



Geoscience
P.O. Box 96
Norwell, MA 02061

July 20, 2021

Hanson Conservation Commission
Hanson Town Hall
542 Liberty St.
Hanson, MA 02341
ATTN: Dr. Frank Schellenger, Agent

RE: Infiltration Analysis -Proposed Fern Hill Sub-Division, Hanson MA

Dear Dr. Schellenger:

The purpose of this letter is to present stormwater infiltration analysis results for the proposed stormwater system at the proposed Fern Hill Sub-division in Hanson. The purpose of this analysis is to assess the 72-hour drain time requirements in the DEP Stormwater Guidelines. The 72-hour drain time has been calculated here using the volume for Basin 1P and 2P of 16,000 cubic feet (cf) and 1739 cf respectively which is believed to be above the Required Recharge Volume required by the Guidelines.

The infiltration analysis was performed using the program MODRET which was specifically developed to evaluate infiltration of stormwater run-off to retention basins. This computer program allows local geologic/hydrogeologic sub surface conditions, combined with the basin geometry and specified water volumes to be entered into a pre-processor. The data is then incorporated into the United State Geological Survey (USGS) finite difference numerical groundwater flow model MODFLOW that can account for instantaneous changes in groundwater gradients in saturated/unsaturated conditions. MODFLOW is the USGS's modular hydrologic model and is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. Selected documentation of the MODRET model is provided in the Appendix containing the mounding information.

For this analysis after entering the geologic/hydrogeologic information and basin elevations and characteristics the pollution abatement recovery analysis, module was run. This module specifies the total runoff volume and the corresponding total recovery period. For Basin 1P this was specified as 16,000 cf with a recovery period of 72-hours and for Basin 2P as 1739 cf for 12-hours. MODRET will subtract the unsaturated infiltration volume from the total runoff volume, recharge the pond with the remaining volume in a period of 1 hour and then divide the remaining time of recovery into 8 equal time increments.

Water Table

Maximum groundwater elevation or the most conservative water table was established by a Certified Soil Evaluator was reported in the test pit logs. For Basin 1P that elevation is 76.9 feet MSL and for Basin 12P 82.3 feet MSL.

Hydraulic Conductivity

Two soil samples were collected from each basin at a depth of 3 and 8 feet. The samples were submitted to Briggs Engineering and testing for grain size analysis.

Using the grain size results the excel spreadsheet HydroGeoSieveXL was used to classify these samples, determine total porosity and d_{10} to d_{60} values and evaluate hydraulic conductivity.

The samples were classified as poorly sorted sand with low or with fines. HydroGeoSieveXL has a number of hydraulic conductivity solvers. Based on the d_{10} value (less than 0.01 centimeters) of these samples only the Shepard (1989) method was determined to be applicable to these soil conditions where the d_{50} value was between 0.0063 and 2 millimeters.

Grain size indicates that the hydraulic conductivity in Basin 1P is between 17.85 and 31.43 feet/day. The hydraulic conductivity in Basin 2P is between 17.20 and 20.47 feet/day.

For this analysis the lower hydraulic conductivity value was used. Vertical hydraulic conductivity was assumed to be one-tenth the horizontal conductivity. Which is an industry norm.

Vertical and horizontal hydraulic conductivity values of 1.75 and 17.5 feet/day respectively were used for Basin 1P. In the Basin 2P analysis vertical and horizontal conductivity were 1.72a and 17.22 feet/day.

The documentation for HydroSieveXL and the 1989 Shepard paper are attached in the grain size attachment.

Aquifer Depth

Aquifer depth was assigned a depth of twenty feet based on borings from a previous proposed project on the site the Boring logs are also attached.

Fillable Porosity

The HydroSieveXL analysis of the grain size distribution indicate a porosity of 0.26 for all four samples. The fillable porosity or effective storage coefficient was calculated to be 75 percent of this value or 0.20. This value is similar to specific yield which has a range of 0.1 to 0.3 for these types of soils.

This data was into MODRET for analysis of the 2, 10 and 100-year storm event.

Basin 1P

The bottom of the infiltration system is 78.9 feet MSL and will fill to 81.1 feet with a capacity of 16,000 cf. When 16,000 cf of stormwater is added almost instantaneously to the basin 2,654.40 cf will fill the unsaturated zone the remaining 13,345.60 cf will infiltrate into saturated conditions. The basin will fill to its maximum elevation for this event of 80.63 feet MSL (approximately 2 feet above the basin bottom) at approximately 6.5 hours. The basin will drain to the 78.9 in approximately 60 hours. Meeting the 72-hour DEP drain requirement. The analysis is reported in tabular and graphical form in the mounding analysis attachment.

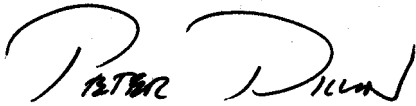
Basin 2P

The bottom of the infiltration system is 84.30 feet MSL and will fill to 85.1 feet with a capacity of 1,739 cf. When 1,739 cf of stormwater is added almost instantaneously to the basin 706.40 cf will fill the unsaturated zone the remaining 1,032.60 cf will infiltrate into saturated conditions. The basin will fill to its maximum elevation for this event of 84.63 feet MSL (0.33 feet above basin bottom) at approximately 6.5 hours. The basin will drain to the 84.30 in approximately 12 hours. Meeting the 72-hour DEP drain requirement. The analysis is reported in tabular and graphical form in the mounding analysis attachment.

It should be noted that this analysis was performed by loading on a maximum flat (0 hydraulic gradient) water table and should therefore be considered conservative. A lower water table and a hydraulic gradient will have a significant effect on decreasing mound height and drain time.

Please contact me if there are any questions regarding this report. I can be reached by phone at (781) 424-5939 or by email at pmdillon143@gmail.com.

Sincerely,

A handwritten signature in black ink, appearing to read "Peter Dillon".

Peter Dillon P.G.
Hydrogeologist

A handwritten signature in black ink, appearing to read "Jeff Hassett".

Jeff Hassett P.E.

Attachments

Grain Size Analysis



Briggs Engineering & Testing

A DIVISION OF PK ASSOCIATES, INC.

July 9, 2021

Morse Engineering
3 Garden Road
Scituate, MA 02066-2212

Attn: Mr. Gregory Morse

Title V Soil Analysis

Address: Hanson Subdivision 1P3'
Briggs # 24975
Tested: 07/09/21

1.	Lab Ref. No.	Description	Source
	M-32743	- #10 Fraction	Hanson Subdivision 1P3'

2. Particle Size Analysis {ASTM D 6913/D 6913M and D 7928}:

Sieve Size		Results
Standard	Alternate	{% Passing by Wt.}
2.0 mm	#10	100
0.850 mm	#20	88
0.425 mm	#40	70
0.180 mm	#80	48
0.150 mm	#100	43
0.053 mm	#270	29
0.0342 mm		27
0.0220 mm		23
0.0129 mm		18
0.0093 mm		15
0.0066 mm		14
0.0032 mm		14
0.0014 mm		12

D10 = 0.0008 mm (extrapolated)

3. The above analysis was performed in accordance with D.E.P. policy# BRP/DWM/PeP-001-1, Appendix 2.

Respectfully Submitted,

BRIGGS ENGINEERING & TESTING
A Division of PK Associates, Inc.

Sean Skorohod
Director of Testing Services
Construction Technology Division

enclosures: graph

www.briggsengineering.com

100 Weymouth Street - Unit C-2
Rockland, MA 02370
Phone (781) 871-6040 • Fax (781) 871-4340

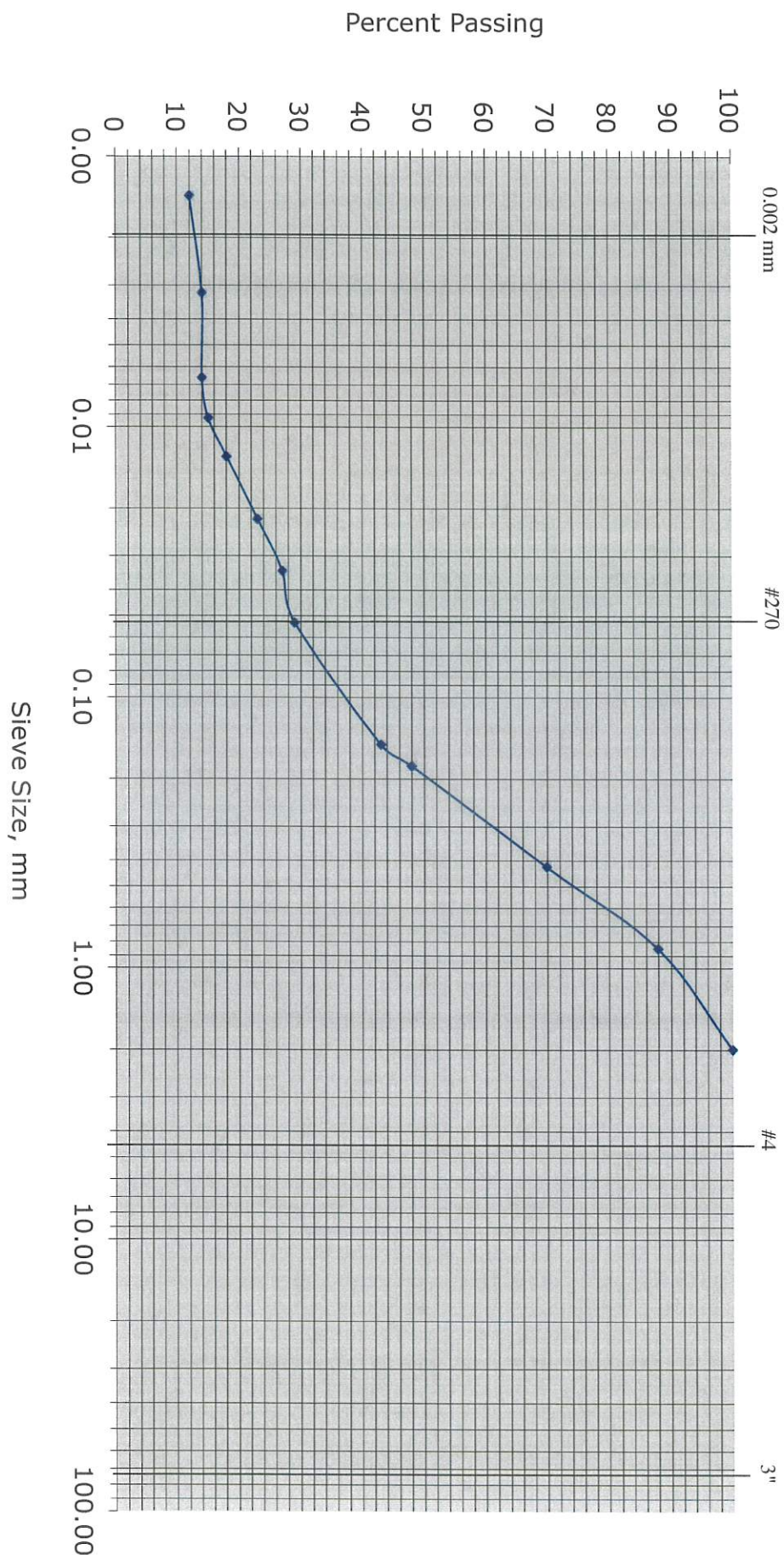
100 Pound Road
Cumberland, RI 02864
Phone (401) 658-2990 • Fax (401) 658-2977



Briggs Engineering & Testing
A Division of PK Associates, Inc.

Project:	Hanson Subdivision 1P3'
Date Tested:	7/9/21
Lab Ref. No.:	M-32743

Particle Size Analysis



Note: The illustrated graph represents the sand fraction only as defined by D.E.P. policy# BRP/DWM/PeP-P00-1, Appendix 2.



