. Well 256853 also shows static water levels are around 150 ft. Thus, the Cameron Bench received high ratings for all four criteria in this analysis. Long-term groundwater levels measured below the bench (GWIC well 256853) demonstrates an annual recharge response influenced by irrigation (Madison, 2023) suggesting surface infiltration can be used to recharge the aquifer.

The Yellowstone River terrace gravels near Terry and Glendive (fig. 4C) also have high suitability scores. The terrace deposits are generally 30–100 ft thick, consisting of moderately well-sorted sand and gravel (Vuke and Colton, 2003), and can overlie other Quaternary–Tertiary unconsolidated deposits (Smith and others, 2000). Yields are estimated to average 35 gpm for the terrace and river gravels (Smith and others, 2000), with static water levels ranging from 58 to 180 ft (Patton and others, 1998). The terraces are topographically flat to gently sloping and are about 300 ft above the Yellowstone River (Smith, 1998). The calculated soil permeability of these terraces is also high (>5 ft/d), particularly near the edges of the terraces. Overall, the Yellowstone River terraces receive high scores for each criterion in the analysis. However, these terraces are underlain by less permeable Tertiary bedrock, which may perch and limit the amount of storage in the gravels and/or result in spring formation at the gravel–bedrock contact along the sides of the terrace. However, hydrographs for wells completed in the Tertiary bedrock show an apparent response to periods of high precipitation, suggesting that recharge to regional aquifers occurs over relatively short time periods.

Other locations within this statewide MAR suitability analysis can be similarly understood by looking at the ratings of each criteria. For further investigation, the Web App “Analysis” and “Explore” tabs can be used to look at each criterion, criteria rating, final suitability scores, and other GIS datasets.

SENSITIVITY ANALYSIS

A sensitivity analysis was performed to assess the spatial and quantitative impact of the criteria weights (e.g., 30% geologic/aquifer properties, 30% DTW, 30% soil permeability, 10% topographic slope). Three additional analyses were performed in which the topographic slope weight was held at 10 percent and one of the other criteria (geologic/aquifer properties, DTW, or soil permeability) was emphasized by increasing its weight to 40 percent, and the other two criteria weights changed to 25 percent. For example, the map emphasizing geology (fig. 5A) used the following weights: 40 percent geologic/aquifer properties, 25 percent DTW, 25 percent soil permeability, 10 percent topographic slope. Then, to evaluate the changes in suitability when one of the criteria was emphasized, the raster values of the original suitability map (plate 1) were subtracted from the new emphasized raster values. The geographic distribution and magnitude of the changes were used to understand the sensitivity of each criterion.

Emphasizing geologic/aquifer properties changed suitability scores by -10 to +9 (fig. 5A). Suitability scores decreased for valley and basin margins and increased near the rivers. Surficial geologic deposits near the rivers typically consist of Quaternary alluvial sands and gravels. These units are given high geologic/aquifer properties ratings of 100 (table 1); therefore,

