Standard Operating Procedure for Testing and Analysis for Deep Infiltration Facilities

Seattle-Tacoma International Airport

Prepared by Aspect Consulting, LLC

1 Introduction

This technical Standard Operating Procedure (SOP) is provided by the Port of Seattle (Port) to assist developers in design and approval of Low Impact Development (LID) stormwater management facilities that employ deep infiltration methods. UIC wells that extend below an upper confining layer and discharge into the underlying vadose zone are designated by Ecology as deep UIC wells. Deep infiltration wells generally infiltrate stormwater into receptor soils that are 10-feet or more below the final ground surface.

The recommendations presented here include summaries of deep infiltration testing and design guidance in the 2019 Stormwater Management Manual for Western Washington prepared by the Washington State Department of Ecology (SWMMWW, 2019; Volume 5) in accordance with the Port's LID Guideline (RKI, 2019). In addition, since detailed deep infiltration testing and analysis procedures are not provided by Ecology or King County, this guideline references the City of Seattle Stormwater Manual (City of Seattle, 2016) and other technical resources regarding appropriate testing, analysis, and design methods. This document summarizes many complex analyses and decisions that must be made when siting and designing deep infiltration best management practices (BMPs) and is not intended to replace detailed guidance within the SWMMWW or other reference documents. Readers should review the referenced materials during infiltration design projects.

To help project managers understand implications on project schedule and budget, Section 2 of this document provides a summary of major steps for deep infiltration planning, testing, analysis, and design, as well as an example schedule and cost estimate for a larger and more complex deep infiltration project. Sections 3 through 5 provide more detailed deep infiltration planning, testing, analysis, and design guidance.

Attachments 1 through 3 are included as tools for project planning, and include:

- An example project timeline, broken down by anticipated tasks
- A planning-level example project budget
- A checklist identifying key activities and requirements for Port approval of the facility

2 Summary of Deep Infiltration Steps, Example Duration and Costs

Section V-5.2 of the SWMMWW describes eight steps for design of infiltration LID facilities,[1] which have been adapted to apply to the design of deep infiltration facilities. These steps are listed below.

- ***Preliminary Step:***
  - Determine if Proposed Site is Mapped as Infeasible for Deep Infiltration (Figure 1, from Aspect, 2018)
  - Early Coordination with Port
- ***Step 1:*** Select Preliminary Locations for Deep Infiltration Facilities, Complete Initial Site Investigation, Groundwater Monitoring
- ***Step 2:*** Estimate Stormwater Runoff from the Project Using Hydrologic Modeling
- ***Step 3:*** Develop Trial Deep Infiltration Facility Details, Sizes, and Depths
- ***Step 4:*** Complete Detailed Site Characterization and Deep Infiltration Testing
- ***Step 5:*** Analyze Infiltration Test Data and Determine Aquifer Properties and the Design Bulk Saturated Hydraulic Conductivity of the Receptor Unit
- ***Step 6:*** Size and Design Deep Infiltration Facilities to Meet Performance Standards, Initial UIC Registration
- ***Step 7:*** Conduct Groundwater Mounding Analysis (if needed)
- ***Step 8:*** Construct the Deep Infiltration Facility, Update UIC Registration, Conduct Performance Monitoring

For facility approval, each of the elements listed above must be addressed in a report prepared by a licensed engineer, geologist, or hydrogeologist and submitted to the Port. The checklist in Attachment 3 must be completed and signed by the Project Manager or the licensed professional.

[1] Subsurface infiltration systems such as deep infiltration wells will likely be classified as Underground Injection Control (UIC) facilities. In most cases, deep infiltration wells will be classified as deep UIC wells. Refer to Sections I-2.14 and I-4 of the SWMMWW for additional siting, design, treatment, and registration requirements for these facilities.

The remainder of this section provides an example of overall activities, costs, and durations associated with deep infiltration planning, testing, analysis, and design for a larger and more complex site, typical of significant Port/STIA development projects. To establish a baseline for estimating costs and durations, the following example site characteristics are assumed:

- Planned redevelopment site is 20 acres, will be mixed office/commercial, and is not served by any existing on-site or regional stormwater treatment or flow control facilities.
- Site runoff would discharge to a non flow control exempt water body.
- The redevelopment site has been identified by the Port as likely feasible for deep infiltration.
- Redevelopment site has active businesses/operations that need to be accommodated until later in the development process.
- The upper boundary of the deep infiltration receptor soil is estimated to be under about 20 feet of nearly impermeable glacial till.
- The deep infiltration receptor soil is estimated to be about 20 feet below ground surface and groundwater is first encountered about 40 feet below ground surface.
- Deep infiltration receptor soil is estimated to be sandy gravel outwash with some silt, expected to have medium to high infiltration rates.
- Groundwater aquifer is estimated to be a 30-foot-thick sandy silt soil bounded on the bottom by a clay layer.
- Groundwater hydraulic properties and flow direction are unknown.
- No steep slopes, contamination sites, or nearby drinking water wells are known to exist.
- Initial stormwater management approach involves treating stormwater with Port allowed surface/shallow Best Management Practices (BMPs) and then infiltrating stormwater on-site to meet Port SWMM standards.
- The goal is to infiltrate runoff using banks of multiple deep infiltration wells located in three different areas of the site.

An example Gantt chart schedule and an order of magnitude budget have been prepared for the assumed site conditions (Attachments 1 and 2). Note that order of the steps in the example Gantt chart and budget show the mounding analysis being conducted before and partially in parallel with the design of the infiltration facility, which reflects the proper flow of work when a mounding analysis is required. The schedule and budget account for some uncertainties and situations that could drive the need for extra time or work, such as:

- The need to conduct groundwater monitoring to establish the maximum expected groundwater level.

- The need for the geotechnical and hydrogeologic fieldwork to sometimes avoid disrupting active businesses.
- Exploration results that indicate a portion of the planned infiltration area is not suitable, which requires extra work to identify a new location.
- Infiltration testing results that indicate additional, unplanned, infiltration wells will be needed to handle the targeted maximum cumulative infiltration flow rate.
- Indications of significant mounding during infiltration testing, which raises concerns about potential mounding under full-scale long-term operation and thereby triggers a formal groundwater mounding analysis (MODFLOW Groundwater Model). The Mounding analysis results in revision to infiltration well spacing, depths, and flow rates to control mounding to an acceptable level.

The example schedule and budget do not include construction and performance testing of the infiltration system (Step 8).

The Gantt chart is included as Attachment 1 and illustrates that the process from initial investigations and preliminary layout through detailed design and permitting can take on the order of 19-20 months for a larger and complex site. Smaller, simpler sites could require substantially less time and budget.

A budget corresponding with the Gantt chart is included as Attachment 2 and indicates that multidisciplined deep infiltration related investigations, testing, analysis, design, and permitting costs for a larger and complex site is on the order of $205,000, including roughly $161,000 in consultant costs; $40,000 in survey, driller and well drilling/construction costs; and $4,000 in miscellaneous instrumentation, equipment, travel, and laboratory costs. Costs could easily increase above this level depending on the required level of documentation, team coordination, drilling/testing needs, detailed design effort, and site challenges encountered. Similarly, smaller and simpler sites could require substantially less cost. In addition, while non-stormwater infiltration related costs were generally excluded from the cost estimate, some costs included in the example budget may be partially redundant when accounting for the survey, exploration, and testing needs of an overall development project. For example, sometimes surveying and some infiltration related geotechnical and hydrogeologic/aquifer explorations are required for other site development purposes, and hydrologic modeling is needed for designing non-infiltration BMPs as well as infiltration BMPs.

3 Detailed Steps for Planning, Designing, and Constructing Deep Infiltration Wells.

When completing the investigations and analyses described below, it is important to be consistent with the infiltration feasibility criteria and procedures described in the Port's LID Guideline - *Low Impact Development Guideline for the Seattle-Tacoma International Airport* (RKI, 2019). For instance, Section 3.4 of the Port's LID Guideline provides an overview of the general steps involved in assessing the feasibility of on-site infiltration, and Figure 3.3 provides a flow chart illustrating the feasibility assessment process, including infeasibility off-ramps.

A general activity checklist has been prepared to help project managers successfully track and complete the detailed deep infiltration planning, testing, analysis, and design process. The checklist can also help Port plan reviewers determine the completeness of stormwater development submittals and ensure that the proper types of analyses have been completed. The checklist is included as Attachment 3.

Preliminary Step – Determine if Proposed Site is Mapped as Infeasible, Early Coordination with Port.

Deep infiltration facilities can only be considered in areas previously identified by the Port as feasible for deep infiltration (Aspect Consulting, LLC [Aspect], 2018) and where measured infiltration rates are expected to be 0.3 inches per hour or greater per square foot of well infiltration surface area (in/hr/ft^2), as outlined in the Port's LID Guideline. The Port's LID Guideline includes infiltration infeasibility maps that need to be reviewed early in the planning stages. The Deep Infiltration Feasibility Map is included with this document as Figure 1. In addition, to reduce risk, it is recommended that project proponents communicate and coordinate early with Port regarding the planned use of deep infiltration facilities.

3.1 Step 1 – Select Preliminary Locations for Deep Infiltration Facilities, Complete Initial Site Investigation, Groundwater Monitoring

Given that stormwater infiltration testing and site suitability checks must be based on the planned location of deep stormwater infiltration BMPs, it is important for detailed geotechnical explorations and infiltration testing work to proceed after the development of at least a conceptual site and drainage plan that includes preliminary geotechnical and hydrogeologic information.

As described in Section V-5.2 of the SWMMWW, base the location of a deep infiltration BMP on the ability to convey flow to the location and the expected receptor soil conditions of the location, and complete a preliminary check of Site Suitability Criteria to initially estimate feasibility of locating deep infiltration facilities on the site. Section I-4.10 of the SWMMWW provides minimum siting requirements as well as design and construction requirements that apply to all new UIC wells. In addition, review to Section 3.4 of the Port's LID Guideline to review horizontal setbacks and site constraints specific to the Port (RKI, 2019).

Note that if State or Federal funds are involved in the project, it is likely that an Executive Order 05-05 Section 106 cultural resources review and approval process will need to be coordinated with Ecology and completed prior to conducting any ground disturbing activity, including borings and/or monitoring well installation. When required, the cultural resources review and approval process can require 2 months or more to complete.

The recommended process for this step involves:

a. Call for initial utility locates, review available site geotechnical and hydrogeologic data, assess data needs, and develop an initial field exploration work plan, including a safety plan as needed.

b. Complete site survey and initial geotechnical (and hydrogeologic) site characterization work, including preliminary identification of stormwater receptor unit characteristics and placement of groundwater monitoring wells when needed.

c. Analyze the initial geotechnical and hydrogeologic site characterization data and estimate the approximate seasonal high groundwater level and preliminary bulk saturated hydraulic conductivities of the potential receptor unit at key locations across the site. Use the preliminary hydraulic conductivity estimates, assumed infiltration well details, an appropriate analytical model, and reasonable safety factors to estimate infiltration well flow rates for various well diameters and screen heights.

d. Prepare a conceptual development site layout (grading, buildings, landscaping, parking, stormwater BMPs, deep infiltration facilities, etc.). Per Section I-4.15 of the SWMMWW, the conceptual site layout must include basic treatment in advance of deep infiltration BMPs regardless if treatment can be provided by the vadose zone (i.e., the unsaturated geologic material between the bottom of the UIC well and the top of an unconfined aquifer). However, in other cases, additional treatment (e.g., oil removal) may be required to protect groundwater quality based on geologic conditions, land use, and activities at the project site. Further information on these assessments and their application are included in Section I-4.16 Determining Treatment Requirements and Section I-4.17 Classification of Vadose Zone Treatment Capacity of the SWMMWW.

e. Continue groundwater level monitoring through at least one wet season (December 1 through April 1) as needed.

The following additional steps should be taken to protect the long-term functionality of deep infiltration system:

- Planning for redundant sediment control BMPs in advance of deep infiltration systems, such as a robustly sized pre-settling basin followed by a basic treatment BMP.

- Including a pre-settling, scum, and floating oil control BMP (such as a large settling manhole or vault with downturned elbow) for flows in excess of the water quality flow if the high flow will bypass the normal treatment BMPs and be infiltrated. This BMP can be omitted if flows above the water quality flow rate will be discharged to surface waters or an off-site drainage system that discharges to surface waters.