Grain Size Analysis Report

Date:

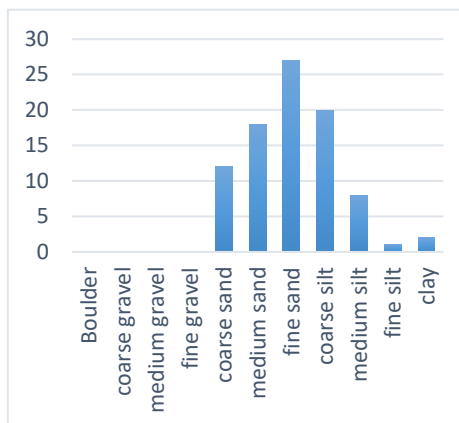
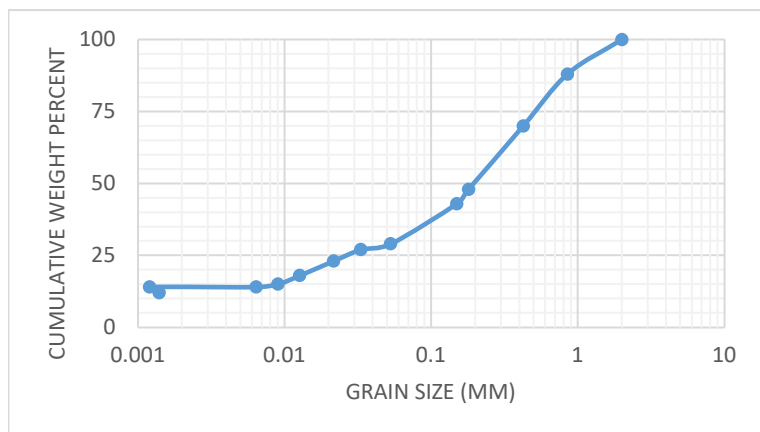
7/12/2021

Sample Name: Basin 1P 3 feet down

Mass Sample (g): 100

T (oC) 20

Poorly sorted sand low in fines



Sieve opening (ps) di (mm)	Mass of retained (mr) (g)	mass fraction (mf)	Percent Passing (pp)
2	0	0	100
0.85	12	0.12	88
0.425	18	0.18	70
0.18	22	0.22	48
0.15	5	0.05	43
0.053	14	0.14	29
0.0332	2	0.02	27
0.0216	4	0.04	23
0.0127	5	0.05	18
0.009	3	0.03	15
0.0064	1	0.01	14
0.0012	0	0	14
0.0014	2	0.02	12

Effective Grain Diameters (mm)		Other Useful Parameters	
d10	0.001	Uniformity Coef.	284.12
d17	0.011	n computed	0.26
d20	0.016	g (cm/s ²)	980.00
d50	0.195	ρ (g/cm ³)	0.9981
d60	0.284	μ (g/cm s)	0.0098
de (Kruger)	0.000	ρg/μ (1/cm s)	9.9327E+04
de (Kozeny)	0.000	tau (Sauerbrei)	1.053
de (Zunker)	0.000	d _{geometric mean}	0.223
de (Zamarin)	0.000	σ _ψ	3.233
lo (Alyameni)	-0.047		
mm		0 % in sample	
>64		Boulder	
16 - 64		coarse gravel	
8 - 16		medium gravel	
2 - 8		fine gravel	0
0.5 - 2		coarse sand	12
0.25 - 0.5		medium sand	18
0.063 - 0.25		fine sand	27
0.016 - 0.063		coarse silt	20
0.008 - 0.016		medium silt	8
0.002 - 0.008		fine silt	1
<0.002		clay	2



K from Grain Size Analysis Report

Date: 7/16/2021

Sample Name: 1P 3 feet down

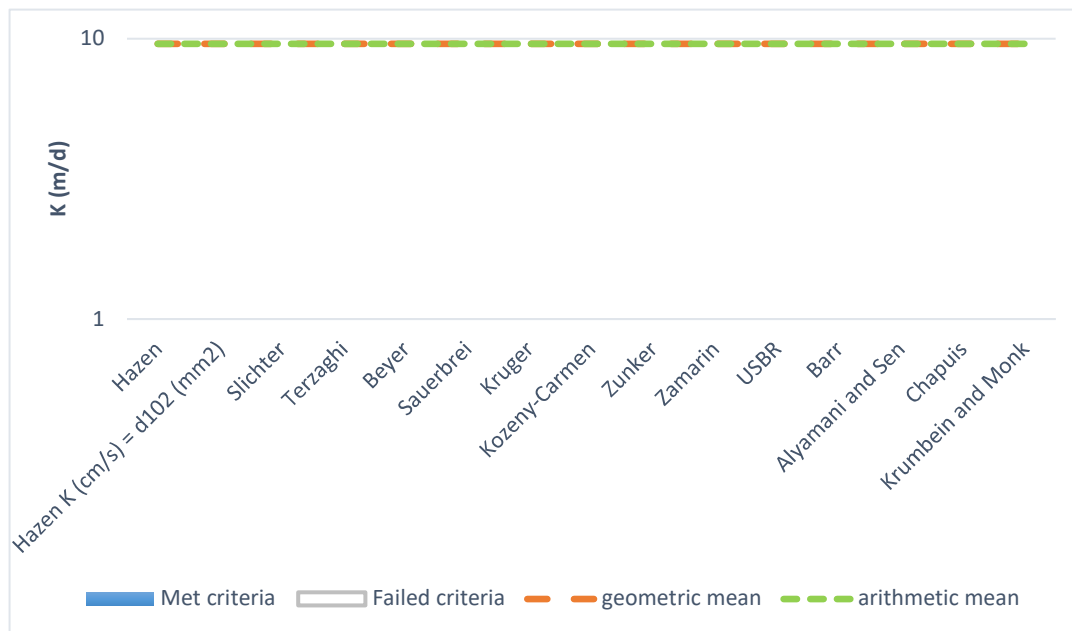
Mass Sample (g):

100

T (oC)

20

Poorly sorted sand low in fines



Estimation of Hydraulic Conductivity	cm/s	m/s	m/d	de
Hazen		.000E+00	0.00	
Hazen K (cm/s) = d_{10} (mm)		.000E+00	0.00	
Slichter		.000E+00	0.00	
Terzaghi		.000E+00	0.00	
Beyer		.000E+00	0.00	
Sauerbrei		.000E+00	0.00	
Kruger		.000E+00	0.00	
Kozeny-Carmen		.000E+00	0.00	
Zunker		.000E+00	0.00	
Zamarin		.000E+00	0.00	
USBR		.000E+00	0.00	
Barr		.000E+00	0.00	
Alyamani and Sen		.000E+00	0.00	
Chapuis		.000E+00	0.00	
Krumbein and Monk		.000E+00	0.00	
Shepherd	.111E-01	.111E-03	9.58	
geometric mean	.111E-01	.111E-03	9.58	
arithmetic mean	.111E-01	.111E-03	9.58	

9.58 m/d = 31.43 ft/day



Briggs Engineering & Testing

A DIVISION OF PK ASSOCIATES, INC.

July 9, 2021

Morse Engineering
3 Garden Road
Scituate, MA 02066-2212
Attn: Mr. Gregory Morse

Title V Soil Analysis

Address: Hanson Subdivision 1P8'
Briggs # 24975
Tested: 07/09/21

1.	Lab Ref. No.	Description	Source
	M-32745	- #10 Fraction	Hanson Subdivision 1P8'

2. Particle Size Analysis {ASTM D 6913/D 6913M and D 7928}:

Sieve Size		Results
Standard	Alternate	{% Passing by Wt.}
2.0 mm	#10	100
0.850 mm	#20	87
0.425 mm	#40	73
0.180 mm	#80	56
0.150 mm	#100	52
0.053 mm	#270	35
0.0336 mm		32
0.0215 mm		29
0.0127 mm		23
0.0091 mm		21
0.0065 mm		18
0.0032 mm		14
0.0014 mm		10

D10 = 0.0014 mm

3. The above analysis was performed in accordance with D.E.P. policy# BRP/DWM/PeP-001-1, Appendix 2.

Respectfully Submitted,

BRIGGS ENGINEERING & TESTING
A Division of PK Associates, Inc.

Sean Skorohod
Director of Testing Services
Construction Technology Division

enclosures: graph

www.briggsengineering.com

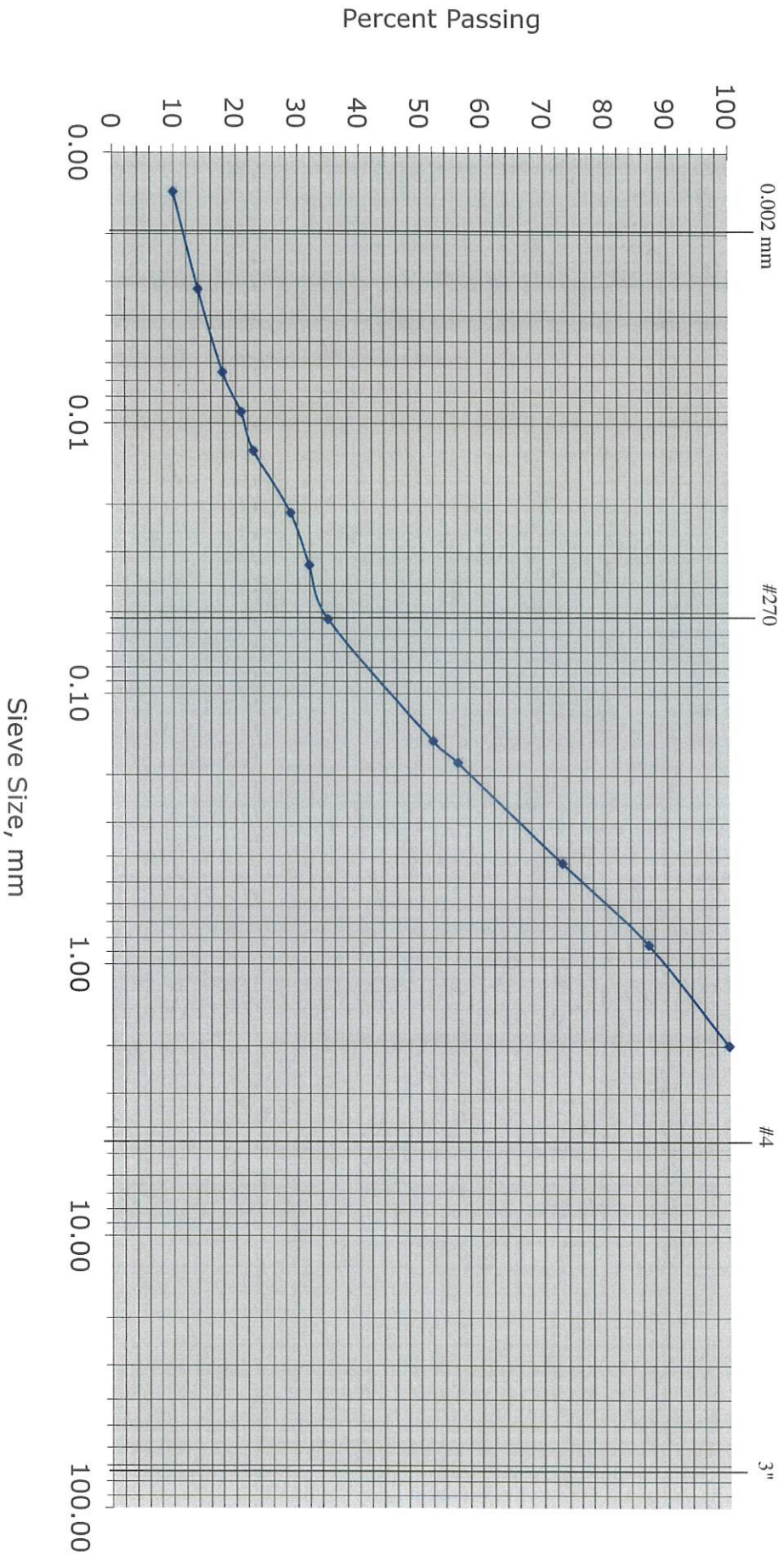


Briggs Engineering & Testing

A Division of PK Associates, Inc.

Project:	Hanson Subdivision 1P8'
Date Tested:	7/9/21
Lab Ref. No.:	M-32745

Particle Size Analysis



Note: The illustrated graph represents the sand fraction only as defined by D.E.P. policy# BRP/DWM/PeP-P00-1, Appendix 2.



Grain Size Analysis Report

Date:

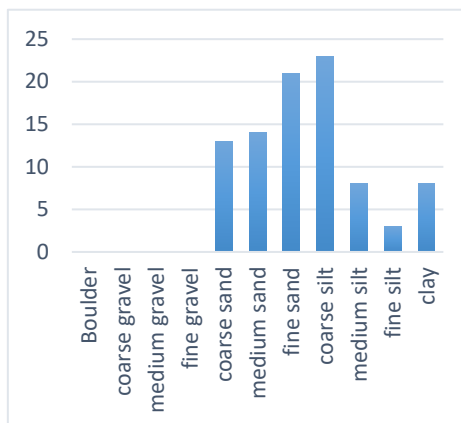
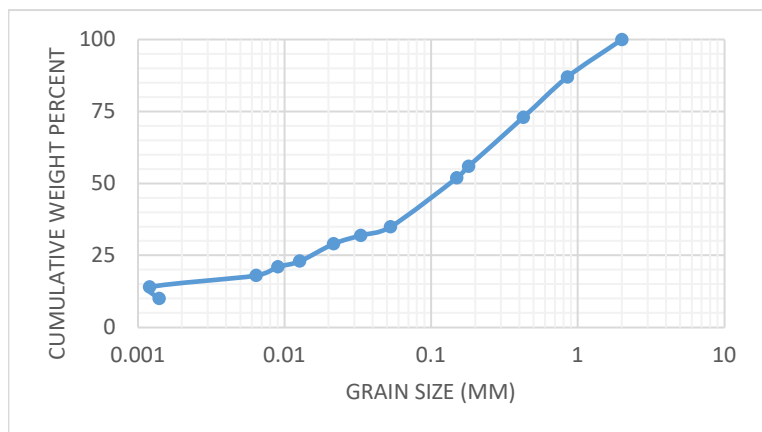
7/12/2021

Sample Name: Basin 1P 8 feet down

Mass Sample (g): 100

T (oC) 20

Poorly sorted sand with fines



Sieve opening (ps) di (mm)	Mass of retained (mr) (g)	mass fraction (mf)	Percent Passing (pp)
2	0	0	100
0.85	13	0.13	87
0.425	14	0.14	73
0.18	17	0.17	56
0.15	4	0.04	52
0.053	17	0.17	35
0.0332	3	0.03	32
0.0216	3	0.03	29
0.0127	6	0.06	23
0.009	2	0.02	21
0.0064	3	0.03	18
0.0012	4	0.04	14
0.0014	4	0.04	10