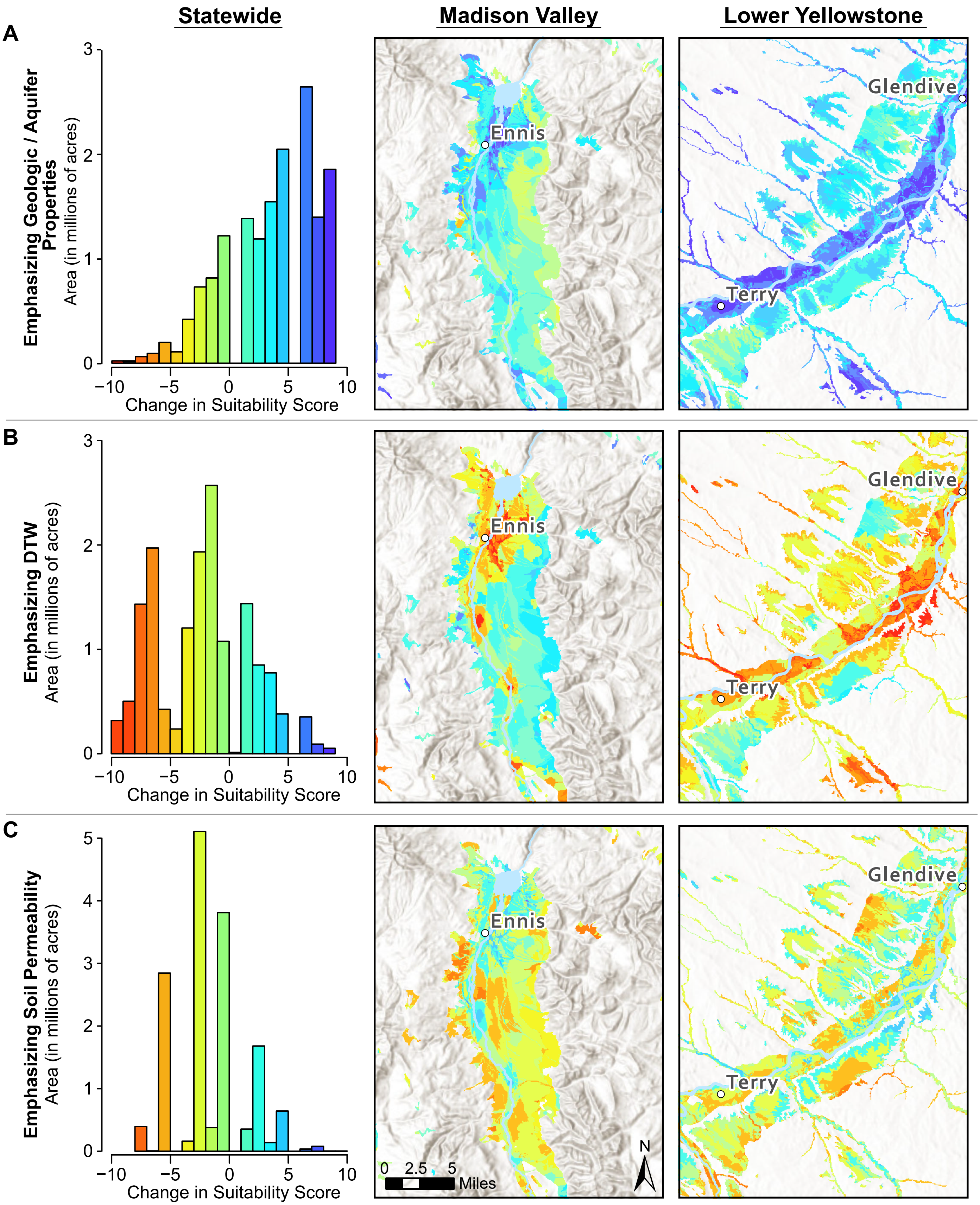


Figure 5. Sensitivity analysis showing the change in MAR surface infiltration suitability scores when (A) geologic/aquifer properties, (B) depth to groundwater (DTW), or (C) soil permeability was emphasized. The emphasized criteria's weight changed from 30% to 40% while the other two criteria weights changed from 30% to 25% and the topographic slope weight remained at 10%. Suitability scores mostly increased when emphasizing geologic/aquifer properties, mostly decreased when emphasizing DTW, and changed least when emphasizing soil permeability. The Madison Valley and the Lower Yellowstone are shown as examples of the spatial change in suitability scores.

increasing the geologic/aquifer properties weighting directly increases the suitability of these areas. Conversely, valley and basin margins generally consist of older surficial units (Tertiary semi-consolidated sediments and formations). Older and semi-consolidated sediments are commonly more compacted and partially cemented, which decreases K and S_y; these units were given a lower rating (≤50; table 1). Emphasizing the geologic/aquifer properties increases the weight of these lower ratings in the suitability score. Overall, emphasizing geology increases the suitability of 77 percent of the analyzed area: 18 percent was now considered high suitability (up from 15 percent), 61 percent was considered medium suitability (up from 53 percent), and 21 percent was considered low suitability (down from 32 percent).

Emphasizing DTW changed suitability scores by -10 to +9 (fig. 5B). Suitability scores decreased near rivers and increased for valley and basin margins. The DTW near rivers tend to be shallow, and these areas receive lower ratings because there is less unsaturated storage above the aquifer (table 2). On the other hand, valley and basin margins have greater DTW, which received higher ratings. Emphasizing DTW increases the suitability of areas with deeper DTW and decreases the areas with shallower DTW. Weighting DTW higher decreased the suitability of 68 percent of the analyzed area: 12 percent was now considered high suitability (down from 15 percent), 47 percent was considered medium suitability (down from 53 percent), and 41 percent was considered low suitability (up from 32 percent).

Emphasizing soil permeability (fig. 5C) had the least impact on the suitability scores; scores changed by -8 to +10. Areas with fine-grained deposits (Tertiary sediments, glacial sediments) showed the greatest decreases. However, locations with high suitability also show moderate decreases (-3 to -5) where they had top ratings for the other three criteria (geologic/aquifer properties, DTW, and topographic slope), but not soil permeability; by emphasizing soil permeability, those top ratings were weighted less in the suitability score. In total, 78 percent of the analyzed area changed less than 5 by emphasizing soil permeability. The percentage of area within the high, medium, and low suitability ranges changed by <1 percent.

Overall, the sensitivity analysis showed that emphasizing soil permeability had a relatively small effect on the suitability while emphasizing DTW decreased suitability and emphasizing geologic/aquifer properties increased suitability. Since both geologic/aquifer properties and DTW are important for surface infiltration, the weights were kept equivalent.

LIMITATIONS

The results presented here are intended as an initial screening for surface infiltration suitability to help identify locations of interest for further investigation. Each level of this analysis has limitations: the scope of the analysis, the resolution of the criteria, and the quality of the data within the criteria.

First, only the hydrogeologic properties relevant to surface infiltration were accounted for in this analysis. Some additional factors not assessed include source water availability, water quality, regulatory considerations, land use, site access, construction capacity, site-specific hydrostratigraphy, and water supply needs. Therefore, the suitability map results can only be used to understand the hydrogeologic suitability at a location; additional investigations will be necessary before implementing MAR methods (see Additional Considerations section below).