3.2 Step 2 – Estimate Stormwater Runoff from the Project Using Hydrologic Modeling

Estimate stormwater runoff from the development site following the methods and guidelines described in Volume III of the 2017 Port of Seattle Stormwater Management Manual (SWMM) for Port Aviation Division Property and Section V-5.2 of the SWMMWW:

a. Determine the continuous hydrograph and volume of stormwater runoff using an approved continuous runoff model (Western Washington Hydrology Model [WWHM], MGSFlood, or King County Runoff Time Series [KCRTS]) as approved by the Port. Utilize existing Port of Seattle hydrologic models when possible. The runoff hydrograph data file developed for the project site serves as input to the deep infiltration facility, sometimes with modifications.

b. Estimate the peak flow rate that will need to be accommodated by infiltration BMPs located in each infiltration area of the site in order to meet standards. Sometimes storage/detention BMPs are located upstream of an infiltration BMP in order to reduce peak infiltration flow rates. This is acceptable if the overall required system drain-down period is met.

If preferred by the developer and approved by the Port, this step (runoff modeling) may be completed later in the project. For example, the developer may prefer to first evaluate Site Suitability Criteria (Step 1) and conduct several initial deep infiltration tests to confirm site infiltration rates are likely to exceed the required minimum of 0.3 in/hr before moving forward with the hydrologic modeling effort.

3.3 Step 3 – Develop Trial Deep Infiltration Facility Details, Sizes, and Depths

By estimating runoff volumes, peak infiltration flow rates, and assuming a minimum receptor soil bulk saturated hydraulic conductivity, a designer can estimate the preliminary characteristics, number, and individual flow rates for proposed deep infiltration facilities and identify areas for infiltration testing and construction that consider the setback requirements outlined in the Port's LID Guideline. The proposed location of the deep infiltration facility should be used for planning purposes, initial hydrologic modeling of the proposed condition, and for developing the geotechnical and hydrogeologic subsurface investigation plan.

For deep infiltration facilities sized to meet the LID Performance Standard and/or the Flow Control Performance Standard (see the LID Guideline), the facility must infiltrate either all of the influent hydrograph data file, or a sufficient amount such that any overflow/bypass meets the standard. Note that Ecology requires a minimum of basic stormwater treatment, and a maximum of basic treatment plus formal oil control, prior to all deep infiltration BMPs.

Deep infiltration UIC wells may be used to provide flow control for stormwater runoff where pollutant concentrations that reach groundwater will meet the Washington State groundwater water quality standards in the following situations:

- For flows greater than the water quality design flow rate in accordance with SWMMWW Section III-2.6 Sizing Your Runoff Treatment BMPs.
- Where stormwater is treated prior to discharge into the UIC well in accordance with SWMMWW Section I-4.16 Determining Treatment Requirements.

Completing Step 3 generally involves:

a. Developing preliminary estimates of deep infiltration facility well details and depths based on peak infiltration flow rates and estimated geotechnical and hydrogeologic conditions.

b. Refinement of the number, locations, and details of deep infiltration facilities through iterative modeling and BMP revisions and layout updates to meet performance standards. Estimate infiltration well flow rates for various well diameters and screen heights using: (a) preliminary estimate of seasonal high groundwater level; (b) preliminary estimate of bulk saturated hydraulic conductivity of the potential receptor unit; (c) assumed infiltration well details; (e) an appropriate infiltration well analytical model such as the U.S. Bureau of Reclamation (USBR) Well Permeameter Method (USBR, 1989); and (d) reasonable safety factors on the predicted infiltration flow rate. Assume a water level in the infiltration well no greater than the top of the screened section with the top of the screen no greater than the top of the receptor soil.

c. Preliminarily verifying that non-infiltration-related Site Suitability Criteria are met (setbacks, groundwater protection areas, groundwater depth, contamination, etc.). See SWMMWW Sections V-5.5 and V-5.6.

d. Preliminarily verifying that UIC related Site Suitability Criteria and design and construction requirements are met. See SWMMWW Sections I-2.14 and I-4 for additional siting, design, treatment, and registration requirements for these facilities.

3.4 Step 4 – Complete Detailed Site Characterization and Deep Infiltration Testing

The SWMMWW (Sections I-4.10 and I-4.15) details the subsurface and surface suitability criteria for constructing deep infiltration facilities. These criteria can be evaluated from new or, in part, from existing studies.[2] A substantial portion of the suitability criteria can be evaluated concurrent with deep infiltration testing, so an assessment of existing data should be completed prior to field investigations to identify data gaps to be addressed. Detailed site characterization and deep infiltration testing involves the following overall activities:

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[2] Existing studies and data may include geologic maps, cross sections, and models for the area; well logs from Ecology's online well log database; water levels, including seasonal variations, taken from well logs, groundwater studies, or collected from local monitoring wells; and/or geotechnical reports for nearby sites.

a. Based on the preliminary information developed in the preceding steps, determine the number, location, and depths of geotechnical test pits or borings, soil samples, groundwater aquifer tests, and deep infiltration tests (see Sections V-5.5, V-5.6, and I-4 of the SWMMWW); determine instrumentation requirements; estimate test water needs; and develop a detailed field work plan, including a safety plan as needed. Call for utility locates, survey utilities, and update the exploration and testing plan as needed.

b. Develop deep infiltration test well details (depth, diameter, screen interval, packing requirements, drilling method, etc.). Install test wells using a qualified contractor with ample involvement and oversight by the infiltration specialist or their representative.

c. Complete detailed field geotechnical/hydrogeologic explorations and deep infiltration tests. Monitor groundwater response during testing. Aquifer slug tests can be used to determine the transmissivity/hydraulic conductivity and Storativity of the material the well is completed in. Log soils and submit samples for laboratory analysis.

The Port's deep infiltration feasibility map considers mapped surficial geologic conditions and general setbacks presented in the Port's LID Guideline. Site characterization details that must be addressed for each deep infiltration project include[3]:

1. **Continuously logged soil conditions** through the infiltration receptor soil unit to at least 15 feet below the planned bottom of full-scale infiltration wells, or to groundwater, whichever is deeper.

2. **Seasonal high groundwater levels (through at least one wet season) and groundwater flow direction.** The wet season is defined as December 1 through April 1. This may be able to be accomplished through evaluation of existing groundwater data, where present. Otherwise, determining groundwater flow direction typically involves installation of at least three groundwater monitoring wells. Per SWMMWW Section I-4.15, deep infiltration wells must have a minimum of 15 feet of separation to high groundwater.

3. **Horizontal hydraulic conductivity of the soil below the water table** to determine groundwater mounding potential. This may be estimated from grainsize data, field aquifer tests, or existing data sources, if appropriate.

4. **Volumetric holding capacity of the receptor soil** (soil layer between point of injection of stormwater runoff into the subsurface soil and the seasonal high-water level). This may be determined from laboratory testing of site samples.

5. **Soil Cation Exchange Capacity (CEC) and organic matter content** to evaluate treatment capacity of the vadose zone. See the SWMMWW Section V-5.6 regarding

[3] The final characterization evaluation will also need to evaluate whether the site has any known contaminated soils (from existing environmental databases) and consider whether there would be any adverse effects from groundwater seepage from the infiltration facility on nearby structures.

the CEC and organic content necessary for the soil to count as a treatment media. Note that per SWMMWW Section I-4.15, all deep infiltration wells require a minimum of basic treatment in advance of the well, regardless of site land use and soil treatability properties. However, CEC and organic matter tests are still required for deep infiltration facilities in order to determine the final treatment requirements, which may include oil removal (see Section I-4.16 Determining Treatment Requirements and Section I-4.17 Classification of Vadose Zone Treatment Capacity of the SWMMWW).

Elements 1, 4, and 5 can potentially be evaluated using samples collected during borings completed for field infiltration testing (Field Infiltration Testing and Analysis described below) and can be completed within several weeks. Element 2, if not addressed through existing data sources, will likely require contracting a licensed well driller for monitoring well construction, and Element 3 will require consultation with a qualified professional to complete aquifer testing and/or analysis.

Depending on the existing data, the site characterization may require up to 3 to 6 months to complete over the wet season (December 1 through April 1). A developer should consider completing Elements 2 and 3 after infiltration testing so that deep infiltration feasibility is at least preliminarily confirmed prior to investing in additional groundwater characterization.

3.4.1 Deep Infiltration Test Well Installation

The planning, selection, and installation of infiltration test wells should consider the following:

- Review of existing project data on site geology and hydrogeology. It is recommended that chip trays and/or bulk samples obtained from detailed geotechnical/hydrogeologic explorations be reviewed to ensure that soils encountered meet receptor soil criteria.
- Visit the site to observe site conditions and potential access for a drilling rig, to secure a water supply for drilling (if needed), and to check for hazards to personnel and equipment (such as utilities on and near the project site).
- Selection of drilling, well development, and sampling methods.
- Infiltration test well-construction details and materials including well-construction specifications, including casing and screen materials, casing and screen diameter, screen length and interval, and filter pack and screen size.
- Determine need for disposing of potentially contaminated soils and water generated by the test well installation process.
- Preparation of a written work plan including site safety plan, methods, listing of materials and equipment specifications, and plan for disposal/treatment of contaminated materials.
- Preparation and execution of the drilling contract.
- Field implementation of the test well drilling program/plan.

- Final report preparation documenting background data, field procedures, and monitoring well and test well construction data, including well logs and test well construction information.

It is recommended that all drilling activities be performed by a Washington licensed well driller in accordance with Chapter 173-160 WAC, which governs standards for the construction and maintenance of water supply wells (not deep infiltration wells). Drilling and infiltration test well construction activities should be overseen by a licensed engineer, geologist, or hydrogeologist.

The following should be completed prior to and during drilling:

- The horizontal and vertical locations of the proposed infiltration test wells must be surveyed by a licensed land surveyor and accurately shown on the design drawings in advance of drilling. Ensure that the contractor locates and stakes all test well locations as depicted on site plans.
- Chip trays and/or bulk samples obtained from detailed geotechnical/hydrogeologic explorations should be reviewed for comparison to samples to be collected in the field to ensure that soils meet receptor soil criteria and target depths.
- Review site plans and specifications; modify drilling program/plan as needed.
- During drilling, soil samples and descriptions will be made in general accordance with ASTM International (ASTM) Method D2488, *Standard Practice for Description and Identification of Soils* (Visual/Manual Procedure). Samples should not be disposed of until they have been logged, photographed, chip-trayed, and the test well screen design has been finalized. Dispose of soil samples at the site contractor's direction.
- Provide potable water as needed to address any field conditions that arise, such as heaving sand, hydrating bentonite chips, mixing concrete, etc. Core barrels are to be decontaminated between holes.
- Any signs of groundwater should be closely observed. Measure and record water levels down-stem if water is encountered.

3.4.2 Deep Infiltration Testing and Analysis

The SWMMWW does not provide recommendations on deep infiltration well testing and analysis. There are multiple deep infiltration test methods, some of which are suitable only for limited conditions, such as relatively shallow depths to the receptor soil. Aspect recommends that testing be conducted in general accordance with Appendix D of the City of Seattle Stormwater Manual (City of Seattle, 2017) with test methods developed and results analyzed generally following the U.S. Bureau of Reclamation (USBR) Well Permeameter Method (USBR, 1989), which is provided as Attachment 4.

Field infiltration testing and analysis should be completed by an experienced professional during the wet season (December 1 through April 1) to best represent anticipated conditions, including higher groundwater levels. A typical duration for deep infiltration planning, design, permitting, fieldwork, and analysis is approximately 30-60 days or more. Costs and duration vary with the number of deep infiltration wells to be tested, and whether additional concurrent site characterization is completed (Section 2).

The following sections identify considerations and recommended procedures for planning and execution of the deep infiltration test program.

Deep Infiltration Test Program Design

Borehole infiltration tests (BITs) are recommended for the design of deep infiltration facilities. As stated above, BITs should be conducted in general accordance with the City of Seattle Stormwater Manual (City of Seattle, 2017). Test results should then be analyzed using the USBR Well Permeameter Method (USBR, 1989), which provides an estimate of the receptor soil bulk saturated hydraulic conductivity (Attachment 4).

