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# Alluvial Aquifer Filtration as a Pre-treatment Option for ASR

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**Abstract:** Surface water diversions from Fifteenmile Creek to support agriculture in rural north-central Oregon, USA have adversely affected native fish species due to low flow and high-water temperature conditions during late summer periods. The use of Aquifer Storage and Recovery (ASR) to capture and inject excess surface water flows into the deep basalt aquifer during the winter and spring months and then recover in the summer time in-lieu of surface water diversions is being evaluated to reduce impacts on the threatened fish populations. Because water treatment costs in this area would be high due to lack of existing infrastructure, a primary question for the proposed ASR program is whether the shallow alluvial aquifer can be used to filter captured surface water prior to ASR injection. A program to characterize the near-surface sediments and shallow alluvial aquifer was performed to determine near-surface and aquifer properties and potential water quality improvement from aquifer filtration. Results indicate there is insufficient alluvial aquifer capacity to meet target filtration rates using vertical or horizontal wells, however, constructed surface recharge basins with horizontal well collection systems may be a viable alternative. No fatal flaws were identified in regards to surface water quality and potential aquifer filtration.

**Keywords:** aquifer filtration; ASR; water treatment; water quality; conjunctive water management; agricultural water supply, endangered species.

## 1. Introduction

Water treatment is typically necessary prior to injection for Aquifer Storage and Recovery (ASR) wells to meet regulatory water quality requirements and/or reduce the potential of ASR well clogging. ASR water treatment can be a significant component of the overall cost of an ASR project and can limit the use of ASR in non-municipal areas where existing water treatment infrastructure is not present.

Fifteenmile Creek in rural north-central Oregon, USA is home to threatened steelhead populations that are exposed to low flow and high-water temperature conditions during late summer periods. To increase summer flows and alleviate high temperature conditions, the Fifteenmile Watershed Council is evaluating the feasibility of ASR to support agricultural irrigation demands in lieu of Fifteenmile Creek summer time surface water diversions. Under the proposed ASR program, Fifteenmile Creek surface water would be injected into the deep basalt aquifer (approximately 245 – 300 m below ground surface) during the winter and early spring when surface water flows are more abundant. The injected ASR water would supplement agricultural demand pumping in the late summer to reduce surface water diversions and allow water to remain instream. A primary question for the proposed ASR program is whether the alluvial aquifer can be used to filter captured surface water to allow direct ASR well injection. Alluvial aquifer, or riverbank, filtration is used in many areas to cost effectively reduce suspended solids, biodegradable material, microorganisms, nitrate, and heavy metals from the water.

Three alternatives for collecting alluvial aquifer/riverbank filtered water were evaluated (Figure 1): 1) vertical wells, or; 2) horizontal collector-type wells placed in the alluvial aquifer adjacent to the creek, and; 3) engineered surface water diversions with passive infiltration and collection systems. Alternatives 1 and 2 rely on groundwater pumping to increase groundwater recharge via induced seepage from Fifteenmile Creek. Alternative 3 uses surface water diversions to constructed surface recharge basins with collection of infiltrated water via horizontal collector-type wells.

A program to characterize the near-surface sediments and shallow alluvial aquifer along a 9 km reach of Fifteenmile Creek was performed to determine near-surface and aquifer properties and potential water quality improvement from aquifer filtration. Using the field investigation data, an analytical model was applied to evaluate drawdown resulting from pumping wells near the creek and to determine well design criteria.