Effective Grain Diameters (mm)		Other Useful Parameters	
d10	0.001	Uniformity Coef.	185.63
d17	0.005	n computed	0.26
d20	0.008	g (cm/s ²)	980.00
d50	0.138	ρ (g/cm ³)	0.9981
d60	0.223	μ (g/cm s)	0.0098
de (Kruger)	0.000	ρg/μ (1/cm s)	9.9327E+04
de (Kozeny)	0.000	tau (Sauerbrei)	1.053
de (Zunker)	0.000	d _{geometric mean}	0.146
de (Zamarin)	0.000	σ _ψ	3.526
lo (Alyameni)	-0.033		
mm	0	% in sample	
>64	Boulder		
16 - 64	coarse gravel		
8 - 16	medium gravel		
2 - 8	fine gravel		0
0.5 - 2	coarse sand		13
0.25 - 0.5	medium sand		14
0.063 - 0.25	fine sand		21
0.016 - 0.063	coarse silt		23
0.008 - 0.016	medium silt		8
0.002 - 0.008	fine silt		3
<0.002	clay		8



K from Grain Size Analysis Report

Date: 7/12/2021

Sample Name: Hanson Basin 1P at 8 feet down

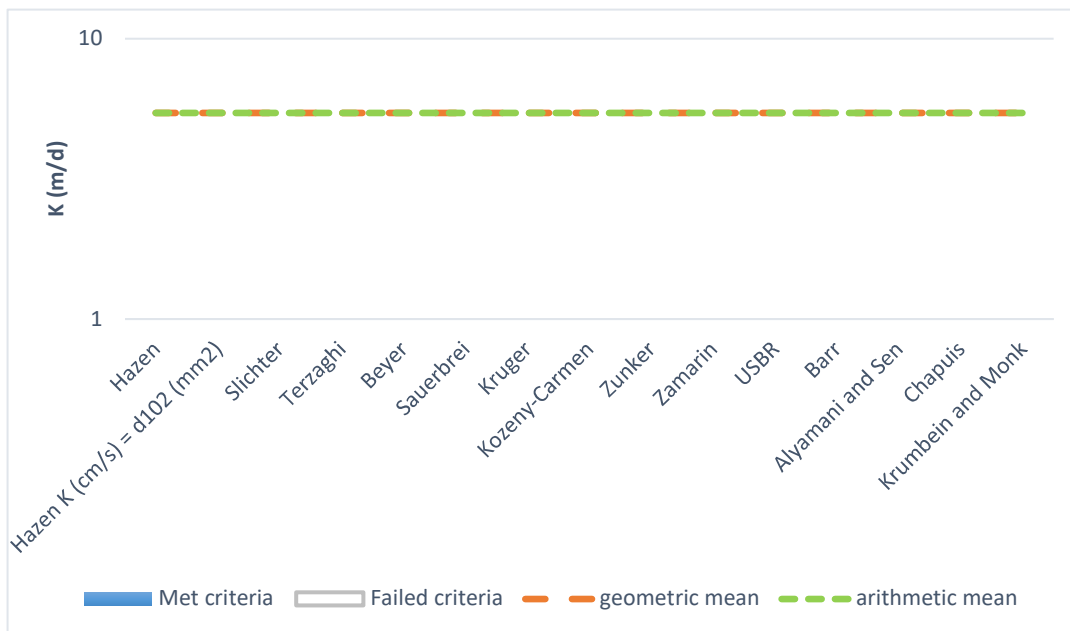
Mass Sample (g):

100

T (oC)

20

Poorly sorted sand with fines



Estimation of Hydraulic Conductivity	cm/s	m/s	m/d	de
Hazen		.000E+00	0.00	
Hazen K (cm/s) = d_{10}^2 (mm)		.000E+00	0.00	
Slichter		.000E+00	0.00	
Terzaghi		.000E+00	0.00	
Beyer		.000E+00	0.00	
Sauerbrei		.000E+00	0.00	
Kruger		.000E+00	0.00	
Kozeny-Carmen		.000E+00	0.00	
Zunker		.000E+00	0.00	
Zamarin		.000E+00	0.00	
USBR		.000E+00	0.00	
Barr		.000E+00	0.00	
Alyamani and Sen		.000E+00	0.00	
Chapuis		.000E+00	0.00	
Krumbein and Monk		.000E+00	0.00	
Shepherd	.630E-02	.630E-04	5.44	
geometric mean	.630E-02	.630E-04	5.44	
arithmetic mean	.630E-02	.630E-04	5.44	

5.44 m/d = 17.85 ft/day



Briggs Engineering & Testing

A DIVISION OF PK ASSOCIATES, INC.

July 9, 2021

Morse Engineering
3 Garden Road
Scituate, MA 02066-2212
Attn: Mr. Gregory Morse

Title V Soil Analysis

Address: Hanson Subdivision 2P3'
Briggs # 24975
Tested: 07/09/21

1.	Lab Ref. No.	Description	Source
	M-32744	- #10 Fraction	Hanson Subdivision 2P3'

2. Particle Size Analysis {ASTM D 6913/D 6913M and D 7928}:

Sieve Size		Results
Standard	Alternate	{% Passing by Wt.}
2.0 mm	#10	100
0.850 mm	#20	88
0.425 mm	#40	74
0.180 mm	#80	56
0.150 mm	#100	52
0.053 mm	#270	39
0.0332 mm		35
0.0216 mm		27
0.0127 mm		23
0.0091 mm		21
0.0064 mm		20
0.0032 mm		15
0.0014 mm		10

D10 = 0.0014 mm

3. The above analysis was performed in accordance with D.E.P. policy# BRP/DWM/PeP-001-1, Appendix 2.

Respectfully Submitted,
BRIGGS ENGINEERING & TESTING
A Division of PK Associates, Inc.

Sean Skorohod
Director of Testing Services
Construction Technology Division

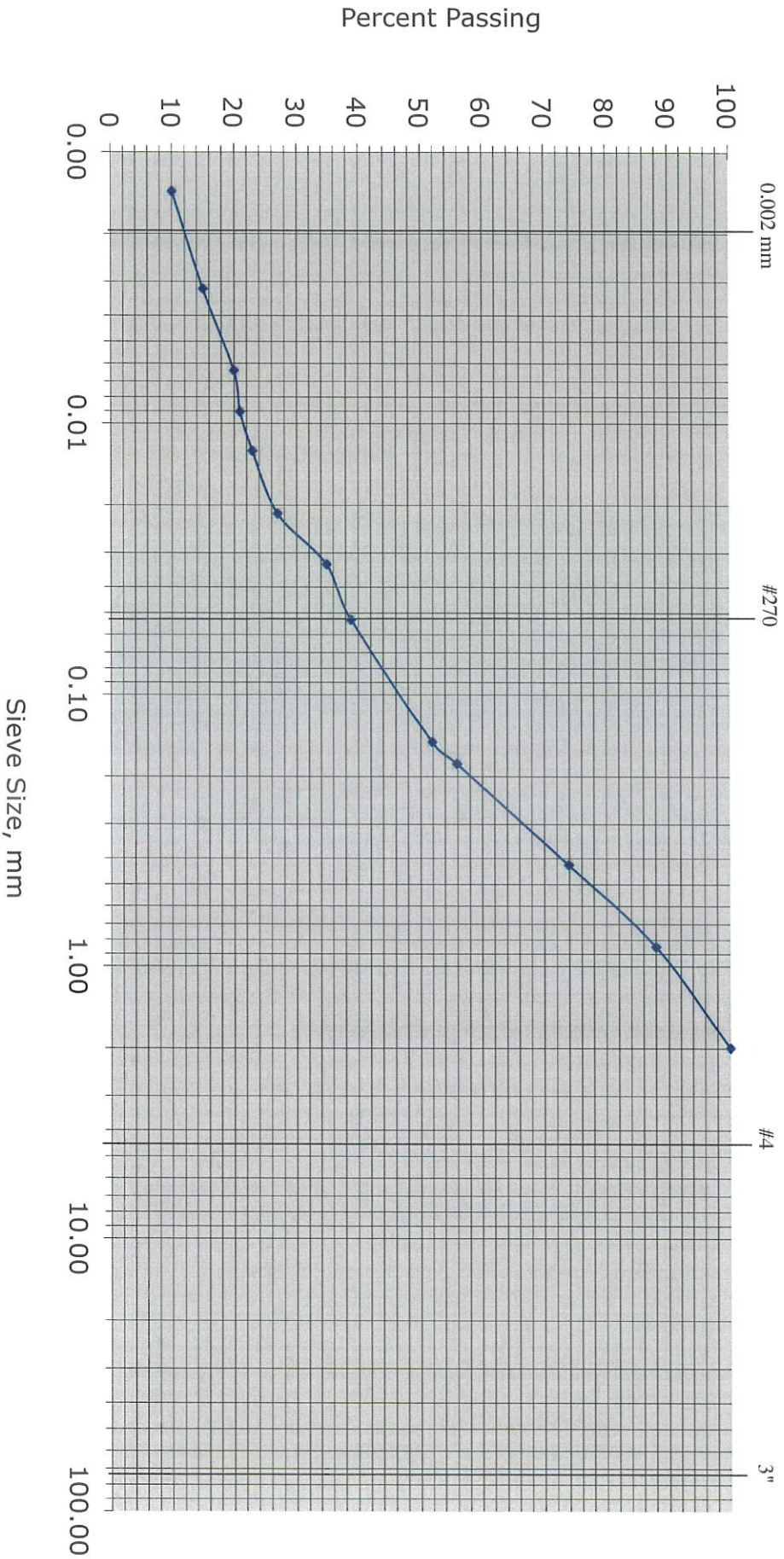
enclosures: graph



Briggs Engineering & Testing
A Division of PK Associates, Inc.

Project:	Hanson Subdivision 2P3'
Date Tested:	7/9/21
Lab Ref. No.:	M-32744

Particle Size Analysis



Note: The illustrated graph represents the sand fraction only as defined by D.E.P. policy# BRP/DWM/PeP-P00-1, Appendix 2.



Grain Size Analysis Report

Date:

7/12/2021

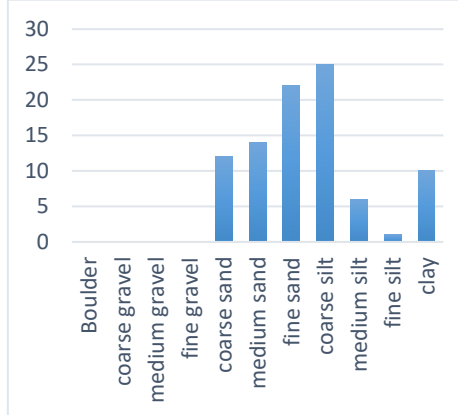
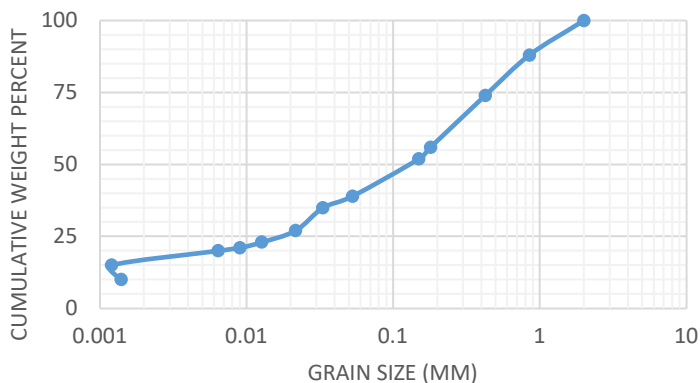
Sample Name: Hanson Basin 2P 3 feet down

Mass Sample (g): 100

T (oC)

20

Poorly sorted sand with fines



Sieve opening (ps) di (mm)	Mass of retained (mr) (g)	mass fraction (mf)	Percent Passing (pp)
2	0	0	100
0.85	12	0.12	88
0.425	14	0.14	74
0.18	18	0.18	56
0.15	4	0.04	52
0.053	13	0.13	39
0.0332	4	0.04	35
0.0216	8	0.08	27
0.0127	4	0.04	23
0.009	2	0.02	21
0.0064	1	0.01	20
0.0012	5	0.05	15
0.0014	5	0.05	10

Effective Grain Diameters (mm)		Other Useful Parameters	
d10	0.001	Uniformity Coef.	177.57
d17	0.003	n computed	0.26
d20	0.006	g (cm/s ²)	980.00
d50	0.135	ρ (g/cm ³)	0.9981
d60	0.213	μ (g/cm s)	0.0098
de (Kruger)	0.000	ρg/μ (1/cm s)	9.9327E+04
de (Kozeny)	0.000	tau (Sauerbrei)	1.053
de (Zunker)	0.000	d _{geometric mean}	0.135
de (Zamarin)	0.000	σ _ψ	3.699
lo (Alyameni)	-0.032		
mm		0 % in sample	
>64		Boulder	
16 - 64		coarse gravel	
8 - 16		medium gravel	
2 - 8		fine gravel	0
0.5 - 2		coarse sand	12
0.25 - 0.5		medium sand	14
0.063 - 0.25		fine sand	22
0.016 - 0.063		coarse silt	25
0.008 - 0.016		medium silt	6
0.002 - 0.008		fine silt	1
<0.002		clay	10