The BIT is typically comprised of two phases: a constant head test (phase 1) and a falling head test (phase 2). Phase 1 is performed by injecting water at a sufficient rate to maintain the water level in the well within the screened interval (see below for detailed procedures). This phase may last approximately 6 to 8 hours to ensure the soil is properly wetted and an infiltration flow rate can be achieved without adjusting the flow rate. Once a constant rate is achieved, the constant head test will be continued for a minimum 4-hour duration. After phase 1 is complete, the falling head test will begin by completely shutting off the flow of water to the well and monitoring the falling water level. Phase 2 is complete when no more water remains in the test well.

A minimum of one BIT is recommended for design of each deep infiltration facility (City of Seattle, 2017). However, pilot borings and additional tests may need to be conducted if subsurface conditions are highly variable and/or at the direction of a consulting engineer, geologist, or hydrogeologist. Pilot borings are less expensive smaller borings that are used to investigate subsurface conditions, such as receptor soil continuity and depth, prior to investing in larger borings, test well (or full scale well) installation, and infiltration testing.

In designing the BIT program, the following should be considered:

- The planned layout of the completed project. Test well installation and deep infiltration well testing should be completed at the anticipated location of the deep infiltration facility.
- The anticipated depth of the facility based on the receptor soil targeted for infiltration. Testing will be completed within the screened portion of the test well; ensure that field testing equipment is of sufficient size or length to compete the tests.
- Whether any additional Site Characterization elements described in Step 4 will be addressed concurrently.
- The number of BITs to be completed, the separation between BITs, and whether multiple BITs can be conducted concurrently.

- Access for contractors and water conveyance equipment.
- Anticipated infiltration rates and associated water supply availability.
- Proximity of buried utilities.
- Traffic control requirements.

3.4.3 Utility Locates and Site Access

Utility locates are required at least 72 hours before ground disturbance, and the area(s) to be disturbed must be marked in advance with paint. Public utility locate information is available from www.callbeforyoudig.org/Washington. For liability reasons, the excavation contractor must call in the public locates. A private utility location provider must also be contracted for remote areas.

Site access should be considered for all contractors, including limitations for:

- Drill rigs and excavators to the project site during the wet season (December 1 through April 1)
- Water supply trucks and conveyance
- Traffic revisions

3.4.4 Secure a Water Source

Infiltration tests require several hours of uninterrupted potable water flow. Flow rates required deep infiltration testing vary greatly depending on receptor soil conditions. It is possible for rates to range from 5 to more than 100 gallons per minute (gpm) to maintain a constant water depth in the test well during testing. To estimate water quantities for testing, the surface area of the screened portion of the test well and an assumed initial infiltration rate should be considered. Some common water sources are listed below.

- **Fire Hydrants** may be accessible if authorized by the Port Fire Department and/or through the City of SeaTac by obtaining a Hydrant Use Permit. A certified backflow prevention device (reduced pressure backflow assembly [RPBA]) must be used and tested by Port AV/Maintenance prior to approval.
- **Water Trucks** can be used in more remote areas but supply a finite amount of water for testing. If operated under gravity flow, constant valve adjustments will be required as the truck empties and multiple trucks may be required to avoid stopping the tests early if high infiltration results are encountered.
- **Other On-site Sources**, including hose bibs, which are typically limited to a capacity of about 5 gpm and may not provide sufficient water supply to conduct testing.

3.4.5 Borehole Infiltration Testing (BIT) Procedures

Step-by-step instructions and best practices for conducting BITs are presented below.

Pre-Testing Procedures

1. Review the final test well installation details and update the testing plan, as needed.
2. Coordinate with site owner or others to secure a water source (Section 3.4.4)
3. Coordinate with the site owner or others to secure site access for contractors and equipment.
4. Secure necessary infiltration testing equipment including:
   - Flow meters, valves, fittings, and appropriate size and length of water hoses.
   - Pressure transducer and dataloggers for down-well deployment water level monitoring and measurement of barometric pressure.
   - Electronic wire tape and tape measure.
   - Field laptop computer with vendor software for deployment of water level sensors.
   - 5-gallon plastic bucket for onsite flow meter calibration.
   - Pre-printed field forms and/or field notebook.
5. Test all infiltration testing equipment prior to field mobilization to verify operation, as needed.

Constant Head Test

1. Once at the project site, coordinate with the site owner or others as needed to locate the water source; set-up water conveyance, metering, and other testing equipment; and prepare for testing.
2. Install a flow meter in-line with the water source hose to monitor flow rates in real time. The flow meter should be capable of measuring flow to within 5 percent of the total flow rate.
3. Calibrate the flow meter with a 5-gallon plastic bucket by filling the bucket and recording the time to fill.
4. Install a down-well pressure transducer and datalogger to monitor and record water levels. Set the datalogger to record water levels on a 1-minute interval.

5. Install a pressure transducer and datalogger onsite. This reference pressure logger will be installed to measure and record variations in atmospheric barometric pressure, so that barometric fluctuations can be removed during data processing allowing for estimation of water head above the sensor.

6. If a pressure transducer or vibrating wire piezometer (VWP) has been installed/set at the bottom of the boring to monitor groundwater levels, re-program the device to record at a minimum of 5-minute intervals for the duration of the testing. Once all testing is completed, download the data and re-program the device to pre-testing recording interval.

7. Begin the test by adding water to the test well. Continue adding water to achieve the targeted hydraulic head. In general, the targeted hydraulic head is at the top of the screened portion of the test well, which is usually at the top of the receptor soil. Refer to the final test well installation details as needed.

8. Periodically monitor the flow rate and water levels in the test well with an electronic wire tape. Adjust the flow rate as needed to maintain the targeted hydraulic head. Record test time, flow rate, and water level on a field data sheet and/or field notebook. Measurements should be recorded more frequently near the beginning of the test and approximately every 10 minutes, at a minimum, once the flow rate has stabilized.

9. Continue to add water until the water level and flow rate is constant (5 percent variation); continue the test for a minimum of 4 hours.

10. As a final step, increase the flow rate and adjust as necessary to reach a targeted hydraulic head of 5 feet above the top of the well screen section. Once equilibrium is reached, maintain a constant flow rate for approximately 30 to 60 minutes.

11. Shut off flow to the test well and monitor the rate that water drains down. Take notes regarding the draindown process and if it appears that the draindown rate substantially slows down, which could indicate that groundwater mounding occurred during the test and additional investigations are warranted.

All borehole injection test data, including recorded field data, instantaneous flow rate measurements, electric wire tape readings, raw/final data files from pressure transducers and dataloggers should be compiled and reviewed for accuracy by a qualified professional.

3.5 Step 5 – Analyze BIT Data and Determine Aquifer Properties and the Design Bulk Saturated Hydraulic Conductivity of the Receptor Unit

Following the detailed geotechnical and hydrogeologic testing process it is necessary to:

a. Review soil boring logs and grain size data to verify the suitability, depth, and continuity of the receptor soil.

b. Review aquifer testing data and the measured groundwater response during infiltration testing and determine key groundwater aquifer properties. Aquifer properties, such as thickness, soil type, grain size distribution, porosity, horizontal and vertical saturated hydraulic conductivities, Transmissivity, Storativity, etc. must be estimated for impact analysis and input into any formal groundwater mounding analysis/model.

c. Analyze groundwater depth, receptor soil data, and deep infiltration test data and estimate the measured bulk saturated hydraulic conductivity of the receptor soil. As discussed above, Aspect recommends that deep infiltration test well results be analyzed using the USBR Well Permeameter Method (See Attachment 4), which provides an estimate of the measured receptor soil bulk saturated hydraulic conductivity (the term Coefficient of Permeability as used in the Well Permeameter Method is synonymous with saturated hydraulic conductivity at 20° C). Refer to Step 5 for additional analysis.

The measured infiltration flow rate from an infiltration test conducted in general conformance with the Well Permeameter Method is used to calculate a measured bulk saturated hydraulic conductivity using an appropriate equation from the USBR Well Permeameter Method that best represents test conditions. Appropriate safety factors are then applied to estimate a long-term design bulk saturated hydraulic conductivity that accounts for uncertainties and performance declines over time. The City of Seattle Stormwater Manual recommends safety factors between 0.2 and 0.5 (multiplied by the measured bulk saturated hydraulic conductivity; City of Seattle, 2017). Selection of an appropriate safety factor is a matter of professional judgment. Safety factors can be applied to either: (a) the measured bulk saturated hydraulic conductivity, yielding a design bulk saturated hydraulic conductivity, or (b) the predicted full-scale infiltration well flow rates, yielding a design infiltration well flow rate. See the Supplemental Guidance presented in Step 6 for additional direction regarding safety factors.

Analysis of the BIT results must be included in the technical report submitted to the Port.

3.6 Step 6 – Size and Design Deep Infiltration Facilities to Meet Performance Standards, Initial UIC Registration

Note that for sites requiring a mounding analysis (Section 3.7), it will be necessary for the design process to account for the mounding analysis results. Addressing groundwater mounding related impacts can require changes in the layout and size of deep infiltration BMPs and/or restricting infiltration flow rates. Therefore, the mounding analysis should be conducted before the final BMP layout, sizing, and design process.

The stormwater designer will need to coordinate across design disciplines, update site hydrology and adjust the development site plan, stormwater treatment BMPs, and full-scale deep infiltration facility layout, details, specifications, and cost estimates as needed to meet standards and proceed with permitting and full design. Deep infiltration facility testing methods, results, and design information need to be included in a site geotechnical/hydrogeology report and stormwater permitting submittal documents. Infiltration system Operation and Maintenance (O&M) procedures are also typically required, which should be included in an overall Stormwater O&M Manual.

Use the design bulk saturated hydraulic conductivity of the receptor soil, the seasonal high groundwater level, and an appropriate deep infiltration well analytical model to estimate full-scale infiltration well details. Given saturated hydraulic conductivity estimates from analysis of the deep infiltration test well data, the USBR Well Permeameter equation can be rearranged and used to estimate design infiltration flow rates for other well configurations (i.e., diameters, receptor soil penetration) and operational conditions (i.e., target water depths/heads for a full-scale deep infiltration well in a similar receptor soil (see Section 15 of Attachment 4). Note that additional deep infiltration facilities may be required to meet the targeted cumulative infiltration flow rate as determined by hydrologic modeling for the proposed site. In such cases, the discharge rate into each well will need to be restricted to the design rate per well. It is also necessary to register deep infiltration wells with Ecology's Underground Injection Control Program prior to construction. Aspect recommends initially registering UICs based on approximately 60% to 90% design information so that any Ecology comments can be included in the final design.

3.6.1 Supplemental Guidance

Generally speaking, relative to their initial measured infiltration rates, low permeability soils experience less of a decrease due to sediment loading over time compared to higher permeability soils such as coarse sandy soils. Clean, coarse, sandy soils often have a very high initial infiltration rate but may experience a dramatic reduction in flow after even a small amount of sediment loading. Clean sands, clean gravely sands, or clean sandy gravels are highly susceptible to plugging. Full-scale deep infiltration well screens are typically packed in graded sand, which is susceptible to plugging over time. In addition, the infiltration surface area of the screened section in a full-scale infiltration well in coarse soils is often significantly less than the infiltration surface area of a bioretention basin or infiltration basin, making the infiltration well more sensitive to sediment loading over time than a surface BMP designed for the same flow rate. For these reasons, in addition to the discussion of safety factors above, Aspect recommends several additional safety-factor related items:

1. For high-permeability soils, such as clean uniform continuous outwash deposits, use a smaller safety factor, such as 0.1, to account for susceptibility of these soils to plugging over time.

2. For deeper infiltration wells, reserve a significant portion of the available head to help maintain design flows over time. This allows head to build-up in the well casing, increasing the hydraulic gradient, to help counteract the effects of inevitable sediment loading over time.

3. Use flow restrictors such as orifices to limit the flow rate into a deep infiltration well to the design flow rate given the available head on the upstream side of the flow restrictor. Higher flows should be detained or bypassed.