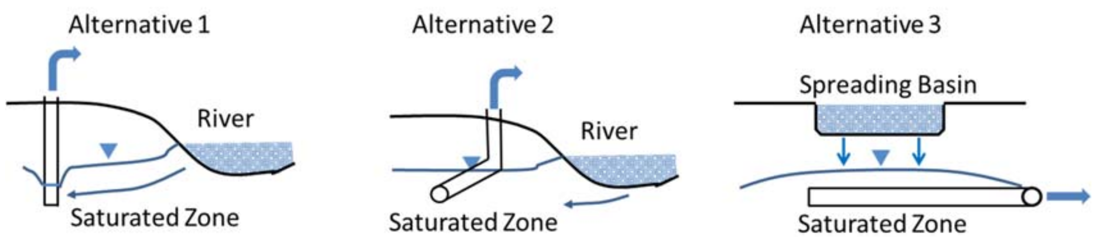


**Figure 1.** Alluvial aquifer/riverbank filtration groundwater collection scenarios.

## 2. Materials and Methods

### 2.1. Characterization Program

#### 2.1.1. Test Pits and Geologic Logging

Near-surface and alluvial aquifer soil physical property evaluations were conducted adjacent to Fifteenmile Creek in February 2018 using test pits to characterize the near surface and alluvial aquifer material texture, depth to groundwater, and alluvial aquifer saturated thickness. Twenty five test pits were excavated with a track hoe at the locations shown in Figure 2. The location of an alluvial aquifer vertical or horizontal well would be restricted to approximately 15 m from the creek in order to remain outside of land being farmed, thus test pits were located outside of protected riparian areas but within 15 m of the creek. Test pits were excavated to the depth of track hoe refusal.

Lithologic layers encountered were texturally logged and classified using visual-manual methods following [1]. Representative grab samples were collected and stored in labeled and sealed plastic bags for further laboratory analysis. Additionally, 15-cm long by 5-cm diameter drive core samples were collected for laboratory analyses of bulk density.

#### 2.1.2. Test Well Installation and In-Situ Testing

In April 2018, three alluvial aquifer test wells were installed at locations shown in Figure 2. The wells were sited to be approximately equidistant over the project area. Boreholes were drilled to the top of the basalt or cemented sand layer using a hollow stem auger (CME-75HT truck-mounted rig). Boreholes were located adjacent to test pits; subsequently, the borehole material was not geologically logged as the subsurface material was assumed to be similar to the adjacent pit.

Test wells were installed in the boreholes to the top of the basalt or cemented sand layer. The wells were constructed of 10-cm diameter schedule 40 PVC with a 1.5-m long screen length and 0.05 cm slot width. A 6/9 silica sand filter pack that extended from the bottom of the well to a minimum of 30 cm above the well screen was placed, followed by a 30 to 60-cm thick hydrated bentonite seal. Each test well was instrumented with a submersible pump and a Level TROLL 400 data logger (In-Situ, Fort Collins, CO) to measure water level and temperature.

All three test wells desaturated at the submersible pump minimum pumping rate of 11 liters per minute (lpm), thus an aquifer test could not be performed. Instead, the Bouwer and Rice [2] slug test method was used to measure in-situ saturated hydraulic conductivity ($K_{sat}$) of the alluvial aquifer material. Slug tests provide an intermediate scale measurement of $K_{sat}$ by quickly withdrawing or adding water from the well and measuring the subsequent rate of change in water elevations over time. Instantaneous lowering of the water level in the well was achieved by pumping until the well went dry and then turning off the pump and monitoring the rebound of the groundwater elevation.

Because of the low sustainable pumping rate, the test wells could not be fully developed for collection of an alluvial groundwater sample. However, a surface water sample and basalt groundwater sample from nearby basalt aquifer wells were collected and analyzed for water quality parameters (e.g. turbidity, conductivity, temperature, common ions, metals, nutrients).