Second, the resolution of this statewide GIS analysis is limited to 1:200,000 (2.5 acres). The GIS layers had varying spatial resolutions (geologic/aquifer properties, 1:500,000; DTW, 1:200,000; soil permeability, 1:12,000; topographic slope, 1:24,000; see Methods section). Spatial interpolation methods for continuous data were used to coarsen the soil permeability and topographic slope layers to a 1:200,000 resolution (see Methods section). A 1:500,000 resolution for geologic/aquifer properties polygons was the finest resolution of statewide geology available, and it was rasterized to a finer 1:200,000 resolution (see Methods section). The hydrogeologic properties are assumed to be homogeneous within a 2.5-acre raster cell for this analysis. However, natural systems are ubiquitously heterogeneous (Freeze, 1975) and site-specific field testing is necessary before implementing MAR methods. It is recommended to use this analysis only at a 1:200,000 resolution or greater.

Third, each criterion in this analysis has uncertainties. For the geologic/aquifer properties criteria, statewide quantitative estimates of aquifer properties (hydraulic conductivity, specific yield) are not available. Aquifer test results that provide aquifer properties are available in some areas, but may not be representative of the same geologic unit in a different location.

Therefore, the lithology of the geologic unit/aquifer was used to approximate ranges for aquifer properties—meaning the geologic/aquifer properties criteria was an estimate of the possible aquifer properties and not based on measured values. For the soil permeability, the SSURGO infiltration rates provide a quantitative method to classify the data, but the values derived from short-term infiltration tests are not equivalent to long-term infiltration rates for MAR facilities (Mike Milczarek, oral commun., 2024). The USGS DEM provides statewide coverage for topographic slope, but higher resolution datasets (such as LiDAR) may be available and more accurate for local studies.

For DTW, the interpolation created for this analysis has uncertainties related to the time dependence of groundwater-level data and resolution at a small scale. The DTW data layer was created from groundwater-level measurements at different times of year, over multiple years, and with varying measurement accuracy. In many places, groundwater levels can fluctuate tens of feet seasonally and groundwater levels reported by drillers may be non-static and/or estimated. In addition, the wells may be inaccurately located. However, all groundwater-level measurements were included to provide enough statewide coverage for the DTW interpolation, which may result in inaccurate DTW estimates in some areas. Locations with high well density (near cities) generally have better constraints on DTW than low well density areas.

Additionally, the inverse distance weighting interpolation for DTW was chosen for its simplicity and relatively small number of assumptions, but it is sensitive to clustering and outliers in the DTW data. Cross-validation of the measured versus predicted DTW values shows a systematic bias in which the predicted groundwater elevations in wells with shallow measured DTW were often deeper, and the predicted elevations in wells with deeper measured DTW were often shallower (on the order of tens of feet error). However, for the statewide suitability analysis, the limitations of the DTW interpolation were known and considered permissible since it provided useful approximations for the DTW within the scope of this study. Higher quality data for aquifer properties and DTW are needed for site-specific analyses.

ADDITIONAL CONSIDERATIONS FOR MAR SURFACE INFILTRATION SITE SELECTION

This suitability analysis allows MAR stakeholders to identify sites with the greatest potential to infiltrate water from the surface to the underlying aquifer. However, detailed site-specific hydrogeologic information is needed to support the design of a MAR project, and additional factors must be considered. This section is not exhaustive but is intended to outline suggestions for a phased approach; evaluations of a site should proceed in sequential steps that can be halted if the project is deemed unfeasible.

Define the Project Purpose(s)

The first step to site selection is defining the need(s) for a MAR project. General project purposes can include replenishing overdrawn aquifers, improving water supply reliability, augmenting late-season stream flows, and improving water quality. However, it is important to be specific as to the project's purpose(s), including the quantity of water required to meet the need(s) and the intended use of the recharge water.

Screening Study

A screening study at a local scale should evaluate potential sites using existing information while identifying data gaps. Information compilation and evaluation should include:

- Geologic data from geologic maps and well logs to create geologic cross-sections and identify the underlying aquifer and aquifer thickness;
- Groundwater information to determine depth to groundwater, seasonal groundwater level patterns, and flow direction;
- Aquifer test data to assess aquifer properties such as K and S_y;
- Soil properties and associated permeability to gauge infiltration capacity;
- Source water availability to identify any seasonal and annual surface-water flow patterns, proximity of source water to the recharge area, and potential water conveyance methods;
- Water quality of the source water and receiving groundwater, and evaluation of potential reactions between them; and

- Land use and property ownership to constrain prospective locations.

The screening study may indicate sites favorable for surface infiltration methods and help identify the type of infiltration method best suited for the site. The Montana Department of Natural Resources (DNRC) can aid in determining the regulatory requirements and water rights associated with the potential operation, whereas the Montana Department of Environmental Quality (DEQ) can provide information and regulatory requirements regarding water quality.