3.7 Step 7 – Groundwater Impact and Mounding Analysis

Groundwater mounding analysis cannot be completed until the Site Characterization and the infiltration testing described Step 4 are completed. A detailed groundwater impact and mounding analysis can involve numerical groundwater modeling by a qualified professional to determine the subsurface buildup of groundwater levels that result from operation of an infiltration facility. Completing the mounding analysis is often an iterative process with Step 6, where: (a) information about groundwater, aquifer properties, and an infiltration well network and flowrates is input into numerical groundwater modeling software; (b) the model is run; (c) the infiltration well system is modified if needed; and (d) the model is updated and ran again, and so on.

The primary reasons to perform a groundwater mounding analysis are to verify that mounding of infiltrating water will not rise to the point where it impedes infiltration, causes the infiltration facility to prematurely overflow, causes slope stability or seepage problems, negatively impacts adjacent buildings or other infrastructure, or interacts with contaminated soils. For UIC facilities such as deep infiltration BMPs, a mounding analysis is also helpful to verify that the mound does not rise to the point where stormwater is directly injecting into the mound (prohibited by the UIC Program Rule, WAC 173-218 as outlined in Section I-4 of the SWMMWW).

Regarding deep infiltration wells, Table 3.2 in Volume 3, Section 3.2 of the City of Seattle Stormwater Manual (City of Seattle, 2017) requires a groundwater mounding and seepage analysis to be conducted for deep infiltration wells where the separation to groundwater is less than 15 feet and greater than or equal to 10,000 square feet of impervious surface is being infiltrated on site. However, Section I-4.15 of Ecology's SWMMWW requires deep infiltration BMPs to have at least 15 feet of separation to high groundwater. The SWMMWW also states that "infiltration testing to determine mounding affects" is required for deep infiltration systems. Given this language, Aspect recommends:

1. That groundwater response be measured during deep infiltration testing. This is typically done using pressure transducers placed in the groundwater under and near the infiltration test well.
2. If significant mounding is measured during infiltration testing (in the professional opinion of the infiltration specialist), then a formal mounding analysis would be triggered.
3. If significant mounding does not occur during infiltration testing (in the professional opinion of the infiltration specialist), then a formal mounding analysis would not be triggered, unless requested for other reasons.

If a formal mounding analysis is required, the analysis can range from using a relatively simple spreadsheet model, to developing a full MODFLOW groundwater model. Following/adapting the mounding analysis requirements in Section 5.2.1 of the 2016 King County Surface Water Design Manual, it is necessary to model the ground water response under a continuous infiltration flowrate hydrograph, which is derived from a project's overall continuous simulation runoff model output. Mounding levels must be assessed for a water year (October 1 through September 30) with the wettest 30-day (cumulative rainfall) volume on record as well as a water year with a 100-year precipitation event included. In addition to the effort to derive the infiltration hydrograph, when a mounding model is required, it is also necessary to verify or estimate aquifer properties such as thickness, soil type, and porosity, and estimate additional aquifer properties such as horizontal and vertical hydraulic conductivities, Specific Yield, and Specific Storage. Sometimes this will require extra hydrogeologic field work and aquifer tests.

3.8 Step 8 – Construct the Deep Infiltration Facility and Conduct Performance Monitoring

Upon completion of the deep infiltration testing, analysis, and design process, the next steps are:

a. Contract with a qualified well driller.

b. Review the unique nature of the work, special requirements, and acceptance criteria with the selected contractor's team.

c. Ensure adequate oversight and observation by an infiltration specialist or their representative.

d. For sites with non-uniform receptor soil conditions, consider pilot borings prior to approval to install full-scale infiltration wells. Specify a number of pilot borings greater than the number of planned full-scale wells to account for the potential to encounter unsuitable receptor units.

e. Based on approved pilot boring data, full-scale deep infiltration wells should be constructed in accordance with final well design and construction specifications.

f. Upon installing a full-scale infiltration well, complete performance verification testing. Performance testing of constructed full-scale deep infiltration facilities is required if not located in the same spot as a test well. This requirement may be waived at the discretion of the Port if the infiltration specialist believes site conditions warrant it. Otherwise, it is recommended that borehole infiltration testing be conducted for each full-scale deep infiltration well to confirm they meet design requirements (less safety factors to account for plugging over time). Performance testing should be planned and conducted by a qualified professional using the borehole injection method.

g. Update UIC registrations as needed based on construction as-built conditions.

4 Contractor Selection and Reporting Requirements

The Port's LID Guideline requires that a report addressing the elements of site suitability and characterization and deep infiltration facility design are signed and sealed by a qualified Engineer, Engineering Geologist, Geologist, or Hydrogeologist. A qualified consultant or team member licensed in one or more of these areas and with proper stormwater infiltration expertise should be consulted early in project development to assist in scoping.

In addition to stormwater, geotechnical, and hydrogeologic engineering/consulting services, the following may also need to be contracted:

- Surveying services.
- Water truck and water conveyance in remote areas (for infiltration testing, often provided by excavation companies).
- Geotechnical drilling/boring (for site characterization and soil sampling).
- Well Construction (for test well installation).

5 Full-Scale Deep Infiltration Post-Construction Considerations and UIC Registration

5.1 Deep Infiltration Well Post-Construction Considerations

As discussed previously, deep infiltration wells have a relatively small infiltration surface area in contact with the receptor soil compared to other infiltration BMPs. This makes them especially susceptible to plugging by sediment. It is imperative that no construction sediment be allowed to discharge into the infiltration wells, and they not be put into service until the site is fully stabilized. Wells should be capped and protected until ready for use. Any sediment that accumulates in pipes, manholes, or other drainage structures during construction should be carefully removed and disposed of. The contributing drainage system should be flushed (while pumping to sanitary sewer or other means of disposal) prior to putting wells into operation.

To allow for long-term inspection and maintenance, infiltration wells should protrude into readily accessible surface housing structures, such as shallow manholes.

5.2 Underground Injection Control Well Registration

Deep infiltration wells are considered UIC facilities and will require registration with the Washington State Department of Ecology prior to use. Based on King County's standards, UIC wells must be registered prior to receiving stormwater review approvals. This means that it will be necessary to register the wells based on the design, obtain a registration number, and then update the registration information based on construction as-builts.

6 References

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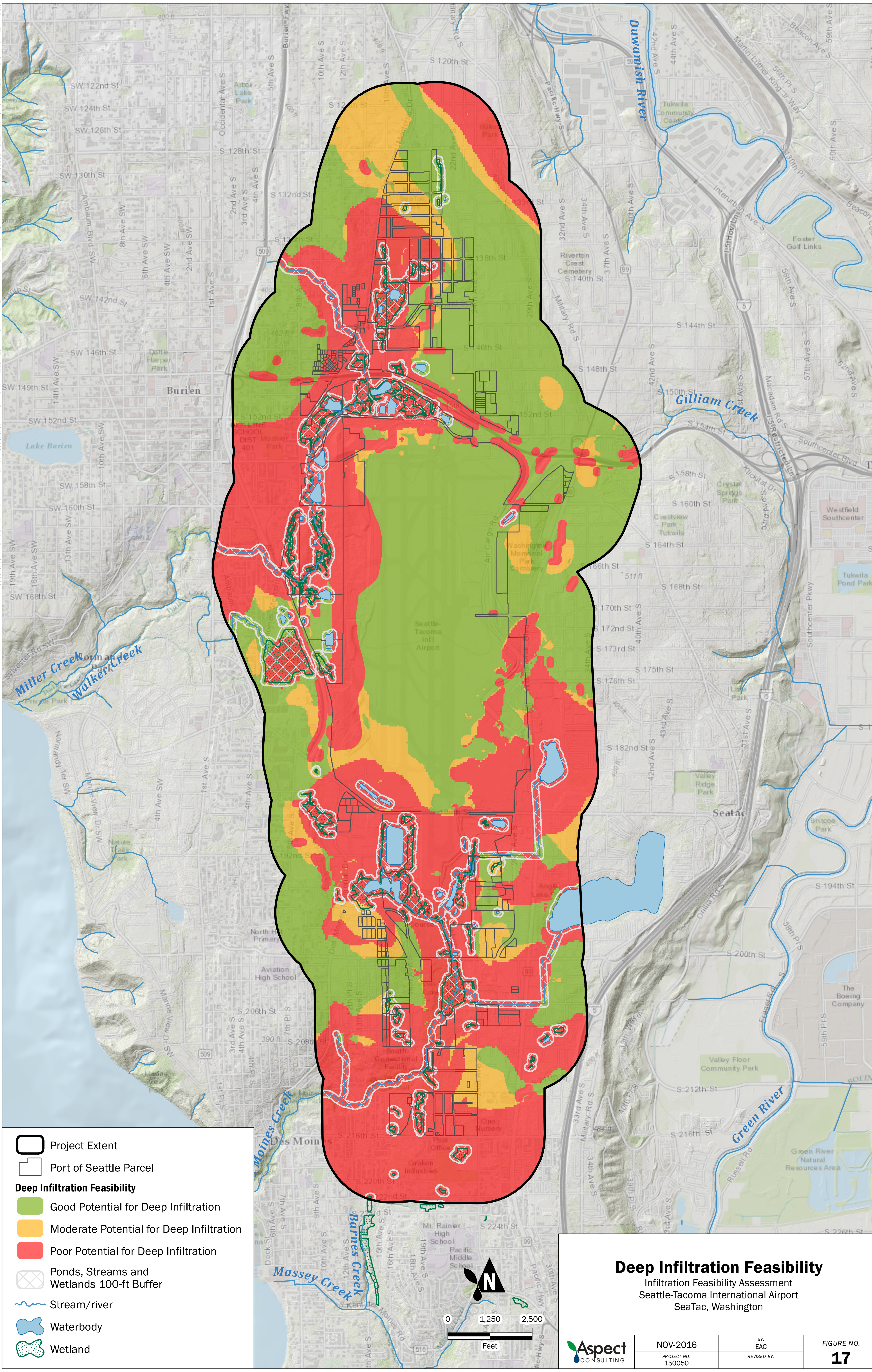
FIGURES



Deep Infiltration Feasibility

Infiltration Feasibility Assessment
Seattle-Tacoma International Airport
SeaTac, Washington

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NOV-2016 | BY: EAC | FIGURE NO. 17
PROJECT NO. 150050 | REVISED BY: - - -

GIS Path: T:\projects_8\Port_of_Seattle\SurfaceWaterDIQ_150050\Delivered\17 Deep Infiltration Feasibility.mxd || Coordinate System: STIA GRID || Date Saved: 11/2/2016 || User: ecrumbaker || Print Date: 11/2/2016

Basemap Layer Credits || Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Attachment 1

Deep Infiltration

Gantt Chart Schedule

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Attachment 1 - Example Deep Infiltration Schedule (Steps 1 through 4)

	Month	1				2				3				4				5				6				7				8				9				10			
TASK	Approximate Duration	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Preliminary - *Verify site is not mapped as infeasible for deep infiltration by the Port. Early coordination with Port.*																																									
Step 1: Select Prelim Locations for Deep Infiltration Facilities, Complete Initial Investigation, Groundwater Monitoring																																									
Task 1.1: Gather/review existing data, initial utility locates, assess data needs, prepare initial field work plan.	0.5 month																																								
Task 1.2: Site survey, initial geotechnical/hydrogeologic site characterization, install monitoring wells.	1.5 month																																								
Task 1.3: Analyze initial geotech./hydrogeo. data, estimate key parameters and potential infiltration rates.	0.5 month																																								
Task 1.4: Prepare conceptual site layout (grading, buildings, parking, stormwater facilities, etc.).	2 months																																								
Task 1.5: Continue groundwater level monitoring through at least one wet season as needed.	6 months																																								
Step 2: Estimate Stormwater Runoff from the Project, Hydrologic Modeling																																									
Task 2.1: Given the conceptual site layout, run hydrologic model of proposed and pre-development conditions.	1 month																																								
Task 2.2: Estimate the peak flow rate to be infiltrated in each infiltration area in order to meet standards.	0.5 month																																								
Step 3: Develop Trial Deep Infiltration Facility Details, Sizes, and Depths																																									
Task 3.1: Develop assumed infiltration well details and depths based on preliminary conditions and flowrates.	0.5 month																																								
Task 3.2: Refine preliminary number/details of infiltration wells using analytical model & safety factors.	0.5 month																																								
Task 3.3: Preliminarily verify other Site Suitability Criteria appear to be met.	0.25 month																																								
Task 3.4: Preliminarily verify UIC Site Suitability Criteria appear to be met.	0.25 month																																								
Step 4: Complete Detailed Site Characterization and Deep Infiltration Testing																																									
Task 4.1: Identify number/locations for geotechnical, hydrogeologic, and infiltration tests. Prepare field plan.	1.5 months																																								
Task 4.2: Develop infilt. test well details, aquifer test well details, contract with well driller, install wells, log soils.	1.5 months																																								
Task 4.3: Complete geotech. investigation (borings, soil logs, GW depth, etc.), aquifer tests, infiltration tests.	0.25 month																																								