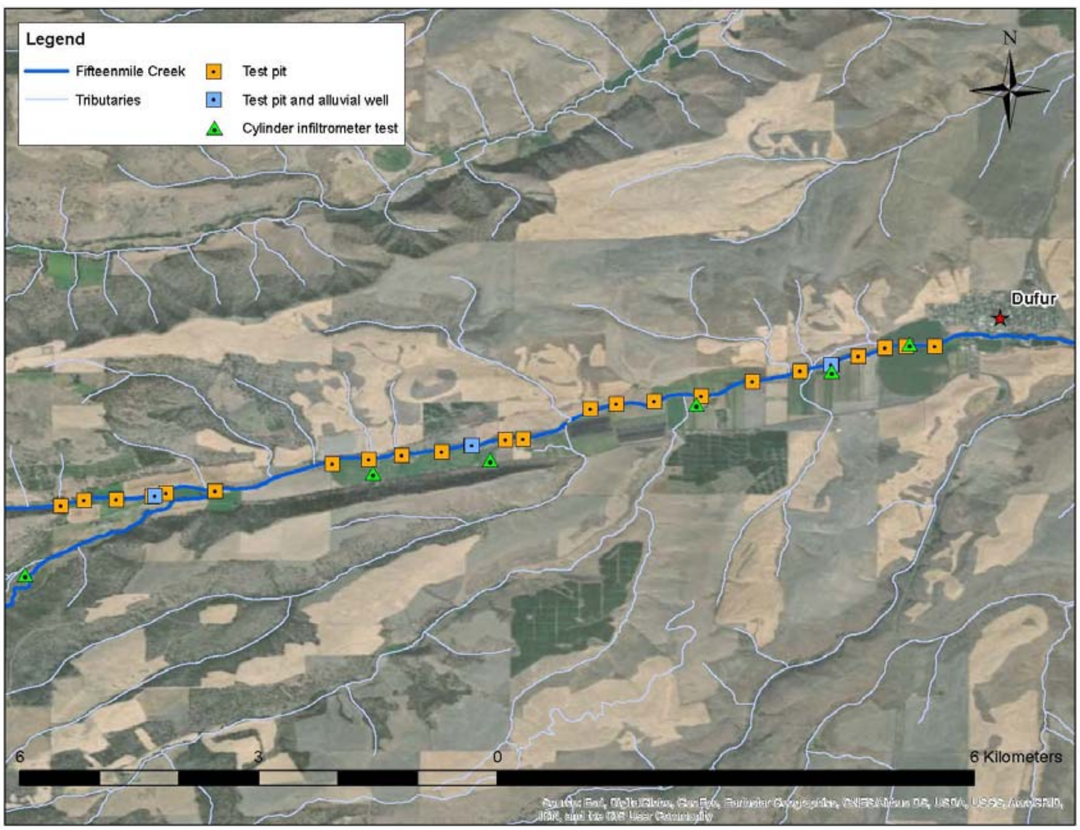


**Figure 2.** Test pit, alluvial aquifer test well, and cylinder infiltrometer test locations.

2.1.3. Near-Surface Cylinder Infiltrometer Testing

Single-ring cylinder infiltrometer (CI) tests with lateral divergence correction [3] were conducted at the soil surface to assess the effective in-situ $K_{sat}$. The CI tests are an intermediate scale test which represents the rate at which water infiltrates into the soil under field conditions. CI tests were performed at the locations shown in Figure 2. A total of six CI measurements were conducted on soils representing the predominant lithologic types observed in the project area.

2.1.4. Laboratory Physical and Hydraulic Property Testing

Eight samples representing the range of observed field textures were selected and analyzed for particle size distribution (PSD) and particle density to allow for laboratory calibration of the field texture estimates. Five grab samples were selected for $K_{sat}$ testing based on the distribution of field texture estimates. Laboratory $K_{sat}$ tests were performed in a 10-cm long by 5-cm diameter repacked column. Three core samples were selected for bulk density and water content measurements, which were used to guide packing bulk density for $K_{sat}$ tests.

2.2. Alluvial Aquifer Groundwater Collection Rate Modeling

2.2.1. Vertical and Horizontal Wells

The maximum water collection rate for a vertical well completed in the alluvial aquifer was estimated using the two-dimensional analytical drawdown solution for a pumping well near a connected stream [4], described as:

$$s_{tot} = \frac{Q}{4\pi T} Ei\left(\frac{-S\left((L-x)^2+y^2\right)}{4Tt}\right) - \frac{Q}{4\pi T} Ei\left(\frac{-S\left((L+|x|)^2+y^2\right)}{4Tt}\right) \quad (1)$$

Where $s_{tot}$ is the total aquifer drawdown (m), $Q$ is the well pumping rate ($m^3$/min), $T$ is aquifer transmissivity ($m^2$/min), $S$ is aquifer specific yield (-), $L$ is the distance from a pumping well to the center of the stream (m), $x$ is the X coordinate measured from the stream center towards a pumping well (m), $y$ is the Y coordinate measured from the stream center perpendicular to x (m).

The analysis assumes the alluvial aquifer is infinite in extent, streambed conductance is greater than the alluvial aquifer $K_{sat}$, and there is no interference from other pumping wells.