K from Grain Size Analysis Report

Date: 7/16/2021

Sample Name: Hanson Basin 2P 3 feet down

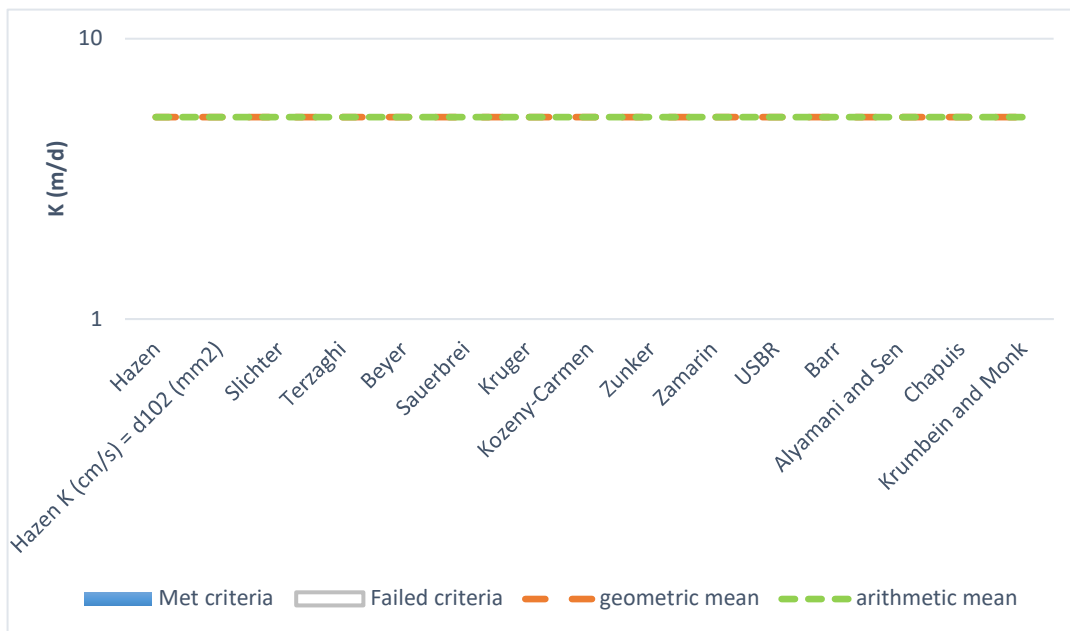
Mass Sample (g):

100

T (oC)

20

Poorly sorted sand with fines



Estimation of Hydraulic Conductivity	cm/s	m/s	m/d	de
Hazen		.000E+00	0.00	
Hazen K (cm/s) = d_{10} (mm)		.000E+00	0.00	
Slichter		.000E+00	0.00	
Terzaghi		.000E+00	0.00	
Beyer		.000E+00	0.00	
Sauerbrei		.000E+00	0.00	
Kruger		.000E+00	0.00	
Kozeny-Carmen		.000E+00	0.00	
Zunker		.000E+00	0.00	
Zamarin		.000E+00	0.00	
USBR		.000E+00	0.00	
Barr		.000E+00	0.00	
Alyamani and Sen		.000E+00	0.00	
Chapuis		.000E+00	0.00	
Krumbein and Monk		.000E+00	0.00	
Shepherd	.607E-02	.607E-04	5.25	
geometric mean	.607E-02	.607E-04	5.25	
arithmetic mean	.607E-02	.607E-04	5.25	

5.25 m/d = 17.20 ft/day



Briggs Engineering & Testing
A DIVISION OF PK ASSOCIATES, INC.

July 9, 2021

Morse Engineering
3 Garden Road
Scituate, MA 02066-2212
Attn: Mr. Gregory Morse

Title V Soil Analysis

Address: Hanson Subdivision 2P8'
Briggs # 24975
Tested: 07/09/21

1.	Lab Ref. No.	Description	Source
	M-32746	- #10 Fraction	Hanson Subdivision 2P8'

2. Particle Size Analysis {ASTM D 6913/D 6913M and D 7928}:

Sieve Size		Results
Standard	Alternate	{% Passing by Wt.}
2.0 mm	#10	100
0.850 mm	#20	88
0.425 mm	#40	71
0.180 mm	#80	53
0.150 mm	#100	50
0.053 mm	#270	38
0.0328 mm		38
0.0212 mm		32
0.0126 mm		26
0.0090 mm		23
0.0064 mm		20
0.0032 mm		12
0.0014 mm		10

D10 = 0.0014 mm

3. The above analysis was performed in accordance with D.E.P. policy# BRP/DWM/PeP-001-1, Appendix 2.

Respectfully Submitted,
BRIGGS ENGINEERING & TESTING
A Division of PK Associates, Inc.

Sean Skorohod
Director of Testing Services
Construction Technology Division

enclosures: graph

www.briggsengineering.com

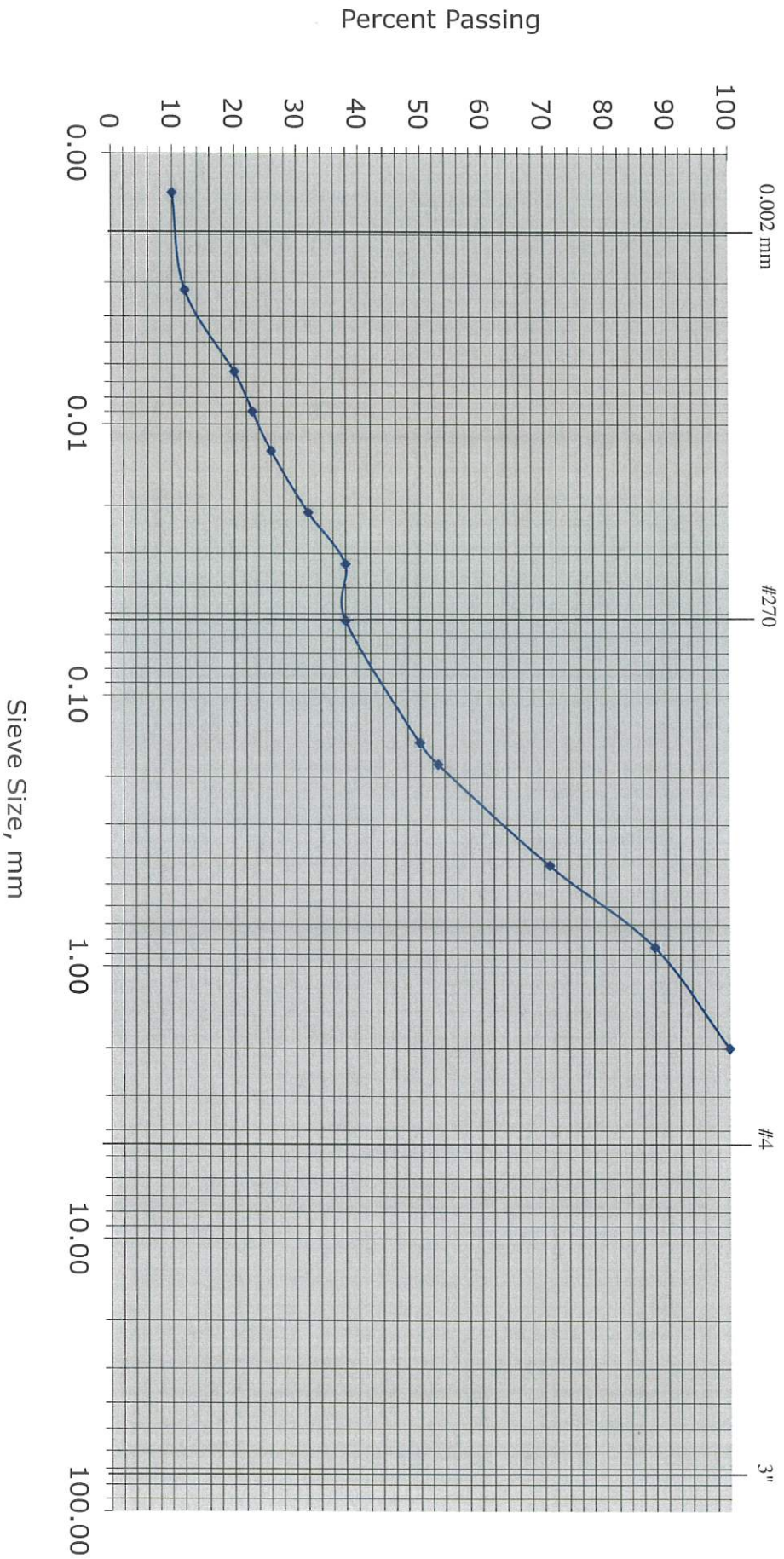


Briggs Engineering & Testing

A Division of PK Associates, Inc.

Project:	Hanson Subdivision 2P8'
Date Tested:	7/9/21
Lab Ref. No.:	M-32746

Particle Size Analysis



Note: The illustrated graph represents the sand fraction only as defined by D.E.P. policy# BRP/DWM/PeP-P00-1, Appendix 2.



Grain Size Analysis Report

Date:

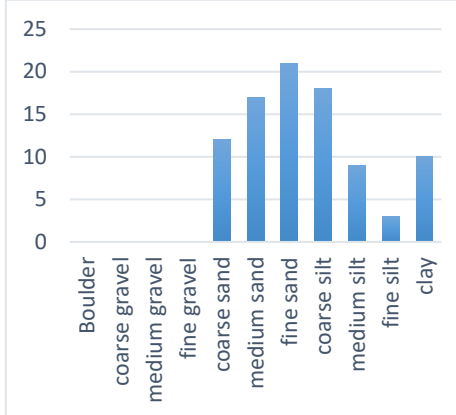
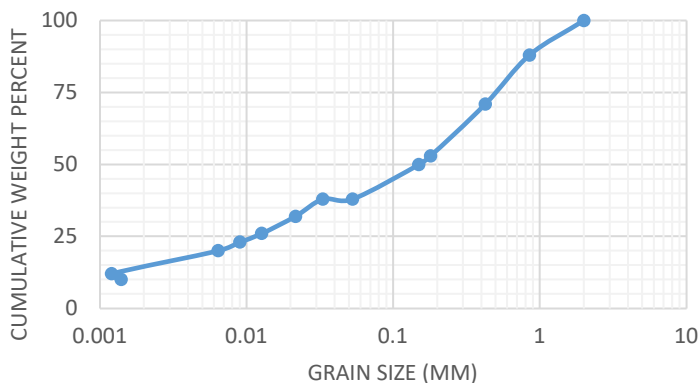
7/16/2021

Sample Name: Hanson Basin 2P 8 feet down

Mass Sample (g): 100

T (oC) 20

Poorly sorted sand with fines



Sieve opening (ps) di (mm)	Mass of retained (mr) (g)	mass fraction (mf)	Percent Passing (pp)
2	0	0	100
0.85	12	0.12	88
0.425	17	0.17	71
0.18	18	0.18	53
0.15	3	0.03	50
0.053	12	0.12	38
0.0332	0	0	38
0.0216	6	0.06	32
0.0127	6	0.06	26
0.009	3	0.03	23
0.0064	3	0.03	20
0.0012	8	0.08	12
0.0014	2	0.02	10

Effective Grain Diameters (mm)		Other Useful Parameters	
d10	0.001	Uniformity Coef.	219.64
d17	0.004	n computed	0.26
d20	0.006	g (cm/s ²)	980.00
d50	0.150	ρ (g/cm ³)	0.9981
d60	0.264	μ (g/cm s)	0.0098
de (Kruger)	0.000	ρg/μ (1/cm s)	9.9327E+04
de (Kozeny)	0.000	tau (Sauerbrei)	1.053
de (Zunker)	0.000	d _{geometric mean}	0.138
de (Zamarin)	0.000	σ _ψ	3.548
lo (Alyameni)	-0.036		
mm	0	% in sample	
>64	Boulder		
16 - 64	coarse gravel		
8 - 16	medium gravel		
2 - 8	fine gravel		0
0.5 - 2	coarse sand		12
0.25 - 0.5	medium sand		17
0.063 - 0.25	fine sand		21
0.016 - 0.063	coarse silt		18
0.008 - 0.016	medium silt		9
0.002 - 0.008	fine silt		3
<0.002	clay		10



K from Grain Size Analysis Report

Date: 7/16/2021

Sample Name: Hanson Basin 2P 8 feet down

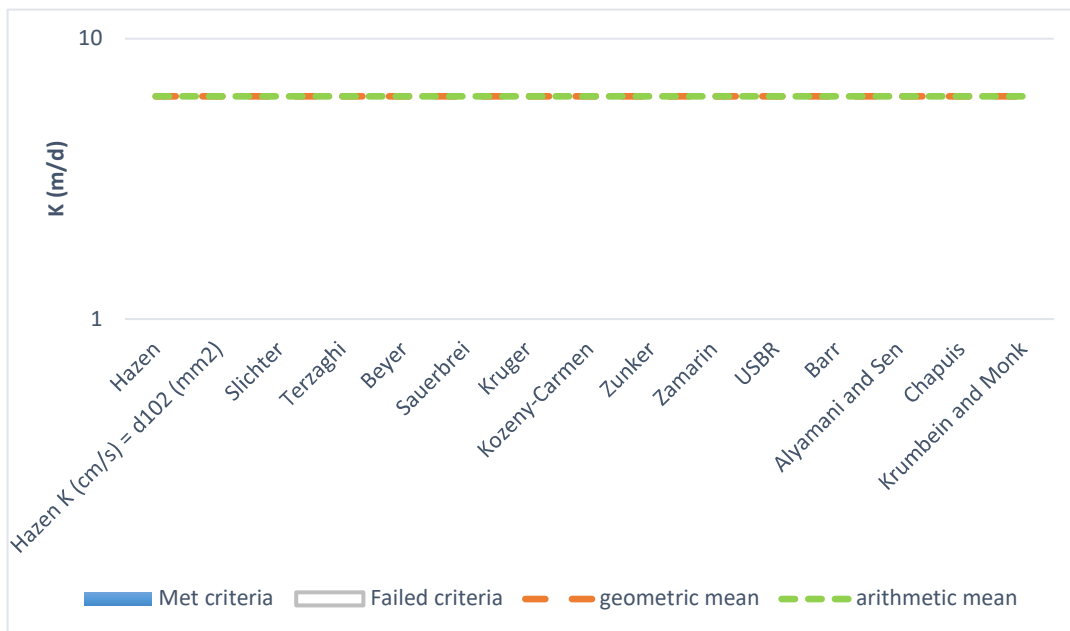
Mass Sample (g):