Attachment 1 - Example Deep Infiltration Schedule (Steps 5 through 7)

	Month	11				12				13				14				15				16				17				18				19				20			
TASK	Approximate Duration	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Step 5: Determine Aquifer Properties & Design Bulk Saturated Hydraulic Conductivity of the Receptor Unit																																									
Task 5.1: Review soil borings & grain size data to verify the suitability, depth, and continuity of the receptor soil.	0.5 month	■	■																																						
Task 5.2: Review aquifer test data, measured groundwater response, determine key aquifer properties.	0.5 month	■	■																																						
Task 5.3: Analyze GW depth, receptor soil data, deep infilt. test data, estimate design bulk Ksat of receptor soil.	0.5 month			■	■																																				
Step 6: Complete Groundwater Impact and Mounding Analysis																																									
Task 6.1: Review aquifer and receptor soil data, proposed infiltration well info., and set-up groundwater model.	1 month					■	■	■	■																																
Task 6.2: Derive wet-year infiltration hydrographs for each infiltration area and well. Document sources of data.	0.5 month							■	■																																
Task 6.3: Calibrate GW model to infilt. testing and GW response data. Run model for wet years, estimate mound.	0.5 month									■	■																														
Task 6.4: Respond to mounding results as needed - change spacing, depths, size, screen, flow, number of infilt. wells.	0.5 month											■	■																												
Task 6.5: Update/repeat GW modeling as needed during Step 7 (sizing full scale infiltration wells).	1 month													■	■	■	■																								
Step 7: Size and Design Deep Infiltration Facilities for Performance Standards, Initial UIC Registration																																									
Task 7.1: Update hydrology, site plan, treatment BMPs, and infiltration BMP layouts based on prior steps.	1 month													■	■	■	■																								
Task 7.2: Use infiltration well analytical model to determine full scale infiltration well details.	0.5 month																	■	■																						
Task 7.3: Coordinate across design disciplines and prepare infiltration well plans, details, specifications, cost estimates.	4 months																			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						
Task 7.4: Register UIC designs with Ecology's Underground Injection Control Program.	0.25 month																							■																	
Task 7.5: Prepare infiltration permitting documents (integrate in geotech. report/stormwater submittal docs.).	2 months																			■	■	■	■	■	■	■	■														
Task 7.6: Support stormwater permitting process, obtain approval for construction.	2 months																											■	■	■	■	■	■	■	■						

Notes

1. Refer to Section 2 of the SOP for Deep Infiltration Testing and Analysis, Appendix C of the Port of Seattle STIA LID Guideline for example project assumptions

Attachment 2
Example Deep Infiltration Budget

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Attachment 2

Example Deep Stormwater Infiltration Planning, Testing, Analysis, and Design Budget Summary

This table provides an example cost estimate (2019 dollars) to complete deep infiltration planning, testing, analysis, and design for a larger and more complex site, typical of significant Port/STIA development projects.

Task Title	Labor[1]	ODC[2]	Subs[3]	Total
Step 1: Select Preliminary Locations for Deep Infiltration Facilities, Complete Initial Investigation, Start GW Monitoring	$40,217	$2,100	$20,000	$62,317
Step 2: Estimate Stormwater Runoff from the Project, Hydrologic Modeling	$7,950			$7,950
Step 3: Develop Trial Deep Infiltration Facility Details, Sizes, and Depths	$ 9,016			$9,016
Step 4: Complete Detailed Site Characterization and Deep Infiltration Testing	$26,164	$2,000	$20,000	$48,164
Step 5: Determine Aquifer Properties & Design Bulk Saturated Hydraulic Conductivity of the Receptor Unit	$10,366			$10,366
Step 6: Complete Groundwater Impact and Mounding Analysis (MODFLOW Modeling)	$28,269			$28,269
Step 7: Size and Design Deep Infiltration Facilities for Performance Standards, Initial UIC Registration	$38,659			$38,659
Total Project Budget	**$160,641**	**$4,100**	**$40,000**	**$204,741**

[1]Labor includes deep infiltration related consultant staff costs at a firm providing services in: (a) stormwater engineering and infiltration; (b) geotechnical engineering, and (c) hydrogeology. Labor for overall site drainage and non-infiltration BMP design is not included.

[2]ODCs (Other Direct Costs) includes cost items such as monitoring and testing instrumentation and equipment, and travel costs.

[3]Subs (subconsultants) include contracted surveyor and driller costs.

Notes

1. Refer to Section 2 of the SOP for Deep Infiltration Testing and Analysis, Appendix C of the Port of Seattle STIA LID Guideline for example project assumptions

Attachment 3

Deep Infiltration
Review Checklist

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Deep Infiltration Planning, Testing, Analysis and Design Review Checklist

This checklist is provided by the Port to help Project Managers track and complete required deep infiltration related analyses and designs as well as provide guidance for the content of deep infiltration permit review submittals. Initial each row and sign and submit the form when complete.

Section 1 – Deep Infiltration Site Suitability, Layout, and Treatment Requirements		
	1.1	Proposed deep infiltration area has not been mapped as Infeasible by the Port.
	1.2	Proposed infiltration flows do not include prohibited discharges.
	1.3	Seasonal high groundwater at each infiltration area has been determined.
	1.4	Site meets key infiltration suitability criteria (landslide, steep slopes, horizontal set-backs, contamination)
	1.5	Stormwater site plan shows the location of all deep infiltration BMPs and preceding BMPs.
	1.6	Compliance with Ecology's Underground Injection Control (UIC) treatment requirements is documented.
	1.7	Preceding BMPs include a minimum of basic treatment for the water quality flowrate or volume.
	1.8	Preceding BMPs include a settling BMP for infiltrating flows in excess of the water quality flowrate or volume.
	1.9	Documentation is provided that all preceding BMPs comply with the Ports SWMM and LID Guideline.
	1.10	Peak infiltration flowrates for each deep infiltration BMP are documented.
	1.11	Peak infiltration flowrates for each deep infiltration BMP have been determined using an acceptable model.
	1.12	Adequate soil borings have been conducted to illustrate the depth and extent of the proposed receptor soil.
	1.13	Adequate soil borings have been conducted to illustrate the depth and extent of the underlying aquifer.
	1.14	Receptor soil grain size distribution data and classifications support the use of infiltration.
	1.15	Grain size distribution data has been provided for the aquifer underlying the receptor soil.
	1.16	Receptor soil Cation Exchange Capacity and Percent Organic Matter data have been provided.
	1.17	Soil borings do not indicate the presence of low permeability layers between the receptor soil and aquifer.
	1.18	There is 15 ft or more of separation between high groundwater and the bottom of all deep infiltration BMPs.
Section 2 – Deep Infiltration Testing and Analysis		
	2.1	The deep infiltration testing plan follows Port SOPs and was reviewed and approved by the Port.
	2.2	Deep infiltration testing method, results, and analyses are properly documented and certified.
	2.3	The configuration and details (size, depth, screen, etc.) of all infiltration test wells have been documented.
	2.4	The Port approved number and locations of deep infiltration testing have been conducted.
	2.5	Groundwater monitoring was conducted during infiltration tests (directly under or within 10 ft of test wells).
	2.6	Insignificant groundwater mounding was observed during infiltration testing (mounding analysis not required).
	2.7	Significant mounding was observed during infiltration tests (mounding analysis required – **Complete Section 4**)
	2.8	Water depths used for hydraulic conductivity calculations do not exceed the top of the test well screens.
	2.9	Average <u>measured</u> infiltration rate for each well (flow divided by area of infiltration) is greater than 0.3 in/hr.
	2.10	Proper infiltration equations and calculations of <u>measured</u> saturated hydraulic conductivity are documented.
	2.11	The <u>measured</u> saturated hydraulic conductivity of the receptor soil is provided for each infiltration test.
	2.12	<u>Design</u> saturated hydraulic conductivities of the receptor soil were calculated using an appropriate safety factor.

Section 3 – Deep Infiltration BMP Design and Specifications		
	3.1	Certified deep infiltration construction plans and specifications are included with a narrative design report.
	3.2	Full scale deep infiltration BMP details were determined using the correct analytical model and equation.
	3.3	When needed, deep infiltration well spacing, depth, and flowrates account for mounding analysis results.
	3.4	Deep infiltration designs include proper casing, screening, packing, seals, vents, surface access structures.
	3.5	Specifications are provided for all infiltration BMP components (casing, screen, packing, seals, restrictors, etc.).
	3.6	The design flowrate for each full scale well assumes water depths no greater than the top of the receptor soil.
	3.7	Flow restrictors are used to limit flows into each deep infiltration BMP to the design flowrate.
	3.8	A functional high flow bypass system is used to accommodate flows in excess of design infiltration flowrates.
	3.9	Plans and specifications include protection from construction sediments and system cleaning prior to service.
	3.10	Specifications require a post-construction performance testing plan, testing, and approval by the Port.
	3.11	Deep infiltration BMP designs have been registered with Ecology's UIC Program.
	3.12	Specifications require update of UIC registrations as needed based on as-constructed data prior to activating.
	3.13	Proper deep infiltration system O&M procedures are included in the project's stormwater O&M Plan.
Section 4 – Groundwater Mounding Analyses (<u>Requirement Depends on Test Phase Mounding Observations</u>)		
	4.1	Mounding analysis and results are properly documented and certified.
	4.2	Groundwater model software and version is listed.
	4.3	Aquifer test methods, data, analysis, and results are provided.
	4.4	Sources/assumptions of aquifer properties (Ksat/Transmissivity, porosity, etc.) are identified.
	4.5	Wet-year infiltration hydrographs have been properly derived and documented.
	4.6	Analytical groundwater model has been calibrated to match mounding observed during infiltration tests.
	4.7	Analytical groundwater model has been updated to match the full-scale infiltration system and operation.
	4.8	Mounding modeling results and recommendations for deep infiltration wells are discussed.
	4.9	Groundwater mound does not reach the bottom of deep infiltration BMPs under planned full scale operation.
	4.10	Groundwater mound does not impact adjacent or off-site structures/infrastructure, slopes, etc.
	4.11	Groundwater mound is not predicted to create or increase seeps or springs.

____

Project Manager or Licensed Professional Signature:

____ ____________________

Port Reviewer Signature: Acceptance Date:

Attachment 4
USBR Test Method
7300-89

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UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

USBR 7300-89

PROCEDURE FOR

PERFORMING FIELD PERMEABILITY TESTING BY THE WELL PERMEAMETER METHOD

INTRODUCTION

This procedure is under the jurisdiction of the Geotechnical Services Branch, code D-3760, Research and Laboratory Services Division, Denver Office, Denver, Colorado. The procedure is issued under the fixed designation USBR 7300. The number immediately following the designation indicates the year of acceptance or the year of last revision.

1. Scope

1.1 This designation is used to determine the coefficient of permeability of semipervious and pervious soils. The types of soil for which the test is applicable range from mixtures of sand, silt, and clay with coefficients of permeability greater than 1×10^{-5} cm/s to relatively clean sands or sandy gravels with coefficients of permeability less than 1×10^{-1} cm/s. There is lack of experience with the test in soils with coefficients of permeability outside these limits. The effects of capillarity on permeability test results were not taken into account during development of the theoretical background.

NOTE 1.-This test is similar to the "Shallow Well Pump-in Test for Hydraulic Conductivity" in the ***Drainage Manual*** [1].[1] However, some of the float valves allow greater waterflow from the water reservoir than the carburetor valve of the ***Drainage Manual*** test.

2. Auxiliary Tests

2.1 Soil sampling by USBR 7010 and classificationof soil from different strata by USBR 5005 are required to identify soil stratification and location of any water table.