The maximum predicted pumping rate ($Q$) that can be achieved without alluvial aquifer drawdown ($s_{tot}$) exceeding the aquifer saturated thickness was calculated for a vertical well placed 6 m from the center of the creek ($x$ = 6 m). A 6 m minimum well distance was established due to riparian protection programs likely to restrict placement of wells closer to the creek. A target total alluvial aquifer groundwater collection rate for all wells of 14,525 lpm was defined based on an evaluation of regulatory and physical surface water availability.

The maximum predicted pumping rate for horizontal wells completed in the alluvial aquifer is calculated using Equation 1 and the principle of superposition by solving for changes in groundwater levels resulting from pumping of a linear system of vertical wells. That is, Equation 1 was solved for multiple Y coordinates (y) and summed to identify the total maximum predicted $Q$ that can be achieved without $s_{tot}$ exceeding the aquifer saturated thickness. The calculation assumes the horizontal well is located near the bottom of the alluvial aquifer and 6 m from the center of the creek. A target total alluvial aquifer groundwater collection rate was again defined to be 14,525 lpm.

2.2.2. Surface Recharge Basins

The water collection rate for a surface recharge basin will in part be controlled by soil $K_{sat}$ and the surface area of the basin. It is assumed the basin(s) will be located far enough off-stream to avoid return flow of infiltrated water back to the stream. The surface recharge basin area required for a defined water collection rate was calculated for a range of measured near surface $K_{sat}$ values assuming 80% of recharge basin infiltrated water can be captured by a subsurface perforated pipe system that is located in the alluvial aquifer beneath the basin(s). An 80% drain pipe water capture has been measured for similar engineered surface recharge basins containing a subsurface water collection system (e.g. [5]). The drain pipe capture percentage will ultimately be guided by perforated pipe system design (e.g. pipe diameter, spacing, and depth).

## 3. Results

### *3.1. Characterization Program*

Field geologic logging estimates of percent gravel, sand, silt and clay were adjusted using the results from the laboratory "wet sieve" PSD testing. Regression equations were determined for percent fines (silt and clay) and clay from the laboratory PSD testing versus manual field estimations to obtain lab to field correction parameters. These parameters were then applied to all field log estimates of soil texture.

Test pit observations were consistent throughout the study area. Silt loam and sandy loam soils were observed from approximately 0 to 1-m below ground surface (bgs), with increasing sand and gravel with depth (Figure 3). The water table was encountered at depths ranging from 1.5 to 3.7 m bgs which coincided with the surface elevation of Fifteenmile Creek, indicating the alluvial aquifer is hydraulically connected to the creek. The alluvial aquifer consists of sandy gravel with large cobbles (Figure 3). Track hoe refusal was encountered in all test pits due to a basalt or cemented sandstone (Figure 3) at approximately 1.5 to 4.9 m bgs. Both units are low permeable material that underly the shallow alluvial aquifer. The alluvial aquifer saturated thickness ranged from 1.2 to 1.5 m.

Observed test well saturated thicknesses were similar to test pit observations, ranging from 1.2 to 2.1 m thick. Table 1 provides slug test measured alluvial aquifer $K_{sat}$ at the test wells. A geometric mean horizontal $K_{sat}$ of $1.5 \times 10^{-4}$ cm/s was calculated from the three slug tests.

CI measured effective surface soil $K_{sat}$ values are summarized in **Error! Reference source not found.**. Geometric mean effective $K_{sat}$ was $1.2 \times 10^{-2}$ cm/s for Tygh fine sandy loam soils, $4.6 \times 10^{-3}$ cm/s for Endersby loam soils, and $7.1 \times 10^{-4}$ cm/s for the single Pedigo silt loam soil measurement. Effective $K_{sat}$ values were less for finer textured surface soils. The geometric mean effective $K_{sat}$ for all tests was $5.5 \times 10^{-2}$ cm/s.

Laboratory measured $K_{sat}$ values are shown in **Error! Reference source not found.**. Geometric mean laboratory measured $K_{sat}$ was $3.8 \times 10^{-4}$ cm/s for repacked samples from above the alluvial aquifer and $1.0 \times 10^{-3}$ cm/s for samples from the alluvial aquifer. The laboratory $K_{sat}$ values for samples from the alluvial aquifer were approximately one order of magnitude greater than the mean slug test $K_{sat}$ value and likely represents an upper end value for alluvial aquifer $K_{sat}$. The laboratory $K_{sat}$ values for samples above the alluvial aquifer were approximately one to two orders of magnitude lower than the CI measurements. Laboratory $K_{sat}$ values for samples above the alluvial aquifer are similar to Natural Resources Conservation Service (NRCS) reported range of $K_{sat}$ for the near surface soils (Soil Survey Staff, 2017). Consequently, it is believed the laboratory measured $K_{sat}$ for soils above the alluvial aquifer is more accurate.