100

T (oC)

20

Poorly sorted sand with fines



Estimation of Hydraulic Conductivity	cm/s	m/s	m/d	de
Hazen		.000E+00	0.00	
Hazen K (cm/s) = d ₁₀ (mm)		.000E+00	0.00	
Slichter		.000E+00	0.00	
Terzaghi		.000E+00	0.00	
Beyer		.000E+00	0.00	
Sauerbrei		.000E+00	0.00	
Kruger		.000E+00	0.00	
Kozeny-Carmen		.000E+00	0.00	
Zunker		.000E+00	0.00	
Zamarin		.000E+00	0.00	
USBR		.000E+00	0.00	
Barr		.000E+00	0.00	
Alyamani and Sen		.000E+00	0.00	
Chapuis		.000E+00	0.00	
Krumbein and Monk		.000E+00	0.00	
Shepherd	.722E-02	.722E-04	6.24	
geometric mean	.722E-02	.722E-04	6.24	
arithmetic mean	.722E-02	.722E-04	6.24	

6.24 m/d =20.47 ft./day

HydrogeoSieveXL

v 2.3.2

Developed by

J.F. Devlin

Dept. of Geology

University of Kansas

Developed April 29, 2014, most recent update September, 2016



This program is electronic supplementary material for the article
Devlin, J.F. 2015. HydrogeoSieveXL: an Excel-based tool to estimate hydraulic conductivity from grain-size analysis. Hydrogeology Journal.

v.2.3.2 updated to include the Shephard, 1989 method, July, 2019

Introduction

HydrogeoSieveXL is a utility aimed at providing hydrogeologists a quick and comprehensive means of obtaining hydraulic conductivity (K) estimates from grain size analyses. Note that the methods tend to be most accurate in handling the coarser fractions of material common to aquifers, i.e., sand and gravel, although the values of K that are generated are generally only approximate. The presence of significant fractions of fine fractions further degrades the quality of the K estimates. This worksheet contains six tabbed worksheets: 1) this manual, 2) the HydrogeoSieveXL worksheet where all the computational work is done, and 3) a worksheet with sample data from selected literature sources 4) a table of equations used in the K estimations, and their sources, 5) a reference list with citations to contributing literature, 6) a sheet that summarizes the grain size data in a format suitable for pdf report generation and 7) a sheet that summarizes the K estimation calculations in a format suitable for pdf report generation. Following is an overview of the operation of the worksheet "Input" in the form of a tutorial that covers all the features of HydrogeoSieveXL.

Before beginning, confirm that the "Input" worksheet is empty of data. Click on the tab called "Input" and verify that it looks like Figure 1, below. If there are any numbers entered in the sheet, click on "Reset" on the upper left corner of the sheet to prepare it for new data.

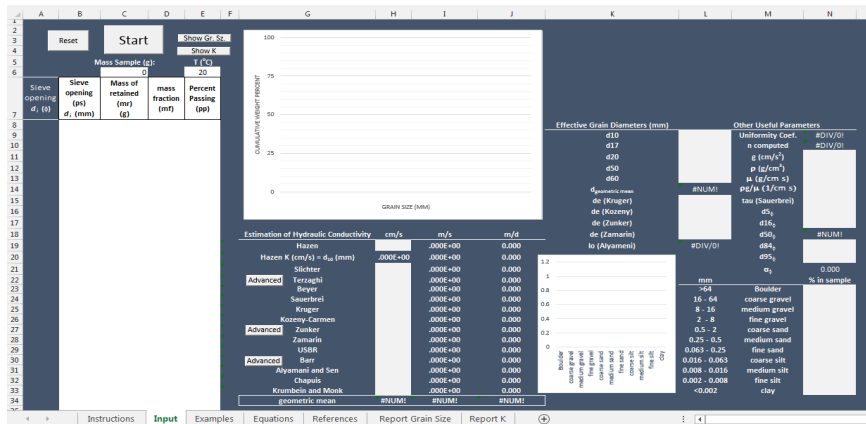


Figure 1: "Input" ready to receive new data.

Data Input

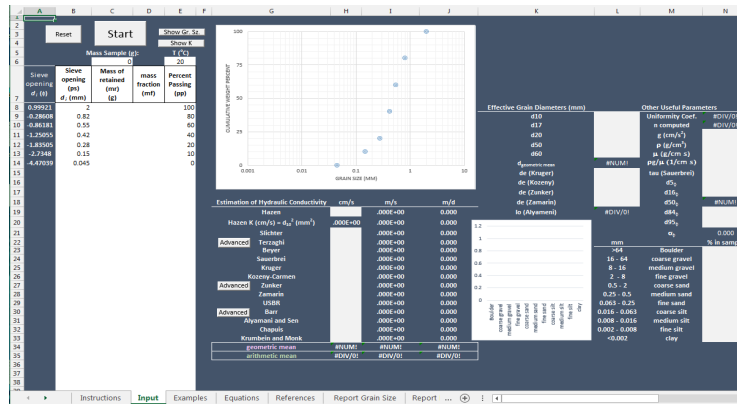
To illustrate the input process, we will use the dataset from the "Examples" worksheet that is called "Case 1 Vukovic 15 oC". Click on the "Examples" tab and select the "Case 1 ..." dataset on the upper left corner of the sheet (Figure 2). The dataset consists of two columns of data: ps - particle size, and pr - percent retained. The two columns are separated by two empty columns to permit the data to be pasted directly into the input space in the "Input" sheet.

	A	B	C	D	E	F	G	H
1	Examples unless otherwise noted							
2								
3	Case 1 Vukovic 15 oC						Sample 1 Odong 20 oC	
4	ps			pr			ps	
5		2		100			10	
6		0.82		80			4.75	
7		0.55		60			2.36	
8		0.42		40			1.18	
9		0.28		20			0.6	
10		0.15		10			0.425	
11		0.045		0			0.3	
12							0.15	
13	Case 2 Vukovic 15 oC						0.075	
14	ns			nr				

15	2		100		
16	1.5		95		Sample 2 Odong 20 oC
17	1.2		90		ps
18	0.95		85		1.18

Figure 2: Selecting data for pasting into the "Input" sheet.

With the data copied (Ctrl-c or using the menus), click on the "Input" tab and then on cell A8. Paste the data you copied (Ctrl-v or using the menus) (Figure 3).



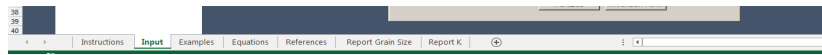


Figure 5: Result of clicking on "Input Prep" in the Dashboard.

The "Input Prep" discovers which particle retention format was placed in the input table and fills in the remaining columns. The interpolated lines are shown in the graph. By default, the program enters a total sample mass of 100 g and a temperature of 20 oC. These values can be changed, at any time.

Calculating Effective Grain Diameters

Almost all attempts to relate hydraulic conductivity to grain size curves begins with the identification of some 'effective grain diameter'. Several of these have been proposed, and the ones relevant to the analyses performed here are estimated with the buttons on the left side of the Dashboard, or with the "Do All" button. The d10 particle size refers to that size that corresponds to 10% of the sample weight being retained on the sieves. Similar definitions apply to d17, d20, d50, and d60, where the numbers are the percentages retained. The d50 number is generally noteworthy because it represents the median grain size.

Specialized formulas are used to calculate the effective grain diameters for the Kruger, Kozeny, Zunker, and Zamarin analyses. The effective diameters for each of these cases is calculated and pasted in the sheet when the corresponding button is selected. The calculated values are pasted in a table on the middle right portion of the sheet (Figure

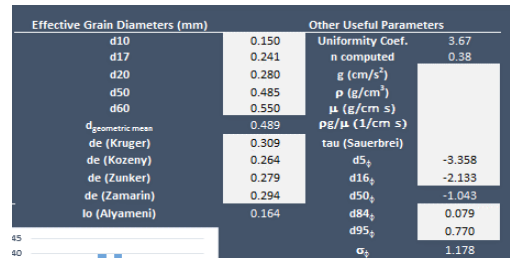


Figure 6: Calculated values of the effective grain diameters.

Uniformity Coefficient and Porosity

With the computation of the effective grain diameters, the uniformity coefficient, $U = d_{60}/d_{10}$, can be calculated as well as an estimate of the porosity, $n = 0.255 \cdot (1 + 0.83 \cdot U)$. If the effective grain size is specified to be the geometric mean (d_{geom}), then the effective porosities presented by Urumovic and Urumovic (2106) are

$$n_e = a_o + a_1 \sin\left(\frac{2\pi \ln(d_{geom})}{Pd} + PS\right) + b_1 \cos\left(\frac{2\pi \ln(d_{geom})}{Pd} + PS\right) + a_2 \sin\left(\frac{2\pi \ln(d_{geom})}{Pd} + PS\right) + b_2 \cos\left(\frac{2\pi \ln(d_{geom})}{Pd} + PS\right) + a_3 \sin\left(\frac{2\pi \ln(d_{geom})}{Pd} + PS\right) + b_3 \cos\left(\frac{2\pi \ln(d_{geom})}{Pd} + PS\right)$$

	dgeometric < 0.1	dgeometric > 0.1		
Constant		U < 2	2 < U < 20	U > 20
a0	0.2399304340	0.0590506780	0.1708658530	0.1678375290
a1	0.0324745780	0.0000101000	0.0000321000	0.0250950160
a2	0.0570213160	0.0000100011	0.0003506030	0.0184118450
a3	0.0000275938	0.0000009962	0.0022730750	0.0036298590
b1	0.116365861	0.1434172940	0.0455873050	0.1052515240
b2	0.05084363	0.1185613460	0.0612605450	0.0271112560
b3	0.0000000000	0.0401330370	0.0540192400	0.0000000000
PS	0.0000000000	0.0146232500	0.0961212630	0.7038497150
Pd	7.087465633	6.6843846040	5.1244023000	4.7352413780

At this point it is also possible to provide a qualitative description of the sample in terms of its uniformity (and to some degree its sorting), textural class, and the presence or absence of fine material. This description is generated by clicking on the "Sediment Classification" button beneath the effective grain diameter buttons on the left side of the Dashboard (Figure 7). The description is also generated by the "Do All" button.

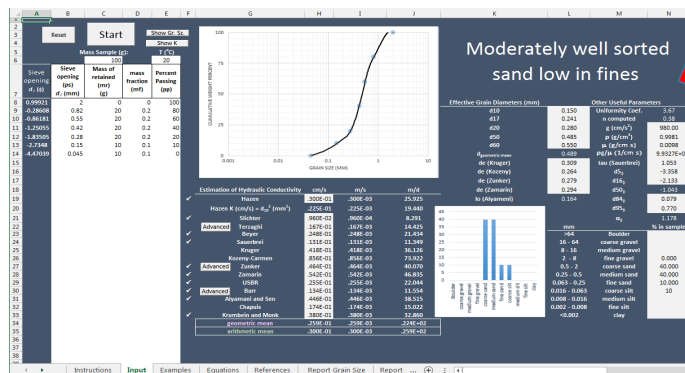


Figure 7: Automatically generated description of the sample. Red arrow shows the location where the description appears.

Grain Size Distribution and Descriptive Sample Classification

As well as generating the sample description, the "Sediment Classification" and "Do All" buttons prompt the calculation of weight percentages of the sample in standard grain size classification ranges. This affords the user the opportunity to assess the percentage of coarse sand or medium silt in the sample, for example. The table of this grain size distribution is reported on the lower right portion of the screen. Immediately to the left of the table is a histogram showing the same information graphically.

Hydraulic Conductivity

In this version of HydrogeoSieveXL, 15 methods of estimating hydraulic conductivity from grain size analysis are computed. If the *K* from *grain size* approach enjoys any success, it seems to be in its application to coarser grained media, including sand. Even in these kinds of sediments the various specific methods have been shown to generate quite different estimates of hydraulic conductivity. One benefit of using HydrogeoSieveXL is to facilitate the comparison of hydraulic conductivity values generated from the specific methods, so an appreciation of the uncertainty associated with the resulting *K* values is gained.

To calculate hydraulic conductivity from each of the methods, simply click on the button for that method in the Dashboard. Alternatively, to calculate them all at once, click on the "Do All" button. The bank of buttons for these calculations are on the right side of the Dashboard (Figure 8). If the grain size curve meets the criteria summarized for each test in the "Equations" sheet, a check mark appears to the left of the test name, in column F.