3. Applicable Documents

3.1 USBR Procedures:
USBR 3900 Standard Definitions of Terms and Symbols Relating to Soil Mechanics
USBR 5005 Determining Unified Soil Classification (Visual Method)
USBR 7010 Performing Disturbed Soil Sampling Using Auger Boring Method
3.2 ASTM Standard:
E 1 ASTM Thermometers

4. Summary of Method

4.1 The method consists of measuring the rate at which water flows out of an uncased well under a constant gravity head. The coefficient of permeability of the soil is calculated using (1) the relatively constant flow rate which is reached after a period of time, (2) the water temperature, (3) the constant height of water in the well, and (4) the radius of the well.

5. Significance and Use

5.1 The method is used to determine the average coefficient of permeability for soil in its natural condition, primarily along proposed canal alignments or at reservoir sites. The permeability results are used in appropriate equations for calculating approximate seepage rates to aid in decisions on lining requirements. Although the test is usually performed in auger holes, it can also be used in test pits.

6. Terminology

6.1 Definitions are in accordance with USBR 3900.

7. Interferences

7.1 Proper use of the test requires soil characteristics which allow excavation of an uncased well of reasonably uniform dimensions with the soil sufficiently undisturbed to allow unrestricted outward flow of water from the hole.

7.2 Test results are adversely affected by using unclean water for the permeant.

7.3 When relatively impervious or highly pervious soil layers are present around the well, this should be considered when evaluating test results.

7.4 For tests during cold weather, a shelter with heat should be used to maintain ground and water temperatures above freezing.

8. Apparatus

8.1 General Apparatus:

8.1.1 Augers.-Hand augers suitable for excavating permeability test holes. Power-driven augers may be used if it is determined that disturbance of soil around the well is no more than for a hand auger.

[1] Number in brackets refers to the reference.

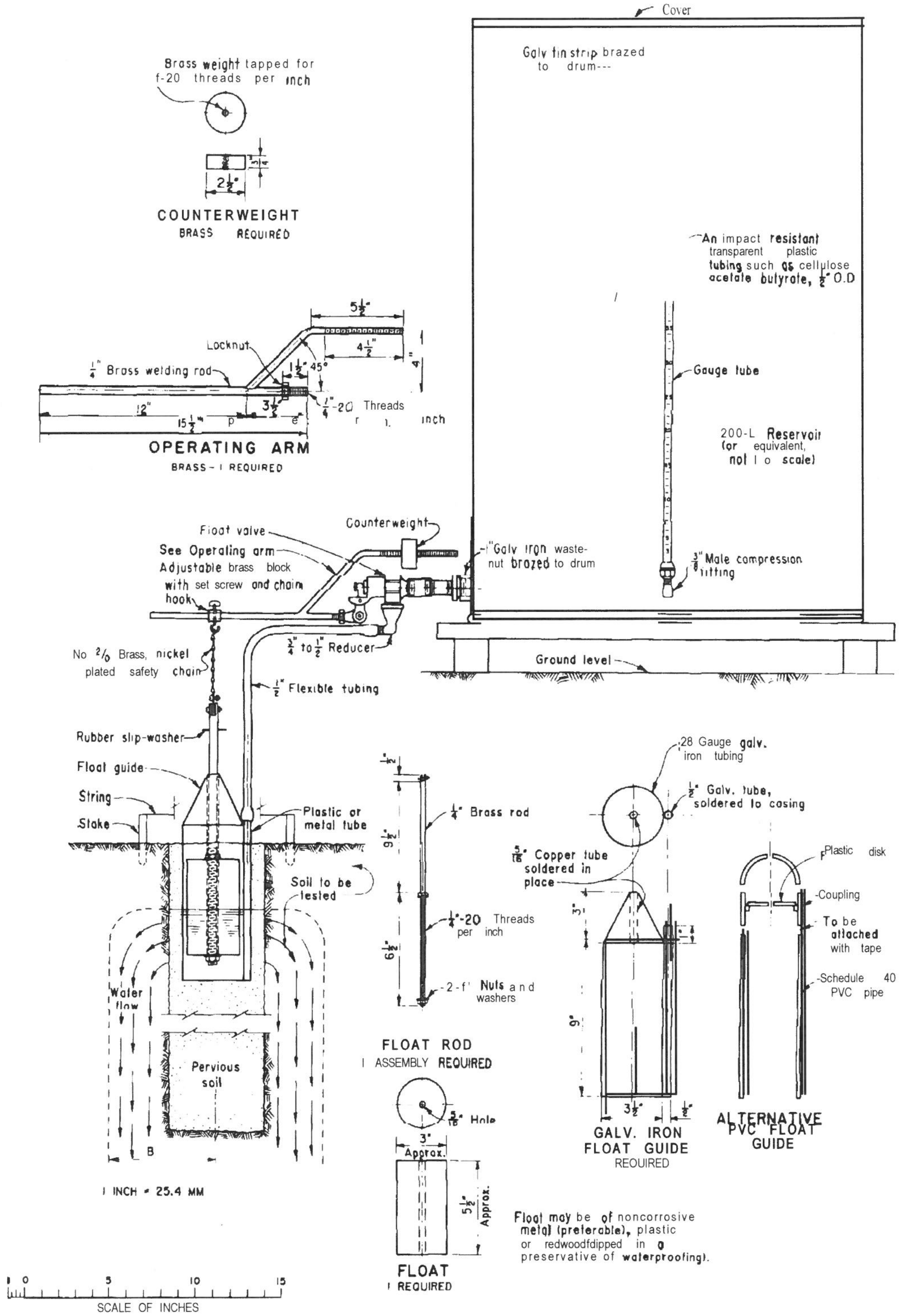

Figure 1. - Drawing of well permeameter test apparatus (101-D-38)

8.1.2 ***Thermometer.-0*** to 50 °C, 0.5 °C divisions, conforming to the requirements of ASTM E 1.

8.1.3 Hammer, surveyors' stakes, and string for depth measurements in the well.

8.2 Equipment Unique to This Procedure (see figs. 1 and 2).

8.2.1 ***Water Reservoir.-A*** clean, covered, watertight reservoir of sufficient capacity which can be conveniently refilled at intervals to provide a continuous supply of water during the test. A 200-liter drum with a volume gauge tube of cellulose acetate butyrate has been found to be suitable for normal usage. Wooden blocking is required to raise the reservoir above the ground level.

8.2.2 K&e.-A float valve with operating arm (see fig. 3 for valve size).

8.2.3 ***Float.-A*** wooden, plastic, or metal float with brass stem.

8.2.4 ***Float Guide.-A*** guide of galvanized iron, PVC (polyvinyl chloride) or other materials to allow the float to move vertically.

8.2.5 ***Counterwe&hts.-Brass*** counterweights for arm of float valve.

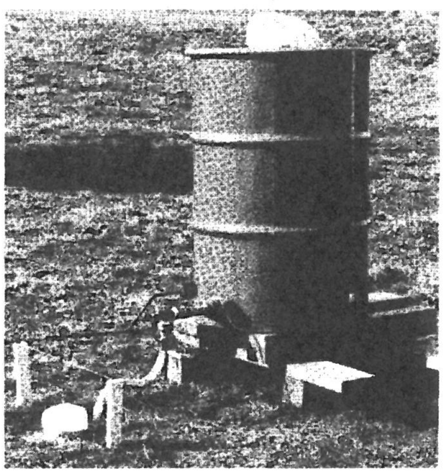

Figure 2. - Typical well permeameter test set-up.

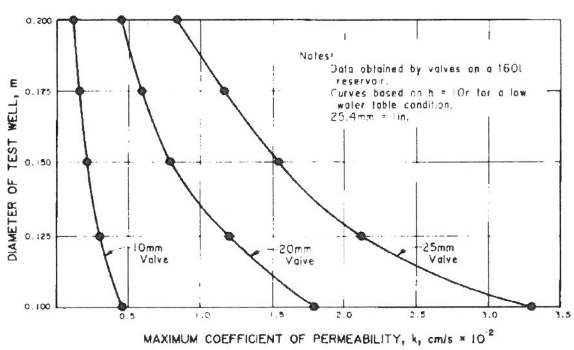

Figure 3. Maximum permeability coefficients measurable with typical float valves commonly used on stock-watering tanks.

NOTE 2.-There may be other appropriate valve-float equipment available for maintaining a constant water level in the test well.

8.2.6 ***Water Truck.-A*** water tank truck or tank trailer of sufficient capacity to provide a continuous supply of clean water for the number of test reservoirs in simultaneous use.

9. Reagents and Materials

9.1 ***Density*** San&Clean, dry, pervious, coarse sand (or fine gravel) calibrated for density and with a coefficient of permeability at least 1 X 10^2 cm/s greater than that of the soil to be tested is to be used for backfilling the test well. A washed sand graded between the U.S.A. Standard series No. 4 to No. 8 sizes (4.75 to 2.36 mm) or gravel graded between the 3/8 to No. 4 (9.5 to 4.75 mm) sizes is recommended. The purpose of the pervious backfill is to (1) distribute water evenly in the well, (2) support the wall of the well and prevent sloughing during saturation of the soil, and (3) provide a means of indirectly determining the average radius of the well. The radius of the well is required for permeability calculations and, as explained later, a standard sand calibrated for mass per unit volume (density) can serve this purpose.

9.2 ***Water.-The*** water for this test is to be clean. Small amounts of suspended soil or other foreign material in the water may become deposited in the soil around the well and may greatly reduce the flow, causing erroneous results. When there is sediment in the water, arrangement should be made to remove the particles by settling or filtration. In some instances, a chemical reaction can take place between water of a particular quality and the soil being tested, which may cause an increase or decrease in soil permeability. Therefore, water similar in quality (exclusive of suspended sediment) to that expected to permeate the soil during project operation should be used for the permeability test.

10. Precautions

10.1 ***SafetyPrecautions.-*** Normal precautions taken for any fieldwork.

10.2 ***Technical Precautions:***

10.2.1 In windy areas, protection from blowing soil may be needed to prevent interference to the operation of the valve-float mechanism and to prevent infiltration of soil into the top of the well.

10.2.2 Test equipment must be protected from disturbance by animals, moving equipment, children, or other sources.

11. Calibration

11.1 ***Water Reservoir*** (fig. 1).-Calibrate the volume of the water reservoir and mark the gauge tube in convenient increments for volume readings. For a 200-L reservoir, mark the volume gauge tube at 5-L intervals with the largest volume reading near the top of the tube so volume readings will decrease downward and permit volume determination by subtracting figures.

NOTE 3.-For a volume tube of cellulose acetate butyrate (which is recommended because it is durable for use under field conditions), ink with an acetate base makes a permanent mark on the tube. India ink can be used for marking if the surface of the plastic is first roughened with emery cloth or steel wool; the tube then should be coated with clear lacquer to preserve the ink marks.

11.2 *Density* San&Calibrate the sand by finding the density obtained by pouring the sand into a pipe or cylinder with dimensions approximately those of the test well. The pouring height above the top of the pipe should be approximately the same as that for the well. The calibrated density of sand is calculated from the mass of sand used to fill the pipe and the volume of pipe occupied by the sand; i.e., density equals mass per volume.

12. Conditioning

12.1 Special conditioning requirements are not needed for this procedure.

13. Procedure

13.1 *Soil* Logs.-Prior to performing field permeability tests for a seepage investigation, exploratory borings should be made at appropriate intervals and logs of the borings should be prepared to show a representative soil profile. Soil classifications of the different strata encountered should be recorded. The form shown in figure 4 can be used for this purpose.

The minimum depth of borings below a proposed canal invert or reservoir bottom should be to the ground-water table, to an impervious soil layer, or to a depth about twice the design water depth, whichever is reached first (see fig. 8). The location of soil layers that appear to be impervious and the depth to a water table, if reached, will affect permeability and seepage calculations. For depths below a canal invert or reservoir bottom greater than twice the water depth, the presence of a water table or soil layers of significantly different permeability than that of overlying soil will not influence permeability test results.