Site Characterization

The site characterization of potential MAR sites is aimed at addressing data gaps and collecting soil and hydrogeologic data to support a MAR facility design. Both the proposed infiltration area and aquifer should be spatially characterized. Site characterization is typically performed in two phases: a near-surface and a deeper subsurface investigation (Milczarek and others, 2003). Near-surface test pits and auger drilling are used to characterize sediment textures to depths up to 20 ft, and infiltration tests can provide effective saturated hydraulic conductivity values for soils. The deeper subsurface investigation requires well drilling and aquifer testing to obtain information regarding the aquifer lithology, depth to groundwater, groundwater flow direction, and aquifer hydraulic characteristics. Drilling allows the identification of confining layers that could restrict groundwater movement and/or result in perched aquifers, as well as highly conductive zones that provide preferred groundwater flow paths.

Evaluation of Potential MAR Surface Infiltration Operations

Information from the site investigation can be used to assess the hydrologic effects and inform a MAR design at a given site. Questions such as how much groundwater mounding will occur during the MAR operations, how MAR will influence groundwater flow directions, whether there is the potential for leakage to underlying aquifers, or how long it will take for the recharged water to discharge into a stream or river can be addressed by groundwater modeling. Potential impacts to property or infrastructure from elevated water levels must also be assessed. High water tables may affect building foundations, septic leach fields, or the operation of gravel pits; it can also create springs that impact neighboring sites and create/permanently saturated downgradient wetlands. If there are sufficient existing data (as evaluated in the Screening Study), an initial model can be developed earlier in the project.

Additionally, any MAR project needs to evaluate the impact on water quality due to surface infiltration. Recharge water may have very different chemistry than the native groundwater; when mixed, it may produce desirable or undesirable water-quality changes. For example, infiltrated water may dilute high total dissolved solids present in groundwater (Levintal and others, 2023), but it can also mobilize arsenic and other metals within the aquifer if the pH and oxidation-reduction state of the recharge water differs from the native groundwater (Pyne and others, 2007). In semi-arid areas, accumulated salt in the unsaturated zone can be dissolved into the infiltrating water, thus introducing higher total dissolved solids into the aquifer (Healy and others, 2011). Geochemical modeling can help evaluate the water-quality changes of the source water as it infiltrates through the soil profile and interacts with the aquifer.

Finally, it is important to note that irrigated agricultural lands make up a significant portion of the areas evaluated for MAR suitability. Irrigated fields are typically flat and have existing water conveyance structures, making them potentially favorable sites for agriculture-related MAR (Ag-MAR; Levintal and others, 2023). Assessing the existing irrigation infrastructure, loss/gains along conveyance canals, potential for water logging (high groundwater elevations), crop types, and crop tolerance due to increased saturation will be necessary when evaluating Ag-MAR (Sustainable Conservation, 2023).

Project Design

A properly designed MAR site will require the services of qualified engineers and consultants with a thorough understanding of the DNRC and DEQ regulatory requirements. Although water may be physically available, it might not be legally available. Furthermore, a cost-benefit analysis—including ongoing operation and maintenance for the project—should also be conducted.

In some cases, a pilot test(s) should be conducted to refine the surface infiltration project design. For example, a pilot test(s) may be warranted if the hydrogeologic conditions suggest potential recharge water has an immediate and direct connection to surface water, which may limit long-term storage and potential re-use. A pilot test(s) should also be considered if subsurface layers restrict surface infiltration rates and/or if the project(s) needs to demonstrate feasibility. A pilot test would include engineering, implementing, and monitoring a scaled-down version of the proposed project for comparison with modeled and/or predicted results. The test objectives would consist of measuring inflows and outflows from the area, monitoring the response of groundwater levels and water quality, calculating infiltration and recharge rates, assessing clogging layers, and evaluating necessary maintenance (Bouwer and others, 2008). After a successful pilot test, the MAR site may be expanded to a full-scale operation with continued monitoring and maintenance.

CONCLUSIONS

The basin-fill and alluvial aquifers in Montana were screened for MAR surface infiltration suitability using GIS and MCDA methods; the results are provided in plate 1 and as a Web App at https://gis-data-hub-mbmg.hub.arcgis.com/apps/93e50821cc9c494392f238c521ef5576/explore. The suitability analysis is based on four hydrogeologic criteria: geologic/aquifer properties, depth to groundwater, soil permeability, and topographic slope. The resultant scores ranged from 8 to 100; high suitability areas had scores greater than 75 (15 percent of the area); medium suitability areas scored between 50 and 75 (53 percent of the area); and low suitability areas scored less than 50 (32 percent of the area).

Suitability scores varied across Montana. High scores occurred along, but were not exclusive to, river terraces where the geologic/aquifer properties consisted of gravels, the depth to groundwater was >50 ft, the surface infiltration was not impeded by fine-grained soils, and the topographic slope was <2 degrees. Low suitability scores occurred in locations with fine-grained and/or semi-consolidated aquifers, groundwater levels within 20 ft of the surface, and/or low permeability in soils derived from fine-grained glacial sediments.

A high suitability score does not necessarily mean surface infiltration will be successful, nor does a medium to low suitability score suggest that surface infiltration is unfeasible. This suitability map provides a first step in identifying locations for MAR surface infiltration. Natural systems are variable and heterogeneous; the resolution and quality of the datasets used for this regional analysis would not be appropriate for a local analysis. Site-specific considerations for a MAR project include defining the project purpose, conducting field investigations for detailed hydrogeologic information and effects of water-quality changes, determining the type of surface infiltration method, establishing physical and legal water availability, and evaluating the economic feasibility.