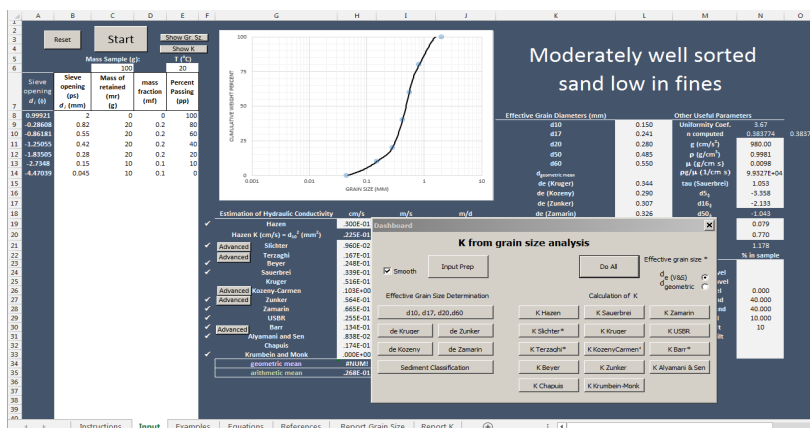


Figure 8: The buttons controlling the calculation of hydraulic conductivity are grouped under the heading "Calculation of K" in the Dashboard. The calculated values are tabulated immediately under the Dashboard in

Advanced Options for Hydraulic Conductivity Calculation

The 'Advanced' buttons that appear beside selected equations offer access to 2 features: 1) they permit the specification of effective grain size (either the Vukovic and Soro values or the geometric mean grain size; 2) they permit users to specify shape factors that account for grain shape. If both options apply, the grain size dialogue box appears first.

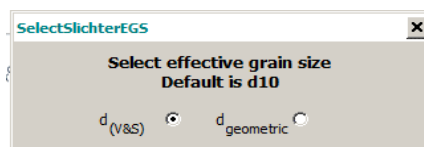


Figure 9: Dialogue box for selecting the effective grain diameter. This box appears for the Slichter, Terzaghi, Kozeny and Barr equations, Advanced buttons.

The hydraulic conductivities calculated by HydroSieve are based on the generalized formula:

$$K = \frac{\rho g}{\mu} C \varphi(n) d_e^2$$

where K is hydraulic conductivity (cm/s), ρ is fluid density (g/mL), g is acceleration due to gravity (cm/s²), μ is dynamic viscosity (poise, or g/cm s), C is a constant related to porous medium characteristics, $\phi(n)$ is a function of porosity, and d_e is the effective grain diameter (cm). Both the density and viscosity terms are temperature sensitive, and are calculated as a function of the fluid temperature entered in cell D6. The values of these parameters are displayed in cells m11 and m12 of the sheet. Three of the methods offer the opportunity to adjust the magnitude of the constant C according the coarseness/smoothness of the grains, the Terzaghi, Zunder, and Barr methods. By default, intermediate values of C are used in the calculations. However these values can be varied over the ranges recommended by the developers of the methods by clicking on the "Advanced" buttons located beside the method names (Figure 10).

For example, selecting the "Advanced" button beside the Terzaghi method the "Terzaghi Advanced" userform appears. One of five option buttons can be selected to characterise the aquifer material as being coarse and angular in grain shape, or smooth and well rounded. The default value of C is indicated (center button in this case), and the current value of C is displayed.

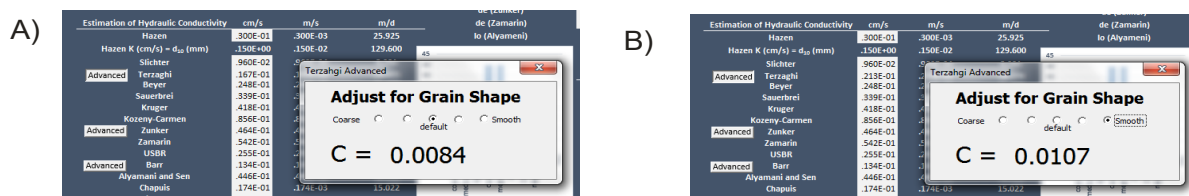




Figure 10: The advanced userform for the Terzaghi method of K estimation. (A) Userform as it appears after the Dashboard driven calculation; C is the default value of

Displaying the Results

Once the hydraulic conductivities have been calculated to the user's satisfaction, the results of the different methods can be compared graphically in a histogram format. To view the histogram, click on the "Show K " button located to the left of the grain retention curve graph at the top of the sheet. The retention diagram is replaced with the K comparison diagram (Figure 11).

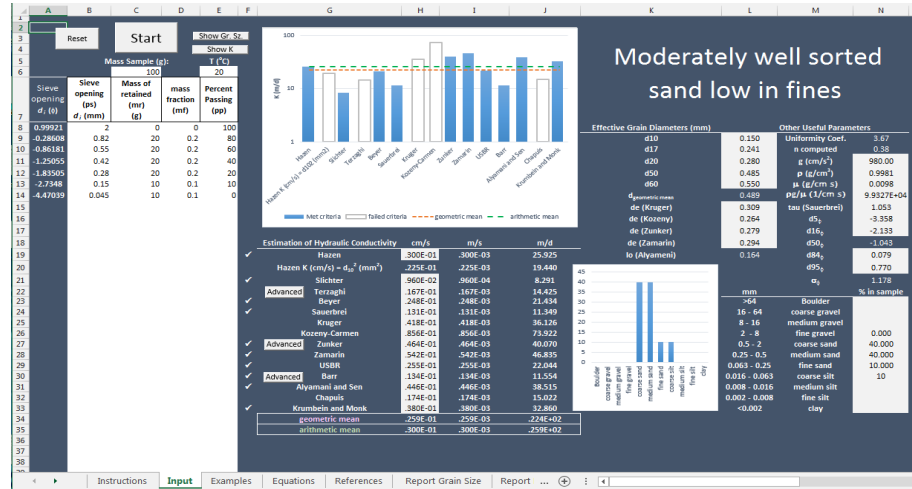


Figure 11: Clicking on the "Show K " button, located above the temperature input cell, replaces the grain retention curve with the K comparison diagram. The geometric and arithmetic means of the estimates of K are shown as red and green horizontal lines, respectively. Open bars represent K estimates from tests that failed their criteria, blue bars represent tests that met their criteria. The criteria are summarized in the 'Equations' sheet.

The grain retention curve can be displayed again by selecting the "Show Gr Sz" button.

Printing Reports

The data displayed on the "Input" worksheet are summarized in a form suitable for printing in the worksheets named "Report Grain Size" and "Report K ". Simple click on the appropriate tab to view these sheets, and then select 'Print' under the 'File' tab at the top of the worksheet to send the file to a printer.

Conclusion

HydroSieve is a utility aimed at hydrogeologists for rapidly conducting grain size analysis on data from sieve tests. It plots grain retention curves, particle size distribution diagrams, and estimated hydraulic conductivity comparison diagrams. It calculates several commonly required effective grain diameters and uses them to estimate useful coefficients such as the uniformity coefficient and porosity. I also use the effective grain diameters in the estimation of hydraulic conductivity by several published methods. The results of these calculations can provide hydrogeologists with potentially useful preliminary estimations of K , while at the same time reminding them of the highly uncertain nature of the parameter estimated in this fashion.

Correlations of Permeability and Grain Size

by Russell G. Shepherd^a

ABSTRACT

Previous theoretical and empirical investigations of the relation between particle size and intergranular permeability have resulted in the well-known formula for intrinsic permeability (k)

$$k = cd^2$$

where d is particle diameter, and c is a dimensionless constant. Statistical power regression analyses were performed on 19 sets of published data on size and laboratory permeability of unconsolidated sediments. The exponent of grain diameter ranged from 1.11 to 2.05, but most values were significantly less than 2.0. Results indicate that the permeability/grain size relation alternatively may be expressed, from an empirical basis, as

$$k = cd^{1.65 \text{ to } 1.85}$$

Values of c and the exponent both generally decrease with decreased textural maturity and increased induration.

INTRODUCTION

Although many hundreds of field and laboratory determinations of permeability have been made by geologists, engineers, and soil scientists, the fundamental relationships between the sedimentologic properties of sediments and sedimentary rocks and flow through them remain poorly understood and inadequately quantified. As an example, the detailed quantitative relationships between grain

size and permeability of nonindurated sediments of sand and silt size should be well-known, it would seem. However, inspection of the better-known recent texts in hydrogeology (Freeze and Cherry, 1979; Bouwer, 1978; Fetter, 1980; Todd, 1980) reveals that only broad ranges of permeability are given for general types and sizes of materials (Freeze and Cherry, 1979, p. 29).

Summers and Weber (1984) recently addressed the problem and emphasized that insufficient data exist, especially from poorly sorted sediments having clay, gravel, and sand mixtures (glacial drift). Nevertheless, hydrogeoscientists commonly are required to make estimates of permeability of unconsolidated sediments having knowledge only of an average grain size or a grain size distribution (Rose and Smith, 1957; Driscoll, 1986). Such estimates of permeability are used for designing aquifer and pump tests, in computer modeling of ground-water flow and solute transport, in oil reservoir characterization, and in geotechnical analysis (Schlichter, 1902; Terzaghi and Peck, 1967; Driscoll, 1986).

PERSPECTIVE AND PURPOSE

Several methods of estimating permeability exist. One of the better methods is a field pumping or injection test, generally an expensive and time-consuming effort. Another is to measure flows of gas or liquid through samples in the laboratory with a permeameter. A third method is to obtain data on grain size and also porosity, sorting, packing, and grain shape, as practicable, and to estimate permeability using empirical relationships. Examples of these are the nomograph presented by Schlichter (1905), the size-packing-sorting graph presented by Driscoll (1986), or the relationships

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Received July 1988, revised December 1988, accepted January 1989.

Discussion open until March 1, 1990.

of Hazen (1892), Schlichter (1899), Terzaghi (1925), Kozeny (1927), Hulbert and Feben (1933), Fair and Hatch (1933), or Louden (1952). Discussions and development of these and other relationships were provided by Wenzel (1942), Muskat (1949), Scheidegger (1974), Bear (1972), Carmen (1956), and Chapman (1981).

It generally has been recognized by previous investigators that grain size is a fundamental independent variable controlling permeability in unconsolidated sediments (Graton and Fraser, 1935; Reyes, 1966; Morrow *et al.*, 1969; Beard and Weyl, 1973; Pryor, 1973; Berg, 1986). This fact is evidenced by the importance of grain size in the basic intrinsic permeability equation, also summarized in the texts cited previously, as follows:

$$k = cd^2 \quad (1)$$

In this well-known equation, k is intrinsic permeability, restricted to properties of the medium alone; c is a dimensionless constant, usually held to include properties such as path tortuosity, particle shape, sediment sorting, and possible porosity; and d is either pore throat diameter or a representative grain diameter (Bear, 1972; Freeze and Cherry, 1979). Here, permeability is in dimensions of length squared, and d is a length parameter, making the equation dimensionally consistent.

That permeability varies as the square of grain diameter was reported by Hazen (1892) and Schlichter (1899), and has been experimentally verified by numerous investigators (Schriever, 1930; Krumbein and Monk, 1943; Burmister, 1954; Keech and Rosene, 1964). Bear (1972), Scheidegger (1974), and Chapman (1981) provided excellent detailed discussions of the derivation and limitations of equation (1) and of variations of it. Terzaghi and Peck (1967) summarized the relation by analogy to Poiseuille's law, in which velocity of flow in a circular tube increases with the square of the tube diameter. In short, the equation can be derived theoretically from considerations of the specific surfaces of grains of different sizes, from which the exponent of d is found to be 2.0 (Muskat, 1949; Bear, 1972; Scheidegger, 1974).

Equation (1) is a simple power equation of the form

$$y = ax^b \quad (2)$$

If permeability (y) is plotted against grain size (x) on log-log paper, as in Figure 1 (Bedinger, 1961), the coefficient a is the value of y at $x = 1$, and b is the slope of the line that is fitted to the data. Plots of permeability against size are common

in the literature, and in these the coefficient (c) can be taken to include all factors intrinsic to the medium that control permeability except size. Although these other factors may be known in some instances, frequently they are not. In such a case, one may choose to estimate permeability using grain size alone (Krumbein and Monk, 1942; Rose and Smith, 1957).

For a given set of data, equation (1) can be statistically estimated using a simple power regression. The best-fit least-squares line provides a simple functional relationship between size and permeability, and the degree to which the data vary from the line is given by the value of R , the simple correlation coefficient. The coefficient of determination (R -squared) is the ratio of the explained variation to the total variation of the data with respect to the regression line (Krumbein and Graybill, 1965). Grain size is the independent variable (x), and permeability is the dependent variable (y).

An initial review of the unconsolidated-clastics permeability literature surprisingly revealed few studies where statistical regression methods have been used to describe the relationship between grain size and permeability for a consistent set of samples. Examples of exceptions are Behnke and

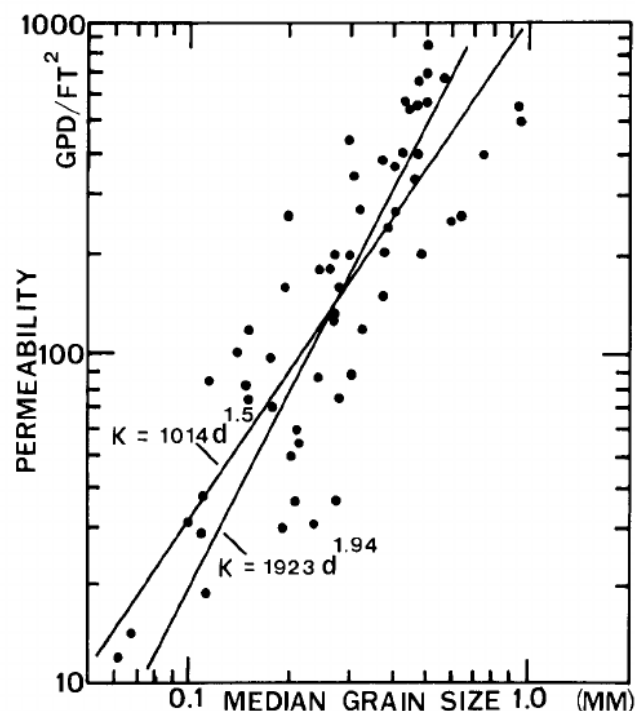


Fig. 1. Plot of permeability against grain size for Arkansas River alluvium, showing comparison of line presented by Bedinger (slope of 1.94) and least-squares line (slope of 1.5). After Bedinger, 1961.