Figure 3. Examples of observed (A) soil profile; (B) silt loam/sandy loam soil; (C) alluvial aquifer material; (D) cemented sandstone.

**Table 1.** Slug test measured saturated hydraulic conductivity.

| Test Well | Lithologic Classification | Saturated Hydraulic Conductivity (cm/sec) |
|---|---|---|
| AW-1 | Gravely sandy loam | 8.4E-05 |
| AW-2 | Gravely sandy loam | 3.2E-04 |
| AW-3 | Gravely sandy loam | 1.3E-04 |
| Geometric Mean | | 1.5E-04 |

**Table 2.** Cylinder infiltrometer measured effective saturated hydraulic conductivity.

| Test ID | USDA Soil Type | Effective Saturated Hydraulic Conductivity cm/sec |
|---|---|---|
| CI-1 | Tygh fine sandy loam | 1.4E-02 |
| CI-2 | Tygh fine sandy loam | 2.2E-02 |
| CI-3 | Endersby loam | 1.3E-02 |
| CI-4 | Pedigo silt loam | 7.1E-04 |
| CI-5 | Tygh fine sandy loam | 5.8E-03 |
| CI-6 | Endersby loam | 1.6E-03 |
| Geometric Mean | Tygh fine sandy loam | 1.2E-02 |
| | Endersby loam | 4.6E-03 |
| | All | 5.5E-03 |

**Table 3.** Laboratory measured saturated hydraulic conductivity.

| Sample | Location | Bulk Density (g/cm³) | Porosity (cm³/cm³) | Saturated Hydraulic Conductivity (cm/s) |
|---|---|---|---|---|
| TP-2 (2-6) | Above alluvial aquifer | 1.45 | 0.472 | 3.2E-04 |
| TP-12 (1-3) | | 1.30 | 0.517 | 1.8E-04 |
| TP-18 (3-7) | | 1.55 | 0.434 | 9.0E-04 |
| Geometric Mean | | | | 3.8E-04 |
| TP-6 (5-7) | In alluvial aquifer | 1.59 | 0.421 | 1.5E-03 |
| TP-11 (6-11) | | 1.50 | 0.450 | 7.0E-04 |
| Geometric Mean | | | | 1.0E-03 |

*3.2. Estimated Alluvial Aquifer Groundwater Collection Rates*

3.2.1. Vertical and Horizontal Wells

The maximum predicted pumping rate that can be achieved from a single vertical well in the alluvial aquifer without exceeding 1.5 m of drawdown was calculated using Equation 1. A 1.5 m drawdown limit was defined since the observed saturated thickness of the alluvial aquifer was approximately 1.5 m. The calculation assumed the lab measured geometric mean $K_{sat}$ value for the alluvium aquifer material ($1.0 \times 10^{-3}$ cm/s, Table 3). The lab measured alluvial aquifer material $K_{sat}$ was approximately 7X higher than the slug-test measured $K_{sat}$ and thus represents a "best case" scenario for alluvial aquifer groundwater pumping. The assigned $K_{sat}$ and 1.5 m saturated thickness translates to an alluvial aquifer transmissivity of 1.3 $m^2$/day. A specific yield for a gravelly sand of 0.25 $cm^3/cm^3$ [6] was assumed.

Table 4 summarizes vertical well (Alternative 1) model results. The maximum pumping rate for a single vertical well is predicted to be 2.7 lpm, requiring approximately 5,400 wells to achieve the target alluvial aquifer groundwater collection rate of 14,525 lpm.

Table 5 **Error! Reference source not found.**summarizes horizontal well (Alternative 2) model results. The same model parameters applied in the vertical well model were applied in the horizontal well model. The maximum pumping rate for a horizontal well in the alluvial aquifer is predicted to be 1.2 lpm per linear meter of well, requiring over 12,100 linear meters of pipe to achieve the target alluvial aquifer groundwater collection rate.