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APPENDIX A

Ratings within the MAR surface infiltration suitability criteria were formed by:

1. Reviewing literature for common classification divisions,
2. Assessing multiple classification schemes, and
3. Using professional judgment in areas where groundwater research has been completed.

This appendix provides additional figures and explanations regarding the process for rating the criteria in this suitability analysis.

Geologic/Aquifer Properties

Classification of geologic/aquifer properties into rating groups was guided by estimated ranges of hydraulic conductivity (K) and specific yield (S_y) for each geologic unit (table A1). However, professional judgment based on authors' experience with the geologic units across the State influenced the ratings.

Geologic units that were considered more carefully included those that encompassed large areas (appendix table A1) and are known to be heterogeneous and/or anisotropic:

- Qgt, glacial sediments that included sediments ranging from clay-rich glacial lake deposits to gravel outwash,
- Qaf, alluvial fan deposits that contain clay- to boulder-sized sediment,
- Qal, river alluvium that contains interbedded clays,
- QTs and Ts, undifferentiated sediments that may range from clay to gravel and be unconsolidated to consolidated, and
- Tgr, gravel that can be consolidated/cemented in some areas.

To avoid excluding suitable areas, the higher K and S_y estimates were used to assign ratings. That is, these "lumped" units were rated generously. It is expected that the aquifer properties will be refined during site-specific studies.

Lower ratings were considered for geologic units in the northeast that are known to be mantled with glacial sediments from the Laurentide Ice Sheet (main text fig. 3). However, the depth of the glacial mantle is relatively unknown and the Vuke and others (2007) glacial extent was only intended as a generalized graphic (Susan Vuke, written commun., 2024). Furthermore, these glacial-mantled areas showed visual similarities with low soil permeability. Thus, to not double count the limitations of the glacial material on the surface in these areas, the geologic units (not the glacial mantling) were used for the geologic/aquifer properties rating, while the low permeability of the near-surface sediments is accounted for by the soil permeability rating.

Depth to Groundwater

Multiple interpolations were completed for the depth to groundwater (DTW) criteria layer, including using all wells with total depth <100 ft compared to using all wells with total depths <200 ft. As discussed in the methods, additional filters were used to remove wells on bedrock and wells with aquifers listed as bedrock. Figure A1 shows the interpolations using the different total well depths. It was clear that the 100- to 200-ft-deep wells were needed to get more accurate DTW on the western basin margins and terraces. Therefore, although some of the 100–200 ft wells may be completed in bedrock, without a site-specific study to interpret well logs, the wells with total depths <200 ft were used to provide a more detailed estimate of DTW. The classes were guided by literature and the known uncertainties in the DTW interpolation, as discussed in the Methods section of the report.

Soil Permeability

Classifying soil permeability into rating groups was dominantly based on currently available literature values. However, multiple classification schemes were evaluated to determine which divisions best captured the variations across Montana; figure A2 shows a subset of these classification schemes.

Figure A2 shows the distribution of soil permeability values (ft/d) for the suitability analysis. The values approximate a lognormal distribution. Therefore, one of the classification schemes that was assessed used a lognormal grouping (Classification 1). However, this scheme did not capture the variation in soil permeability; most of the values occurred between 1 and 10 ft/d.

Soil permeability values were divided more finely between 1 and 10 ft/d in Classification 2. This classification scheme captured the variability within a location better (fig. A2). However, the large number of classes were cumbersome and were reduced for the final classification. Two of the final classification division schemes (fig. A2) were guided by literature: ≤2 ft/

Table A1. Hydraulic conductivity and specific yield range estimates for the basin-fill and alluvial surficial geologic units.

Geologic Label	1:500K Geologic Unit	Area (mi^2)	Geologic Unit Area to Total Analyzed (%)	Estimated Range of K (ft/d)[1]	Estimated S_y Range[2]	Rating (1–100)
Qlk	Quaternary lacustrine deposits	117	0.5	0.001–1	0.01–0.03	1
Qgl	Quaternary glacial lake deposits	332	1.3	0.001–1	0.01–0.03	1
Qtr, Ttr	Quaternary–Tertiary travertine	10	<0.1	0.1–1	0.01–0.05	1
Tk	Kishenehn Formation	179	0.7	0.1–10	0.01–0.03	1
TKw	Willow Creek Formation	165	0.7	1–10	0.01–0.05	5
Tar	Arikaree Formation	50	0.2	1–10	0.01–0.05	5
Tsm	Middle Tertiary sediment or sedimentary rock	814	3.3	1–25	0.01–0.1	25
TKb	Beaverhead Group	373	1.5	1–25	0.01–0.1	25
Ts	Tertiary sediment or sedimentary rock	1811	7.2	1–50	0.01–0.2	50
Tsu	Upper Tertiary sediment or sedimentary rock	964	3.9	1–50	0.01–0.2	50
Tw	Wasatch Formation	363	1.5	1–50	0.01–0.2	50
QTs	Quaternary–Tertiary sediments and basin-fill	54	0.2	1–50	0.01–0.2	50
Qgt	Quaternary glacial deposits	2,699	10.8	0.1–50	0.01–0.2	50
Qaf	Quaternary alluvial fan deposits	505	2.0	1–75	0.01–0.2	75
Tgr	Tertiary gravel	1,910	7.6	10–100	0.1–0.2	100
QTgr	Quaternary–Tertiary gravel	3,408	13.6	50–100	0.1–0.2	100
Qal	Quaternary alluvium	6,272	25.1	50–100	0.1–0.2	100
Qgr	Quaternary gravel	5,008	20.0	50–100	0.1–0.2	100