Table 1. Summary of Data and Results of Regression Analyses

Data source	N	R ²	a	b	Comments
1. Hazen	10	.99	1,505	1.60	Filter sands
2. King	10	.99	11,904	1.56	Sands 36-45
3. Stearns	24	.62	4,272	1.33	Assorted samples
4. Schriever	16	.97	208,818	1.94	Glass spheres
5. Hulbert & Feben	8	.99	15,067	1.79	Ottawa sand, 60F
6. Hulbert & Feben	16	.67	10,927	1.81	Sands 9-25, d60
7. Hulbert & Feben	16	.78	24,857	1.88	Sands 9-25, d10
8. Mavis & Wilsey	12	.79	4,558	1.96	River sand
9. Krumbein & Monk	19	.99	1,229	1.96	Outwash fractions
10. Muskat	8	.78	12,396	1.84	Generalized data
11. von Englehardt & Pitter	35	.83	23,821	1.80	Loose to packed sieve fractions
12. Burmister	66	.92	18,355	1.95	All grain sizes
13. Burmister	20	.82	3,235	1.55	Silt only
14. Rose & Smith	14	.72	5,804	1.11	Assorted data
15. Bedinger	59	.67	1,014	1.47	River alluvium
16. Harleman <i>et al.</i>	10	.98	128,996	2.05	Uniform sizes
17. Keech & Rosene	42	.90	3,297	1.99	River alluvium
18. Masch & Denny	12	.71	1,873	1.41	River sand fractions

Reference numbers correspond to numbered regression lines, Figure 2.

N = Number of data points.

R² = Coefficient of determination for regression.

a = a in equation (2), for units of gallons per day per square foot.

b = b in equation (2).

Schiff (1963), who used linear least-squares regression, and Garcia-Bengochea and Lovell (1981), who used a power regression to relate pore size of silt and clay mixtures to permeability. The latter obtained an exponent of 1.67 for their model that corresponded to equation (1).

Sen Gupta and Nyun (1943) reported a statistically derived slope of 2.05 for a line fit through 23 data points from permeability and grain size measurements from sandstone cores.

Many sets of size/permeability data have been published which are readily amenable to statistical analysis. Most data are in publications from the early part of this century, but some recently obtained data exist. For example, the data presented by Bedinger (1961; Figure 1) constitute a large set of consistently obtained data from one natural environment covering a wide range of size and permeability values. The line Bedinger originally presented has a slope of 1.94 rather than 2.0, but more importantly, the power least-squares regression of the digitized data resulted in a slope of only 1.47 (Table 1; Figures 1 and 2). Indeed, it was the disparate slopes of the two lines fit to the Bedinger data that provided the principal impetus for this study, that is, comparing the functional relations between grain size and permeability represented by consistent sets of published data not previously analyzed by statistical regression methods.

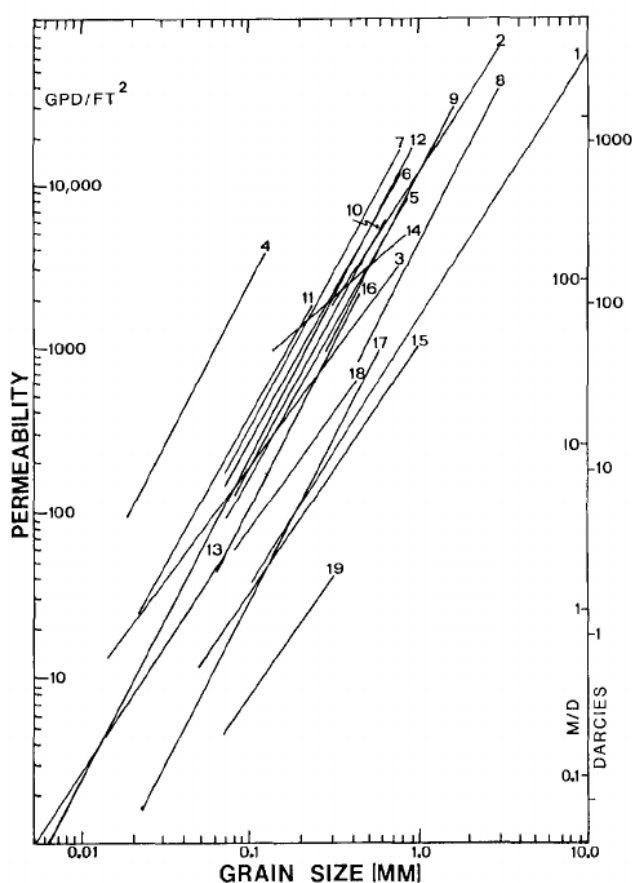


Fig. 2. Graph of permeability against grain size for 19 sets of data from the literature. Lines 1 through 18 are summarized in Table 1; line 19 is from data presented by Hrabar and Potter (1969) for a cemented sandstone from Indiana. Lengths of lines approximate ranges of data.

DATA REQUIREMENTS AND METHODS

Sets of laboratory data including grain size and permeability of unconsolidated clastic sediments were taken from the literature using geologic, hydrologic, engineering, and soils literature indexes, key-word computer searches, and reference trails from books and journal articles. The references provided by Summers and Weber (1984) were of special initial help. Of more than 100 articles inspected, approximately 25 sets of data were selected for regression analyses.

Several requirements for comparable regression data and results were established, resulting in the exclusion of several sets of data. First, samples had to be from a single population and consistently collected. Thus, many of the tables of miscellaneous data reported in U.S. Geological Survey Water-Supply Papers were excluded. Results from one sample set of this type are included in Table 1 and Figure 2 (Rose and Smith, 1957) to illustrate results from inconsistent data. Second, detailed grain size data were required. Many published data could not be used because a mode, mean, or another consistently representative, specifically measured diameter was not reported. Thus, some of the data in the literature were excluded because of incomplete or inadequate reporting, lack of adequate detail of grain size data, inconsistent samples, or representation of several diverse populations.

Nineteen sets of useable data including both grain size and permeability were analyzed (Table 1; Figure 2). Many of the data were published as graphs and were digitized for the regressions. As necessary, data were converted to consistent and comparable units (Freeze and Cherry, 1979, p. 29). The best-fit line was estimated for each data set by power least-squares regression, using a Hewlett-Packard 41-C programmable calculator equipped with an HP Stat-Pac.

REGRESSION RESULTS

Values of the coefficient (c) and exponent of grain size [equation (1)] were calculated (Table 1). The coefficient c ranged from 1014 to 208,818 (units of gallons per day per square foot) but only two values were over 25,000. The exponent ranged from 1.11 to 2.05, with an average of 1.72. In general, values of c were higher for data sets obtained from more texturally mature samples (characterized by uniformly sized particles, better sorted samples, and grains with higher roundness and sphericity). The lowest values of the exponent were from texturally immature sediments and from

miscellaneous samples from different environmental populations, despite being consistently tested for permeability.

Comparison of the best-fit regression lines (Figure 2) reveals some interesting relationships. First, the line with the highest value of c represents uniform glass spheres (Schriever, 1930). The line with the next highest value of c and one of the steeper slopes represents uniformly sized sieve fractions which were increasingly packed through time as permeability measurements were made (von Englehardt and Pitter, 1951). Lines representing samples that are increasingly less well-sorted are below and to the right of these. All the lines representing natural sediments are within a relatively narrow field. Finally, a lower limit for c exists for the samples tested (about 200 gallons per day per square foot).

Several of the data sets contain a dozen or fewer data points, and consequently yielded high values of R -squared. Of the sets with more than a dozen points, those presented by Schriever (1930), Hulbert and Feben (1933), von Englehardt and Pitter (1951), Burmister (1954), Bedinger (1961), and Keech and Rosene (1964) are considered especially valuable.

Schriever (1930) and von Englehardt and Pitter (1951) made consistent measurements of uniformly sized particles throughout the range of packing. The lines fitting their data sets constitute upper limits for texturally mature sediments. In contrast, Bedinger (1961) and Keech and Rosene (1964) provided results from natural, texturally immature sediments. The lines fitting their data sets plot only slightly above the line for a cemented river point bar deposit (Line 19, Figure 2, from Hrabar and Potter, 1969), which may be near the lower limit for unconsolidated sand and silt.

SIGNIFICANCE

From the results of Table 1 and Figure 2, a generalized graphical functional relation of grain size and permeability was prepared, subject to the limitations of the data (Figure 3). The coefficients and slopes of the lines shown are representative of the general trends observed among the 19 lines of Figure 2. The permeability of a texturally mature sediment is estimated using regression equations with slopes higher than 1.75, and that of a texturally immature sediment using regression lines with lower slopes, possibly as low as 1.5. Using maturity criteria and data from the literature, fields of permeability for grain sizes of dune,

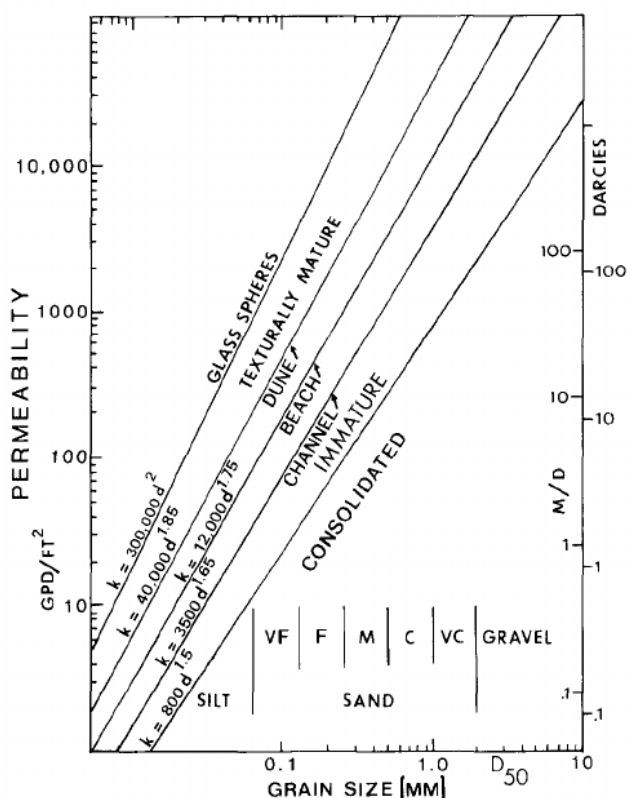


Fig. 3. Graph of permeability against grain size developed from relations seen in Figure 2 and Table 1. The equation for each of the five lines is shown in the form of equation (1) (units are gpd/ft²). Applications for different depositional environments are tentatively compared according to their grain sizes and degree of textural maturity, as generally indicated.

beach, and river sediments were indicated (Figure 3). This method of regression estimation of permeability from grain size offers an empirical alternative to the other methods provided by previous workers (Freeze and Cherry, 1979, p. 29).

ACKNOWLEDGMENTS

I thank John Thraillkill for analytical observations and suggestions.

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* * * * *

Russell G. Shepherd is a specialist in fluvial geomorphology, fluvial sedimentology, geohydrology, and engineering geology living in Des Moines, Iowa. He has bachelor's and master's degrees from Colorado State University, and a Ph.D. from the University of Texas at Austin. He has 20 years of geological experience working in industry, government, private consulting, and university teaching. His principal interests are in the quantitative analysis of fluvial processes, landforms, and sediments. He enjoys trying to solve practical problems in potamology, and especially those involving interactions between ground water and streams. The work reported here was done in 1987 at the University of Kentucky.