13.2 *Size of Test* We&For a low water table condition (see condition I, fig. 8), the depth of the well may be of any desired dimension provided the ratio of water height h in the well to well radius is greater than 1. To fulfill theoretical considerations in development of the equations for high water table conditions (conditions II and III, fig. 8), the ratio of water height h in the well to well radius should be greater than 10. A practical well diameter is usually 150 mm. Normally, in a canal seepage investigation, the water surface elevation in the well and the well bottom should correspond to the elevations of the proposed canal water surface and canal bottom, respectively. Test results would then provide an average permeability for the soils in the canal prism. For pervious soils, well size is limited by the capacity of the equipment to maintain a continuous supply of water at the desired constant head level. If necessary, more than one reservoir can be interconnected to increase water capacity. Figure 3 shows the maximum coefficients of permeability that can be measured in wells of various diameters using float valves of different sizes. This is of assistance in selecting the valve size to be used, although a valve of approximately 20-mm size is often used for general purposes.

13.3 ***Soil Permeability in Test Pits.-The*** well permeameter test method also can be adapted for use in test pits in a low water table condition if the ratio of water depth to pit radius is greater than 1, and sand or gravel backfill is used to prevent soil in the sides of the pit from sloughing. In this case, calibration of backfill is not necessary since dimensions of a test pit of regular shape can be found by averaging linear measurements. If a rectangular pit is used, the effective cylindrical radius for use in permeability calculations can be determined from the pit dimensions (see fig. 5).

13.4 ***Excavation of the Test*** *Well.*-Wells for permeability tests should be prepared carefully to cause as little disturbance to surrounding soil as possible. Where moisture content of the soil is high, the wall of the hole can become smeared and outward flow of water restricted. In this case, the well should be excavated using two hand augers, one having a diameter at least 25 mm smaller than the other. First, auger a pilot hole with the smaller auger and follow this with the larger auger. This causes less disturbance to the wall of the well than if a single auger is used. If it is still apparent that the wall of the well is smeared, the walls should be scraped or scratched with improvised tools to remove the smeared surface. Remove any loose soil from the bottom of the well.

13.5 *Depth* of *the Well* (figs. 1 and 4).-Depth measurements in the well should be measured (and recorded) from a common base line. A convenient method is to measure from a horizontal string line stretched between two stakes driven firmly into the ground on opposite sides of the well (fig. 1). When the bottom of the well extends below ground-water level, insert a casing during excavation to prevent the wall from caving. Carefully pull the casing as the well is backfilled with sand through the casing.

NOTE 4.-For a very high ground-water condition, a "pump out" test for saturated soils is often more satisfactory than the well permeameter test or other "'pump in" types of tests.

13.6 Backfilling the Test Well.-Pour calibrated sand into the well in the same manner as during calibration of the sand for density. The top of the sand should be about 150 mm below the water level to be maintained. After completion of pouring, determine the remaining mass of sand and subtract from the original mass to find the mass of sand in the well. Measure and record the depth to the top of the sand and calculate the height of sand in the well. From the density of the calibrated sand and the mass and height of sand in the well, calculate the

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WELL PERMEAMETER METHOD (SOIL CLASSIFICATIONS AND WELL DIMENSIONS)

Designation USBR 7300-89

TEST NO. 22	PROJECT Example	FEATURE Example
TEST LOCATION Station 257+94	TEST LIMITS: STATION 257+25	TO STATION 258+62
GROUND ELEVATION 122.6	CANAL DATA: SIDE SLOPES 2:1, BOTTOM WIDTH 7.9 m	WATER DEPTH 1.890 m
TESTED BY / DATE	COMPUTED BY / DATE	CHECKED BY / DATE

OBSERVATION HOLE

[X] m [ ] ft

STRATA DEPTH FROM	TO	SOIL CLASSIFICATION
0	0.45	SILTY CLAY: approx. 85% fines with medium plasticity, slow dilatancy, medium dry strength, medium toughness; approx. 15% fine sand; maximum size, fine sand, moist, dark gray; easy to auger; some roots present; no reaction with HCl (CL-ML).
0.45	1.77	CLAYEY SILT: approx. 95% fines with low plasticity, slow dilalancy, low dry strength, low toughness; approx. 5% fine sand; maximum size, fine sand; wet, brown; easy to auger; no reaction with HCl (ML-CL).
1.77	3.87	SILTY SAND: approx. 60% fine to coarse, hard, angular sand; approx. 20% non-plastic fines; approx. 20% predominantly fine, hard, angular to subangular gravel; maximum size, 30mm; moist, brown; moderately hard to auger; slight reaction to HCl (SM).

(1) DEPTH TO WATER TABLE (FROM GROUND SURFACE)	3.75	[X] m [ ] ft

WELL DIMENSIONS (DEPTHS FROM STRING BASELINE)

(2) DEPTH TO GROUND SURFACE	0.213	m [ ] ft
(3) DEPTH TO BOTTOM OF WELL	1.222	[ ] ft
(4) DEPTH TO TOP OF SAND	0.375	[X] m [ ] ft
(5) HEIGHT OF SAND (3) - (4)	0.847	[X] m [ ] ft
(6) DEPTH TO WATER SURFACE IN WELL	0.280	[X] m [ ] ft
(7) HEIGHT OF WATER IN WELL h = (3) - (6)	[illegible]	[ ] ft

DETERMINATION OF WELL RADIUS

(8) DENSITY OF STANDARD SAND	1400	[ ] Kg/m³ [ ] lbm/ft³
(9) MASS OF SAND + CONTAINER BEFORE FILLING WELL	34.02	[ ] kg [ ] lbm
(10) MASS OF SAND + CONTAINER AFTER FILLING WELL	2.86	[ ] kg [ ] lbm
(11) MASS OF SAND USED (9) - (10)	31.16	[ ] kg [ ] lbm
(12) VOLUME OF WELL (11)/(8)	0.0223	[ ] ft³
(13) RADIUS OF WELL $r = \sqrt{(12)/(5)\pi}$	0.092	[X] m [ ] ft

Figure 4. - Well permeameter method (soil classifications and well dimensions) — example

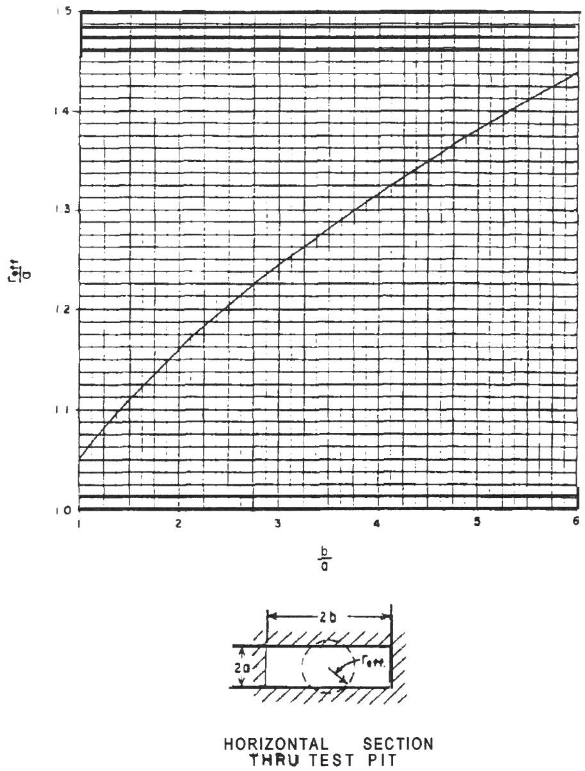

Figure 5. Effective cylindrical radius of rectangular test pits. (fig. 44 of ref. 2)

equivalent radius of the well (fig. 4). Development of the equation for determining the radius is:

$$V_s = \pi r_w^2 h_s = \frac{m_s}{\rho_s}$$

$$r_w^2 = \frac{V_s}{\pi h_s}$$

$$r_w = \sqrt{\frac{m_s}{\pi h_s \rho_s}} \tag{1}$$

where:

V_s = volume of sand
ρ_s = density of sand
h_s = height of sand
m_s = mass of sand
r_w = equivalent radius of well

13.7 ***Test Equipment Set*** Up.-Place the float guide, with the float inside, on top of the sand in the well. Hold the float guide in place vertically and pour sand around it. When a test is to be conducted with the water level more than an arm's length below the ground surface, lower the float guide by the chain and drop sand around the guide to hold it in place during the test. The rubber slip washer on the float stem is to prevent particles of sand from becoming lodged between the float stem and the float guide. The mass of sand around the guide need not be known because it is not used in computations for well radius. Set up the water reservoir and valve-float arrangement with the flexible tube from the float valve to well and the chain attached to the float stem as shown on figures 1 and 2. The reservoir should be set on a firm platform or cribbing at a convenient height.

13.8 Performing the Test:

13.8.1 Open the valve on the reservoir and gradually fill the well with water.

13.8.2 After the water enters the float casing, readjust the counterbalance on the operating arm of the valve and the chain length as necessary to maintain the desired water level in the well.

13.8.3 After the water level in the well has stabilized, begin reading the volume gauge on the reservoir and record the gauge readings at convenient time intervals using the form as shown on figure 6. The well must be kept continuously full of water until the test is completed. In general, dry soil at the start of the test absorbs water at a comparatively high rate. However, as the moisture content of the soil increases around the well, the rate generally decreases and usually stabilizes. It is this constant rate after stabilization that is used to compute permeability.

13.8.4 As records of water discharge from the reservoir and time are made, plot a curve of accumulative flow versus time as shown on figure 7.

14. Test Duration

14.1 Minimum duration for the test is the theoretical time required to discharge the minimim volume of water into the soil to form a saturated envelope of hemispherical shape with a radius ***B*** *(see* fig. 1).

The minimum volume of water is determined by the equation:

$$V_{min} = 2.09\, S \left\{ h \sqrt{\frac{2}{\ln\left[\frac{h}{r} + \sqrt{\left(\frac{h}{r}\right)^2 + 1}\right] - 1}} \right\}^3 \tag{2}$$

where:

V_{min} = minimum volume
S = specific yield of the soil
h = height of water in well
r = well radius

NOTE 5.-The quantity in brackets is the theoretical determination for radius B (fig. 1).

For soils in which this test would most likely be used, the specific yield varies from about 0.1 for fine-grained soils to 0.35 for coarse-grained soils. When the specific yield of the soil is unknown, the value of 0.35 should be used to give a conservative value for minimum volume and to ensure that the test duration is sufficient. Thus,

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Bureau of Reclamation

WELL PERMEAMETER METHOD (TIME AND VOLUME MEASUREMENTS)

Designation USBR 7300 - 89

TEST NO. 22	PROJECT Example	FEATURE Example
TEST LOCATION 257+94	WATER SOURCE Youngfield River	GROUND TEMPERATURE 20° C
TESTED BY / DATE	COMPUTED BY / DATE	CHECKED BY / DATE

WATER VOLUME ☒ L ☐ ft³

TIME		WATER VOLUME						WATER TEMPERATURE °C	
CLOCK (24hr.)	ACCUM. (min.)	DRUM NO. 3		DRUM NO. 4		TOTAL DIFFERENCE	ACCUM. FLOW (q)		
		READ	DIFFERENCE	READ	DIFFERENCE			WELL	RESERVOIR
8:00	0	201	--	204	--	---	---	--	--
8:50	50	127	74	124	80	154	154	19	25
9'40	100	80	47	74	50	97	251	19	--
10:30	150	42	36	34	40	76	329	19	--
11:20	200	8	34	1	33	67	396	20	26
11:30	210	202	--	201	--	--	---	--	--
12:10	250	179	23	179	22	45	441	20	--
13:00	300	153	26	153	26	52	493	21	--
13:50	350	124	29	125	28	57	550	21	27
14:40	400	97	27	98	27	54	604	22	--
15'30	450	71	26	70	28	54	658	22	--
16:20	500	46	25	44	26	51	709	21	--
17:10	550	19	27	19	25	52	761	20	--
17:20	560	204	--	202	—	--	---	--	--
18:00	600	181	23	181	21	44	805	20	27
18:50	650	154	27	154	27	54	859	20	--
19'40	700	127	27	127	27	54	913	19	--
20'30	750	100	27	99	28	55	960	19	--
21'20	800	74	26	73	26	52	1020	18	25
23:00	900	35	39	33	40	79	1099	17	--
24'40	1000	5	30	3	30	60	1159	15	--

Figure 6. Well permeameter method (time and volume measurements) — example.