**Table 4.** Maximum estimated alluvial aquifer pumping rate for a single vertical well and quantify of vertical wells to achieve the target collection rate.

| Target Collection Rate (lpm) | Single Well Pumping Rate (lpm) | Number of Wells Needed for Target Recharge |
|---|---|---|
| 14,525 | 2.7 | 5,400 |

**Table 5.** Estimated horizontal well maximum pumping rate and linear meter of horizontal wells to achieve the target alluvial groundwater collection rate.

| Target Collection Rate (lpm) | Linear Foot Pumping Rate (lpm) | Linear Meter of Horizontal Well for Target Recharge |
|---|---|---|
| 14,525 | 1.2 | 12,100 |

3.2.2. Surface Recharge Basin

Table 6 summarizes the estimated total recharge basin (Alternative 3) area required to capture the target collection rate of 14,525 lpm assuming the laboratory measured near surface $K_{sat}$ and CI measured effective $K_{sat}$ for the three NRCS soil textures tested. The needed total recharge basin area is greatest for the laboratory measured $K_{sat}$ (7.7 hectares), whereas the CI measured effective $K_{sat}$ indicated a total needed recharge basin area of 4.1 hectares for Pedigo silt loam, 0.6 hectares for Endersby loam, and 0.2 hectares for Tygh fine sandy loam. The surface recharge basin area is sensitive to soil material $K_{sat}$ and specific soil $K_{sat}$ measurements are necessary to improve predicted basin size requirements in any target area. Nonetheless, the calculated total basin area based on the laboratory measured $K_{sat}$ represents the best estimate based on current data because the $K_{sat}$ is believed to be most representative of near surface soils, based on NRCS reported $K_{sat}$ values, and it is similar to the $K_{sat}$ of the alluvial aquifer in which the subsurface collection system is assumed to be installed.

In general, the areas shown in green within Figure 4 are anticipated to have higher surface permeability and would likely need less area for an infiltration basin. Near surface loamy soils may be excavated in order to access underlying coarser textured soils that are more permeable. Additionally, multiple basins of smaller size may be constructed within the project area, as opposed to a single large basin.

**Table 6.** Total recharge basin surface area to achieve the target alluvial aquifer groundwater collection rate.

| Measurement | Soil Type | Near Surface Saturated Hydraulic Conductivity (cm/sec) | Total Spreading Basin Surface Area (Hectare) |
|---|---|---|---|
| Lab | NA | 3.8E-04 | 7.7 |
| CI | Pedigo silt loam | 7.1E-04 | 4.1 |
| CI | Endersby loam | 4.6E-03 | 0.6 |
| CI | Tygh fine sandy loam | 1.2E-02 | 0.2 |