[1]Hydraulic conductivity (K) estimated from Heath (1983).
[2]Specific yields (S_y) estimated from Fetter (2001).
Note. See report table 1 for descriptions.

day (similar to Ghayoumian and others, 2007; Russo and others, 2015) and ≤5 ft/day (similar to Shaw and others, 2020). It should be noted that the infiltration rates from Ghayoumian and others (2007) and Russo and others (2015) were not determined from SSURGO (USDA, 2024) data and therefore may not directly correspond to the same SSURGO infiltration rates.

Overall, the final classification (fig. A2) appeared to capture the variability in soil permeability seen in figure A2, Classification 2, with minimal groups. A site-specific study is needed assess long-term infiltration rates in a more quantitative manner.

Topographic Slope

Initial classification schemes for topographic slope were based on Shaw and others (2020) with divisions at 2 and 5 degrees (fig. A3, Classification 1). This classification emphasizes the need for low slope area (<2 degrees) for constructing infiltration ponds. However, there were many western basins that have slopes between 2 and 10 degrees with transecting canals (fig. A3, Classification 1) that are known to recharge the aquifer. To not exclude areas that could be suitable with appropriate infiltration methods, we extended the classification scheme up to 20 degrees (slope at the edges of the basins).

A second classification scheme assessed slopes up to 20 degrees and divided more finely between 0 and 10 degrees (Classification 2). The finer divisions resulted in 80% of the area being in the highest 3 out of 8 ratings—limiting the effectiveness of the slope criteria (i.e., everything was “suitable”).

Thus, the final scheme minimized the number of groups, included the 2- and 5-degree divisions from Shaw and others (2020), and recognized the potential suitability for higher slopes (albeit, with lower slope ratings).