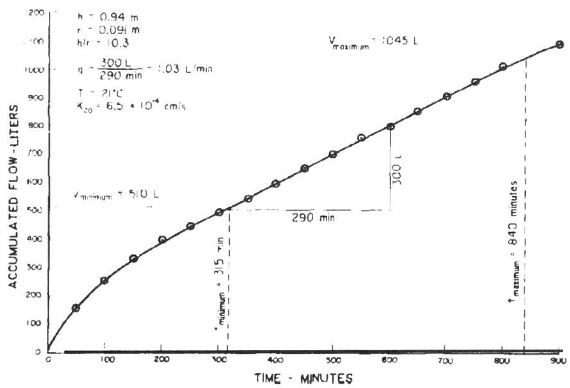

Figure 7. - Time-discharge curve for well permeameter test — low water table example.

with a known or assumed specific yield for the soil and with the dimensions of the well, the minimum volume can be computed and the test discontinued when the minimum volume has been discharged through the well. In pervious soils, it may appear that the volume-time curve has reached a uniform slope after several hours when points are plotted over short time intervals. However, in order to avoid discontinuing a test prematurely, it must be continued for at least 6 hours from the starting time so the slope can be determined over a period of 2 to 3 hours. The first straight portion of the curve should be used for determining the rate of discharge (fig. 7). The test must be conducted continuously without allowing the reservoir to run dry until the test has been completed.

14.2 Maximum Time.-If the test is continued for a long period, a water mound may build up around the well and render the test results inaccurate. The maximum time for test duration is the time necessary to discharge through the test well the maximum volume of water as determined using equation (2), substituting 15.0 for 2.09 and in this case, using an assumed minimum value (when the true value is unknown) of 0.1 for specific yield.

$$V_{max} = 2.05\ V_{min} \tag{3}$$

15. Calculations

15.1 Computing Coefficient of Permeability.-Equations (4), (5), or (6) are provided for calculating coefficient of permeability, for the well permeameter test. The presence or absence of a water table or impervious soil layer within a distance of less than three times that of the water depth in the well (measured from the water surface) will enable the water table to be classified as condition I, II, or III, as illustrated on figure 8.

15.1.1 *Low Water* Table.-When the distance from the water surface in the test well to the ground-water table, or to an impervious soil layer which is considered for test purposes to be equivalent to a water table, is greater than three times the depth of water in the well, a low water table condition exists as illustrated by condition I (fig. 8). For determination of the coefficient of permeability under such a condition, equation (4) given in subparagraph 15.2 should be used.

15.1.2 High Water Table.-When the distance from the water surface in the test well to the ground-water table, or to an impervious layer, is less than three times the depth of water in the well, a high water table condition exists as illustrated by condition II or III. Condition II shows a high water table with the water table below the well bottom, and for this condition equation (5) should be used. Condition III shows a high water table with the water table above the well bottom. For this condition, equation (6) should be used.

15.2 Equations:

Condition I:

$$k_{20} = \frac{qV}{2\pi h^2}\left\{ \ln\left[\frac{h}{r} + \sqrt{\left(\frac{h}{r}\right)^2 + 1}\right] - \frac{\sqrt{1 + \left(\frac{h}{r}\right)^2}}{\frac{h}{r}} + \frac{1}{\frac{h}{r}} \right\} \tag{4}$$

Condition II:

$$k_{20} = \frac{qV}{2\pi h^2}\left[\frac{\ln\left(\frac{h}{r}\right)}{\frac{1}{6} + \frac{1}{3}\left(\frac{h}{T_u}\right)^{-1}}\right] \tag{5}$$

Condition III:

$$k_{20} = \frac{qV}{2\pi h^2}\left[\frac{\ln\left(\frac{h}{r}\right)}{\left(\frac{h}{T_u}\right)^{-1} + \frac{1}{2}\left(\frac{h}{T_u}\right)^{-2}}\right] \tag{6}$$

where:

k_{20} = coefficient of permeability at 20 °C
h = height of water in the well
r = radius of well
y = discharge rate of water from the well for steady-state condition (determined experimentally, see example, fig. 7)
$V = \frac{\mu_T,\ \text{viscosity of water at temp. } T \text{ (see fig. 9)}}{\mu_{20},\ \text{viscosity of water at 20 °C}}$
T_u = unsaturated distance between the water surface in the well and the water table

15.3 The preferred metric unit for coefficient of permeability is cm/s (centimeters per second). The value of 1 X 10^{-6} centimeters per second is approximately the same as the inch-pound unit of 1 foot per year.

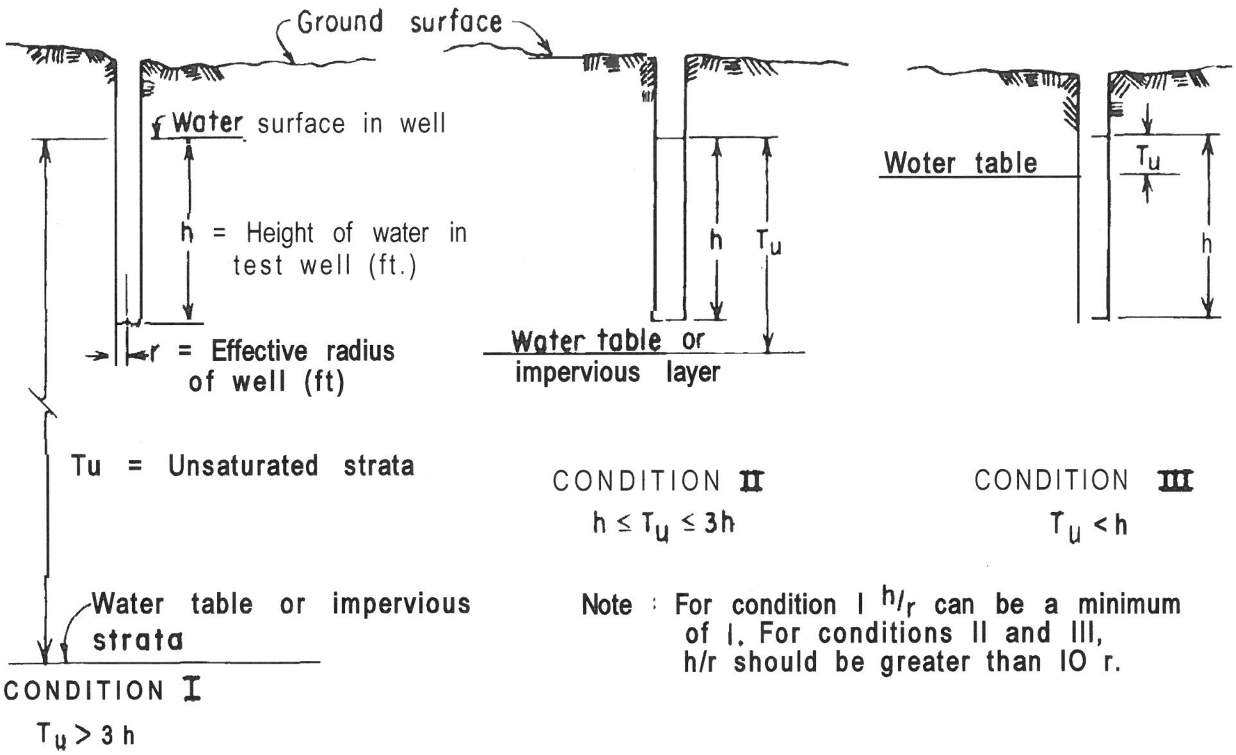

Figure 8. Relationship between depth of water in test well and distance to water table in well permeameter test.

16. Report

16.1 The report is to consist of the following completed and checked forms:

"Well Permeameter Method (Soil Classifications and Well Dimensions)" (fig. 4).

"Well Permeameter Method (Time and Volume Measurements)" (fig. 6).

Time-Discharge Curve (example on fig. 7).

Calculation of coefficient of permeability from equations (4), (5), or (6).

16.2 All calculations are to show a checkmark and all plotting must be checked.

17. References

[1] ***Drainage Manual,*** 1st ed., Bureau of Reclamation, U.S. Government Printing Office, Washington, D.C., 1984.

[2] Zanger, Carl ***Z., Theory and Problems of Water Percolation,*** Engineering Monograph No. 8, (app. B "Flow from a Test Hole Located Above Groundwater Level," development by R. E. Glover) Bureau of Reclamation, Denver, Colorado, April 1953.

[3] Ribbens, R. W. "Exact Solution for Flow From a Test Hole Located Above the Water Table," (unpublished technical memorandum), Bureau of Reclamation, Denver, Colorado, 1981.

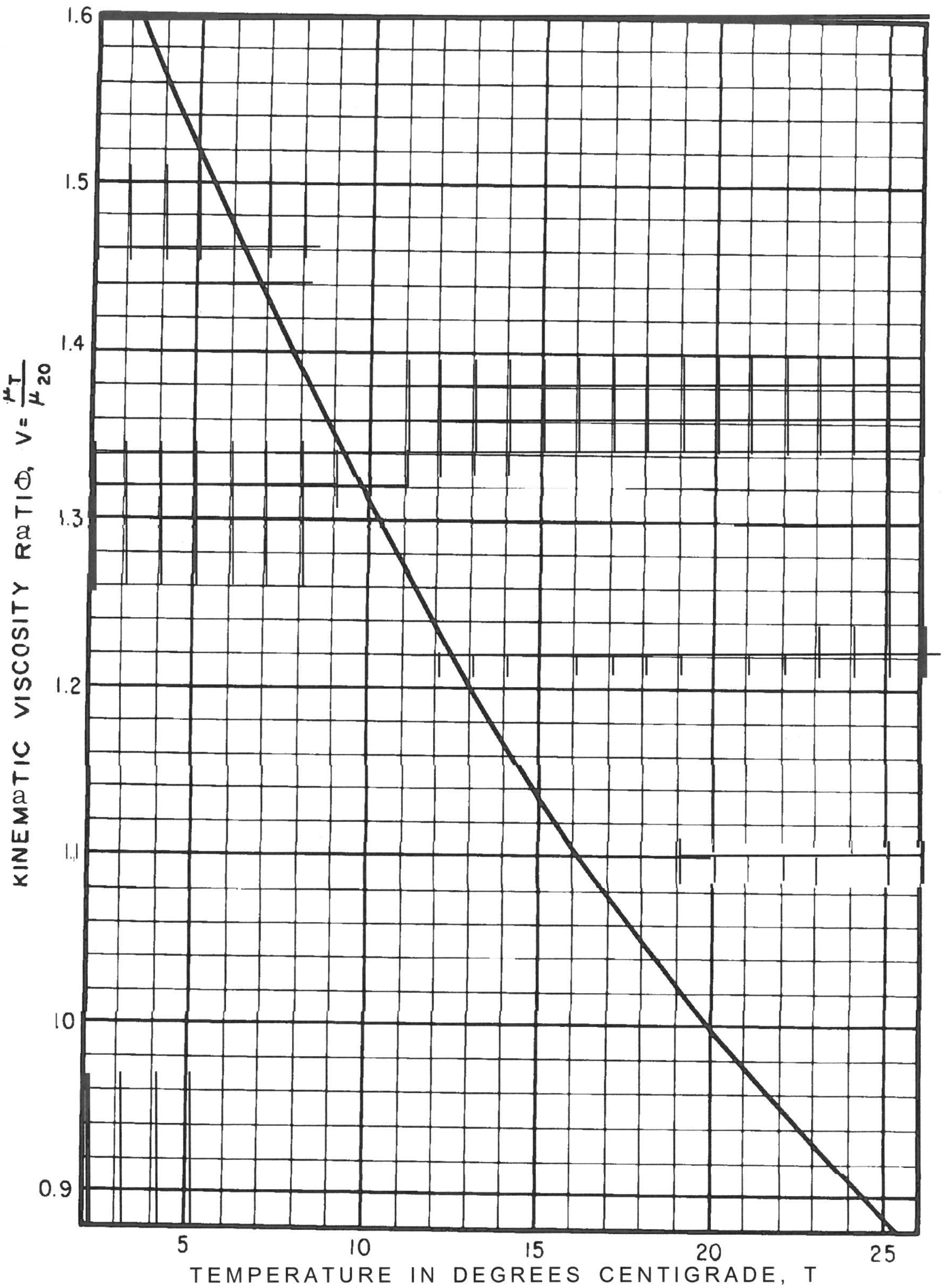

Figure 9. – Relationship between kinematic viscosity ratio of water and temperature