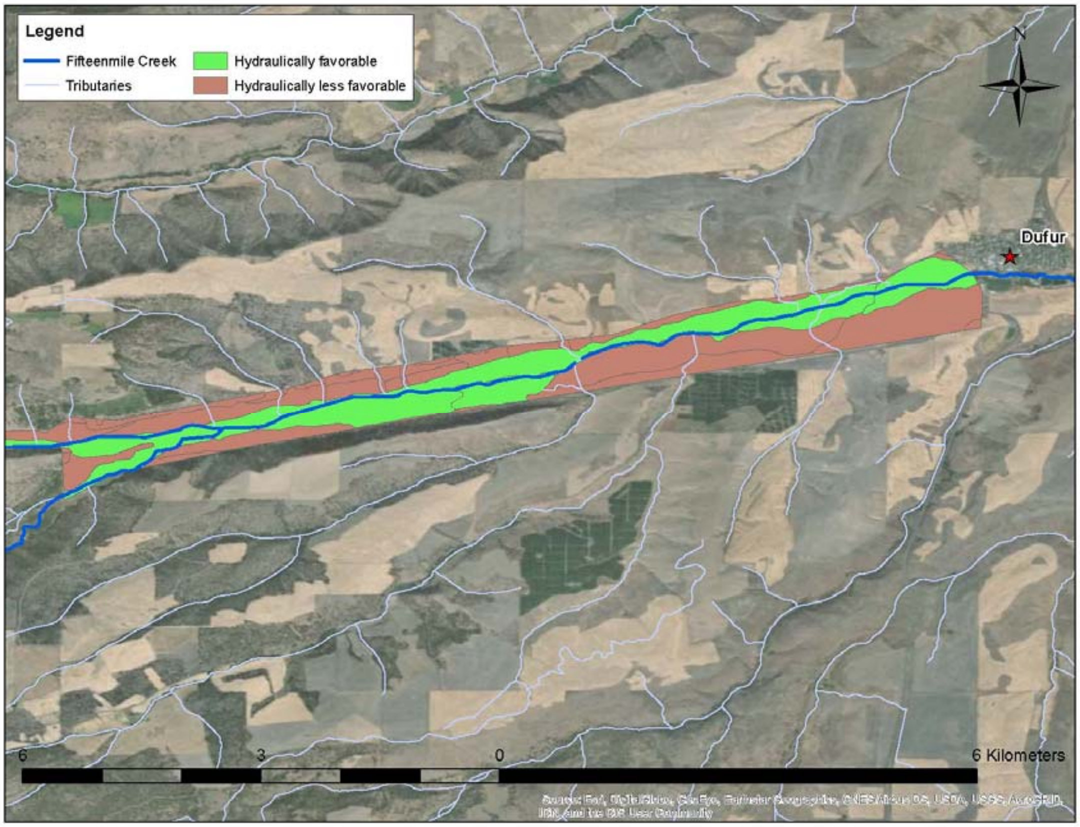


Figure 4. Predicted more and less favorable areas for infiltration basins.

### 3.3. Water Quality Assessment

Concentrations of all surface water analytes, except turbidity, phosphorus, aluminum, barium, iron and coliform bacteria were less than corresponding analyte concentrations in the deeper basalt aquifer groundwater. The differences between concentrations of aluminum, barium and iron reflect the different geochemical characteristics of the two waters, but do not appear to be a fatal flaw with regard to regulatory compliance, particularly if treatment through infiltration basins reduce constituent concentrations. Filtration of surface water from the creek prior to injection is likely to sufficiently remove turbidity and bacteriological constituents (5, 7). The treatment step also is anticipated to remove iron and particulate-bound contaminants. Small scale pilot testing may be needed to determine treatment efficiencies and the optimal distance between the filtration media and collection piping for removal of suspended solids, phosphorus, bacteriological and other constituents.

## 4. Discussion

Based on measured hydrogeologic data for the alluvial aquifer there is insufficient alluvial aquifer capacity to meet target groundwater collection rates using vertical or horizontal wells. Approximately 5,400 vertical wells or 12,100 linear meters of horizontal wells are estimated to be necessary for achieving the target alluvial aquifer groundwater collection rate of 14,525 lpm.

Constructed surface recharge basins with a horizontal well may be a viable alternative; however, there remains large uncertainty in near surface $K_{sat}$ values which dictate the necessary total basin surface area as well as uncertainty in the characteristics (e.g. depth, $K_{sat}$) of the shallow aquifer at potential off-stream basin locations. Near surface loamy soils may be excavated in order to access underlying coarser textured soils that are more permeable. Additionally, multiple basins of smaller size may be constructed within the project area, as opposed to a single large basin.

An evaluation of potential recharge basin sites based on a preliminary review of estimated $K_{sat}$, conveyance costs, probable land acquisition/leasing and right of way costs, and compatibility of land use and ownership is recommended. High priority sites identified from this analysis are recommended to undergo a characterization program to better define infiltration rates and assess aquifer filtration effectiveness.

Sampling of Fifteenmile Creek to assess recharge source water quality standards did not identify fatal flaws for using the creek as a source of water for ASR. As anticipated, some treatment will be necessary to remove suspended solids (turbidity) and microbiological constituents (e.g., coliform bacteria). A time-series surface water quality sampling and small-scale pilot testing of a surface infiltration treatment facility during the winter/spring recharge season is needed to verify treatment needs and methods prior to full-scale implementation.

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**Author Contributions:** All authors conceived and designed the field characterization program. Mr. Rice performed the field characterization; Mr. Keller, Mr. Burt, and Mr. Melady analyzed the data; Mr. Keller wrote the paper.

**Conflicts of Interest:** Wasco County Soil and Water Conservation District performed the cylinder infiltrometer measurements.

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