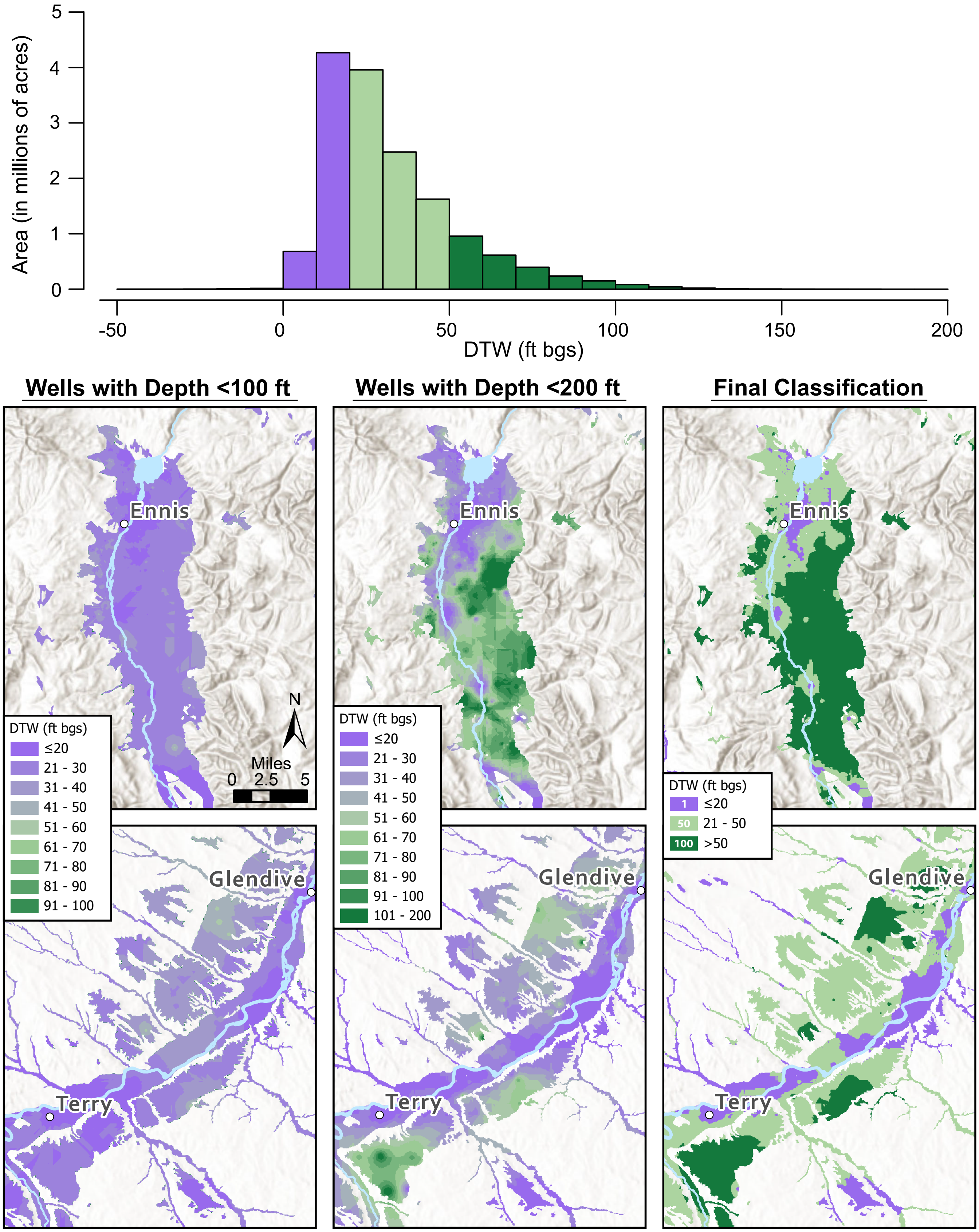

Figure A1. Multiple ways of classifying (or grouping) the data for the depth to groundwater (DTW) criterion were tried before choosing the final DTW classification that was rated from least suitable (1) to most suitable (100) for MAR surface infiltration. The statewide distribution of the DTW is shown and colored based on final classification used for rating. Maps for the Madison Valley and Lower Yellowstone Valley show the interpolation using wells with total depths <100 ft, <200 ft, and the final classification.

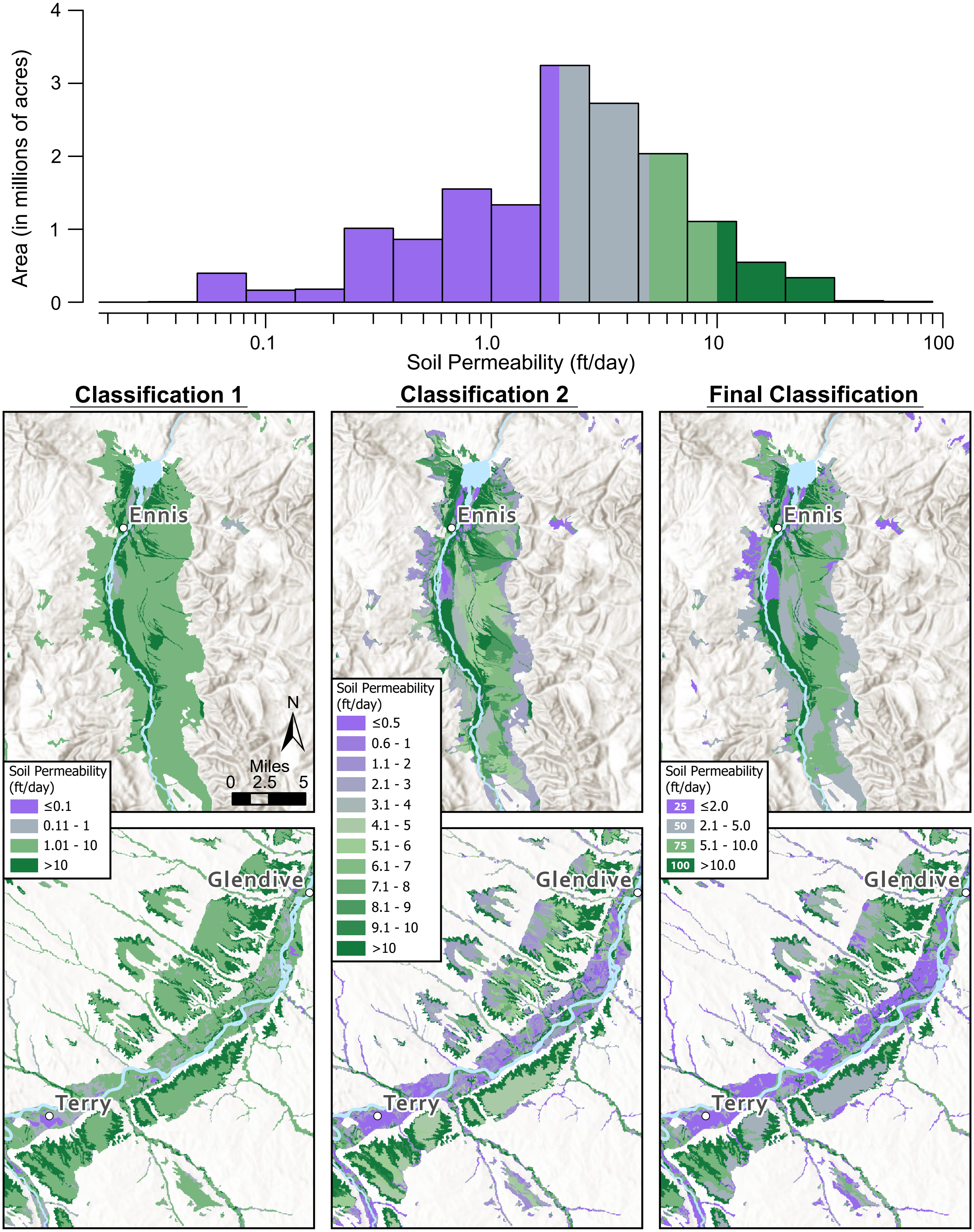

Figure A2. Multiple ways of classifying (or grouping) the data for the soil permeability criterion were tried before choosing the final soil permeability classification that was rated from least suitable (25) to most suitable (100) for MAR surface infiltration. The statewide distribution of soil permeability (ft/d) is shown and colored based on final classification used for rating. Note the log scale on the x-axis. Maps for the Madison Valley and Lower Yellowstone Valley show a lognormal classification (Classification 1), a finely divided classification (Classification 2), and the final classification.

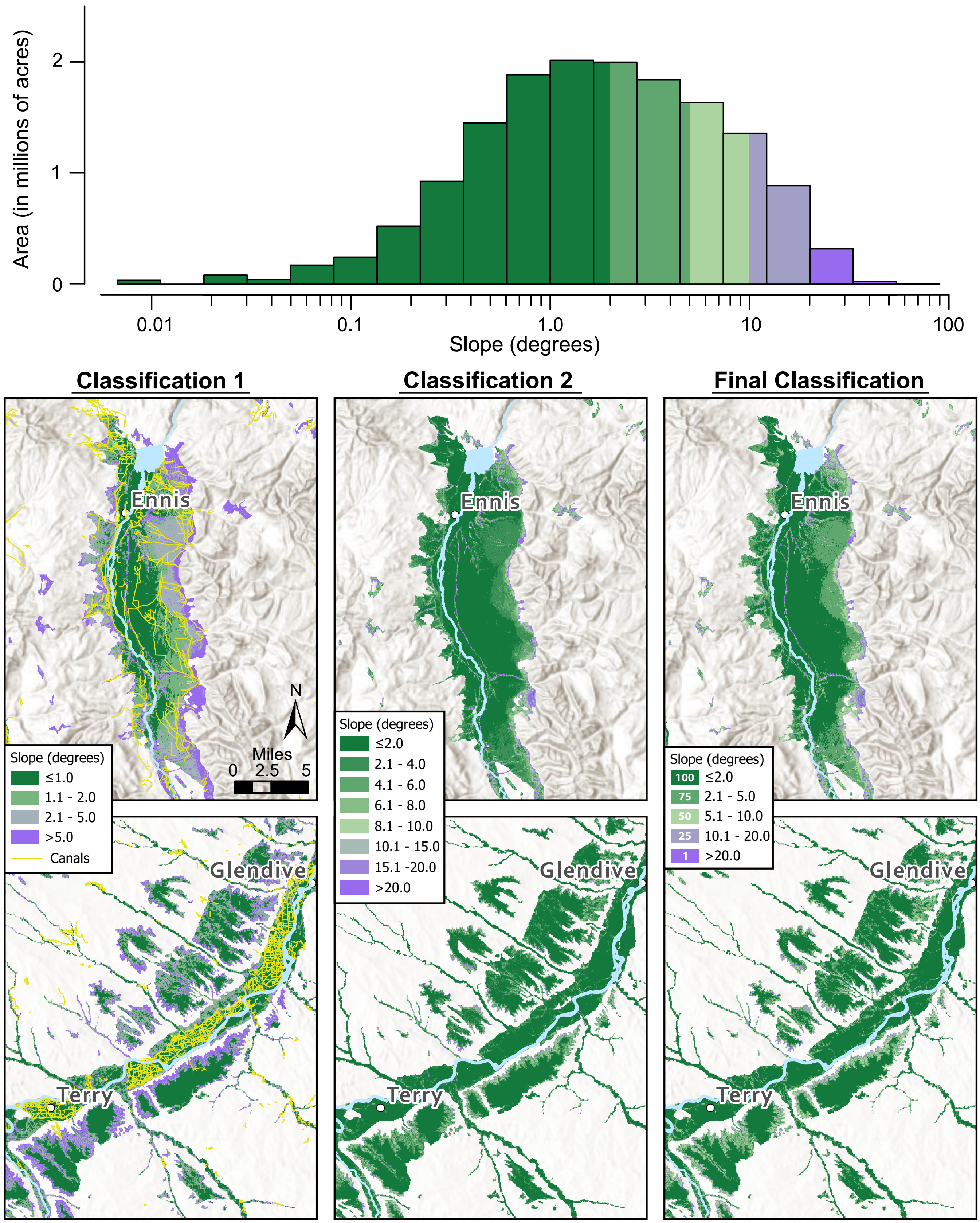

Figure A3. Multiple ways of classifying (or grouping) the data for the topographic slope criterion were tried before choosing the final topographic slope classification that was rated from least suitable (1) to most suitable (100) for MAR surface infiltration. The statewide distribution of topographic slope is shown and colored based on final classification used for rating. Note the log scale on the x-axis. Maps for the Madison Valley and Lower Yellowstone Valley show a classification based on divisions at 2 and 5 degrees (Classification 1), a classification with finer divisions up to 20 degrees (Classification 2), and the final classification.