ASSOCIATION OF GROUND WATER SCIENTISTS AND ENGINEERS

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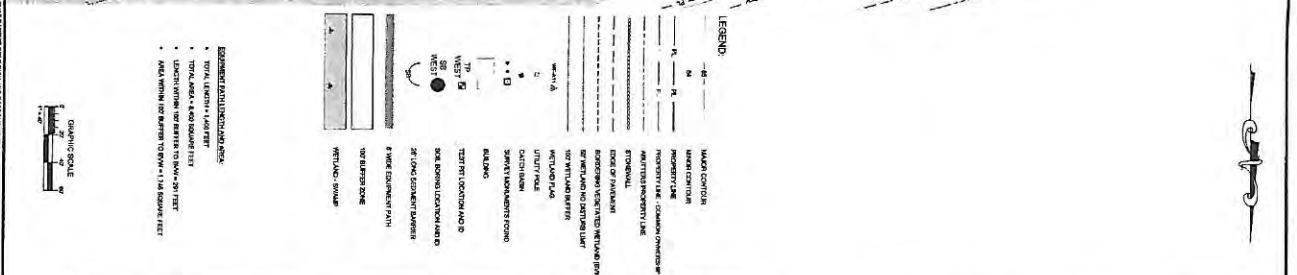
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Boring Logs

[illegible]



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BORING SB-Cent

PAGE 1 OF 1

PROJECT NAME County Road Partners, LLC

CLIENT BMV Corp

PROJECT NUMBER 3652-19-0201

PROJECT LOCATION Hanson, MA

DATE STARTED 3/26/19 COMPLETED 3/26/19

GROUND ELEVATION 85.5 ft Local HOLE SIZE 6

DRILLING CONTRACTOR Hoffman Environmental Services

DRILLING TERMINATION DEPTH 20.5 ft / Elev 65 ft

DRILLING METHOD HSA

REFUSAL DEPTH N/A

DRILLING EQUIPMENT

GROUND WATER LEVELS:

HAMMER TYPE

▼ AT END OF DRILLING 6.00 ft / Elev 79.50 ft

LOGGED BY Avenia, G. CHECKED BY D Tate

24hrs AFTER DRILLING Backfilled, no reading

NOTES

GEOTECH BH PLOTS - TEST TEMP GDT - 5/3/19 15:02 - R:101 - INFRASTRUCTURE DESIGN - 2019 PROJECTS - WOOD NEW ENGLAND\3652-19-0201 HANSON, MA SOLAR SITE\4. FIELD EXPLORATION\HANSON MA SOLAR.GPJ

ELEV. (ft)	DEPTH (ft)	GRAPHIC LOG	MATERIAL DESCRIPTION	SAMPLE TYPE NUMBER	RECOVERY % (RQD)	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	DRY UNIT WT. (pcf)	▲ SPT N VALUE ▲			
									20	40	60	80
86	0								PL	MC	LL	
									20	40	60	80
									□ FINES CONTENT (%) □			
									20	40	60	80
			SILTY SAND, dark brown to brown, poorly graded, fine to medium grained, moist to wet, loose to dense, loam	SS 1		0-1-2-6 (3)						
				SS 2		5-12-16-18 (28)						
81	5			SS 3		9-12-14-15 (26)						
				SS 4		9-16-17 (33)						
76	10		SAND, brown, poorly graded, fine grained, moist, dense, trace gravel	SS 5		9-13-34 (47)						
71	15		SILT, brown, moist, stiff (Sampled as very dense silty sand) SANDSTONE, highly weathered, dark gray, fine, soft, [Rhode Island Formation] with Graywacke, Shale, Conglomerate, fossil Plants	SS 6		12-27-43 (70)						
66	20			SS 7		11-30-41 (71)						

Bottom of borehole at 20.5 feet.



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BORING SB-East

PAGE 1 OF 1

PROJECT NAME County Road Partners, LLC

CLIENT BMV Corp

PROJECT NUMBER 3652-19-0201

PROJECT LOCATION Hanson, MA

DATE STARTED 3/26/19

COMPLETED 3/26/19

GROUND ELEVATION 85.5 ft Local

HOLE SIZE 6

DRILLING CONTRACTOR Hoffman Environmental Services

DRILLING TERMINATION DEPTH 19.2 ft / Elev 66.3 ft

DRILLING METHOD HSA

REFUSAL DEPTH 19.2 ft / Elev 66.3 ft

DRILLING EQUIPMENT

GROUND WATER LEVELS:

HAMMER TYPE

▼ AT END OF DRILLING 3.50 ft / Elev 82.00 ft

LOGGED BY Avenia, G.

CHECKED BY D Tate

24hrs AFTER DRILLING Backfilled, no reading

NOTES

ELEV. (ft)	DEPTH (ft)	GRAPHIC LOG	MATERIAL DESCRIPTION	SAMPLE TYPE NUMBER	RECOVERY % (RQD)	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	DRY UNIT WT. (pcf)	▲ SPT N VALUE ▲			
									20	40	60	80
86	0								PL	MC	LL	
									20	40	60	80
									□ FINES CONTENT (%) □			
									20	40	60	80
			SILT, dark brown, dry, very loose, with organics, (Topsoil)	SS 1		0-1-12 (13)						
			SAND, Mottled tan and, poorly graded, fine to medium grained, wet to moist, medium dense, with loam	SS 2		10-12-10 (22)						
81	5			SS 3		6-12-25 (37)						
			SAND, brown to grayish brown, poorly graded, fine to medium grained, wet to moist, medium dense	SS 4		10-12-14 (26)						
76	10			SS 5		9-10-15 (25)						
71	15		GRAVELLY SAND, gray, poorly graded, fine grained, wet, very dense, with silt	SS 6		15-47-38 (85)						
				SS 7		50/2"						

Refusal at 19.2 feet.
Bottom of borehole at 19.2 feet.

GEOTECH BH PLOTS - TEST TEMP GDT - 5/3/19 15:02 - R:01 - INFRASTRUCTURE DESIGN, 2019 PROJECTS, WOOD NEW ENGLAND\3652-19-0201 HANSON, MA SOLAR SITE\4 FIELD EXPLORATION\HANSON MA SOLAR.GPJ

PROJECT NAME County Road Partners, LLC

CLIENT BMV Corp

PROJECT NUMBER 3652-19-0201

PROJECT LOCATION Hanson, MA

DATE STARTED 3/26/19

COMPLETED 3/26/19

GROUND ELEVATION 84 ft Local

HOLE SIZE 6

DRILLING CONTRACTOR Hoffman Environmental Services

DRILLING TERMINATION DEPTH 5.5 ft / Elev. 78.5 ft

DRILLING METHOD HSA

REFUSAL DEPTH 5.5 ft / Elev 78.5 ft

DRILLING EQUIPMENT

GROUND WATER LEVELS:

HAMMER TYPE

AT END OF DRILLING Dry

LOGGED BY Avenia, G.

CHECKED BY D Tate

24hrs AFTER DRILLING Backfilled, no reading

NOTES

ELEV. (ft)	DEPTH (ft)	GRAPHIC LOG	MATERIAL DESCRIPTION	SAMPLE TYPE NUMBER	RECOVERY % (RQD)	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	DRY UNIT WT. (pcf)	▲ SPT N VALUE ▲			
									20 40 60 80			
									PL	MC	LL	
									20 40 60 80			
									☐ FINES CONTENT (%) ☐			
									20 40 60 80			
84	0		SILTY SAND, brown, poorly graded, fine to coarse grained, dry to wet, medium dense to very dense, trace roots, trace gravel									
79	5					1-7-20-23 (27)						
						6-25-57 (82)						

Refusal at 5.5 feet.
Bottom of borehole at 5.5 feet.



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Telephone: 615.333.0630

BORING SB-West B

PAGE 1 OF 1

PROJECT NAME County Road Partners, LLC

CLIENT BMV Corp

PROJECT NUMBER 3652-19-0201

PROJECT LOCATION Hanson, MA

DATE STARTED 3/26/19 COMPLETED 3/26/19

GROUND ELEVATION 84 ft Local HOLE SIZE 6

DRILLING CONTRACTOR Hoffman Environmental Services

DRILLING TERMINATION DEPTH 14.3 ft / Elev 69.7 ft

DRILLING METHOD HSA

REFUSAL DEPTH 14.3 ft / Elev 69.7 ft

DRILLING EQUIPMENT

GROUND WATER LEVELS:

HAMMER TYPE

▼ AT END OF DRILLING 7.50 ft / Elev 76.50 ft

LOGGED BY Avenia, G.

CHECKED BY D Tate









































24hrs AFTER DRILLING Backfilled, no reading

NOTES

ELEV. (ft)	DEPTH (ft)	GRAPHIC LOG	MATERIAL DESCRIPTION	SAMPLE TYPE NUMBER	RECOVERY % (RQD)	BLOW COUNTS (N VALUE)	POCKET PEN. (tsf)	DRY UNIT WT. (pcf)	▲ SPT N VALUE ▲ 20 40 60 80 PL MC LL 20 40 60 80 □ FINES CONTENT (%) □ 20 40 60 80
84	0		SAND, brown to grayish brown, poorly graded, medium grained, wet to moist, dense to very dense						
				SS 1		6-12-20 (32)			
79	5			SS 2		24-34-39 (73)			
				SS 3		9-16-17 (33)			
74	10		(Sampled as very dense silty sand) SANDSTONE, highly weathered, dark gray, fine, soft, [Rhode Island Formation] with Graywacke, Shale, Conglomerate, fossil Plants						
				SS 4		100/4"			

Refusal at 14.3 feet.
Bottom of borehole at 14.3 feet.

LITHOLOGIC SYMBOLS

	Asphalt		Poorly-graded Sandy Gravel		Poorly-graded Sand with Clay
	Topsoil		Well-graded Gravel		Poorly-graded Sand with Silt
	Concrete		Well-graded Gravel with Clay		Well-graded Sand
	Fill (made ground)		Well-graded Gravel with Silt		Well-graded Gravelly Sand
	Boulders and cobbles		Well-graded Sandy Gravel		Well-graded Sand with Clay
	High Plasticity Clay		Elastic Silt		Well-graded Sand with Silt
	Low Plasticity Clay		Silt		Limestone
	Low Plasticity Silty Clay		Gravelly Silt		Sandstone
	Low Plasticity Sandy Clay		Sandy Silt		Shale
	Clayey Gravel		Clayey Sand		Siltstone
	Silty Gravel		Clayey, Silty Sand		Conglomerate
	Poorly-graded Gravel		Silty Sand		Dolomite
	Poorly-graded Gravel with Clay		Poorly-graded Sand		
	Poorly-graded Gravel with Silt		Poorly-graded Gravelly Sand		

SAMPLER SYMBOLS

	Rock Core
	Split Spoon
	Shelby Tube

CORRELATION OF STANDARD PENETRATION RESISTANCE WITH
RELATIVE DENSITY AND CONSISTENCY

COHESIONLESS SOILS



Relative Density	SPT N-Value
Very Loose	4 or less
Loose	5 - 10
Medium Dense	11 - 30
Dense	31 - 50
Very Dense	Greater than 50

COHESIVE SOILS

Consistency	SPT N-Value
Very Soft	2 or less
Soft	3 - 4
Firm	5 - 8
Stiff	9 - 15
Very Stiff	16 - 30
Hard	31 - 50
Very Hard	Greater than 50

ABBREVIATIONS

LL	-LIQUID LIMIT (%)
PI	-PLASTIC INDEX (%)
W	-MOISTURE CONTENT (%)
DD	-DRY DENSITY (PCF)
NP	-NON PLASTIC
-200	-PERCENT PASSING NO. 200 SIEVE
PP	-POCKET PENETROMETER (TSF)

PID	-PHOTOIONIZATION DETECTOR
UC	-UNCONFINED COMPRESSION
ppm	-PARTS PER MILLION
	Water Level at End of Drilling, or as Shown
	Water Level After 24 Hours, or as Shown

Mounding Equations

MODRET

SUMMARY OF UNSATURATED & SATURATED INPUT PARAMETERS

**PROJECT NAME : Fern Hill Basin 1P Basin Full Volume An
POLLUTION VOLUME RUNOFF DATA USED
UNSATURATED ANALYSIS INCLUDED**

Pond Bottom Area	6,636.00 ft ²
Pond Volume between Bottom & DHWL	16,000.00 ft ³
Pond Length to Width Ratio (L/W)	2.40
Elevation of Effective Aquifer Base	60.00 ft
Elevation of Seasonal High Groundwater Table	76.90 ft
Elevation of Starting Water Level	78.90 ft
Elevation of Pond Bottom	78.90 ft
Design High Water Level Elevation	81.10 ft
Avg. Effective Storage Coefficient of Soil for Unsaturated Analysis	0.20
Unsaturated Vertical Hydraulic Conductivity	1.75 ft/d
Factor of Safety	1.00
Saturated Horizontal Hydraulic Conductivity	17.85 ft/d
Avg. Effective Storage Coefficient of Soil for Saturated Analysis	0.20
Avg. Effective Storage Coefficient of Pond/Exfiltration Trench	1.00

Hydraulic Control Features:

Groundwater Control Features - Y/N

	Top	Bottom	Left	Right
Distance to Edge of Pond	N 0.00	N 0.00	N 0.00	N 0.00
Elevation of Water Level	0.00	0.00	0.00	0.00

Impervious Barrier - Y/N

	Top	Bottom	Left	Right
Elevation of Barrier Bottom	N 0.00	N 0.00	N 0.00	N 0.00

MODRET

TIME - RUNOFF INPUT DATA

PROJECT NAME: FERN HILL BASIN 1P BASIN FULL VOLUME AN

STRESS PERIOD NUMBER	INCREMENT OF TIME (hrs)	VOLUME OF RUNOFF (ft ³)
Unsat	5.49	2,654.40
1	1.00	13,345.60
2	8.19	0.00
3	8.19	0.00
4	8.19	0.00
5	8.19	0.00
6	8.19	0.00
7	8.19	0.00
8	8.19	0.00
9	8.19	0.00

MODRET

SUMMARY OF RESULTS

PROJECT NAME : Fern Hill Basin 1P Basin Full Volume An

CUMULATIVE TIME (hrs)	WATER ELEVATION (feet)	INSTANTANEOUS INFILTRATION RATE (cfs)	AVERAGE INFILTRATION RATE (cfs)	CUMULATIVE OVERFLOW (ft ³)
00.00 - 0.00	76.900	0.000 *		
			0.00000	
0.00	76.900	0.14731		
			0.14731	
6.49	80.627	0.14731		0.00
			0.14731	
14.67	80.030	0.11703		0.00
			0.08675	
22.86	79.678	0.07299		0.00
			0.05924	
31.05	79.438	0.05297		0.00
			0.04670	
39.24	79.249	0.04267		0.00
			0.03864	
47.43	79.092	0.03579		0.00
			0.03294	
55.62	78.959	0.03079		0.00
			0.02864	
59.76	78.900	0.02697		0.00
			0.02530	
72.00	78.740			0.00

Maximum Water Elevation: 80.627 feet @ 6.49 hours

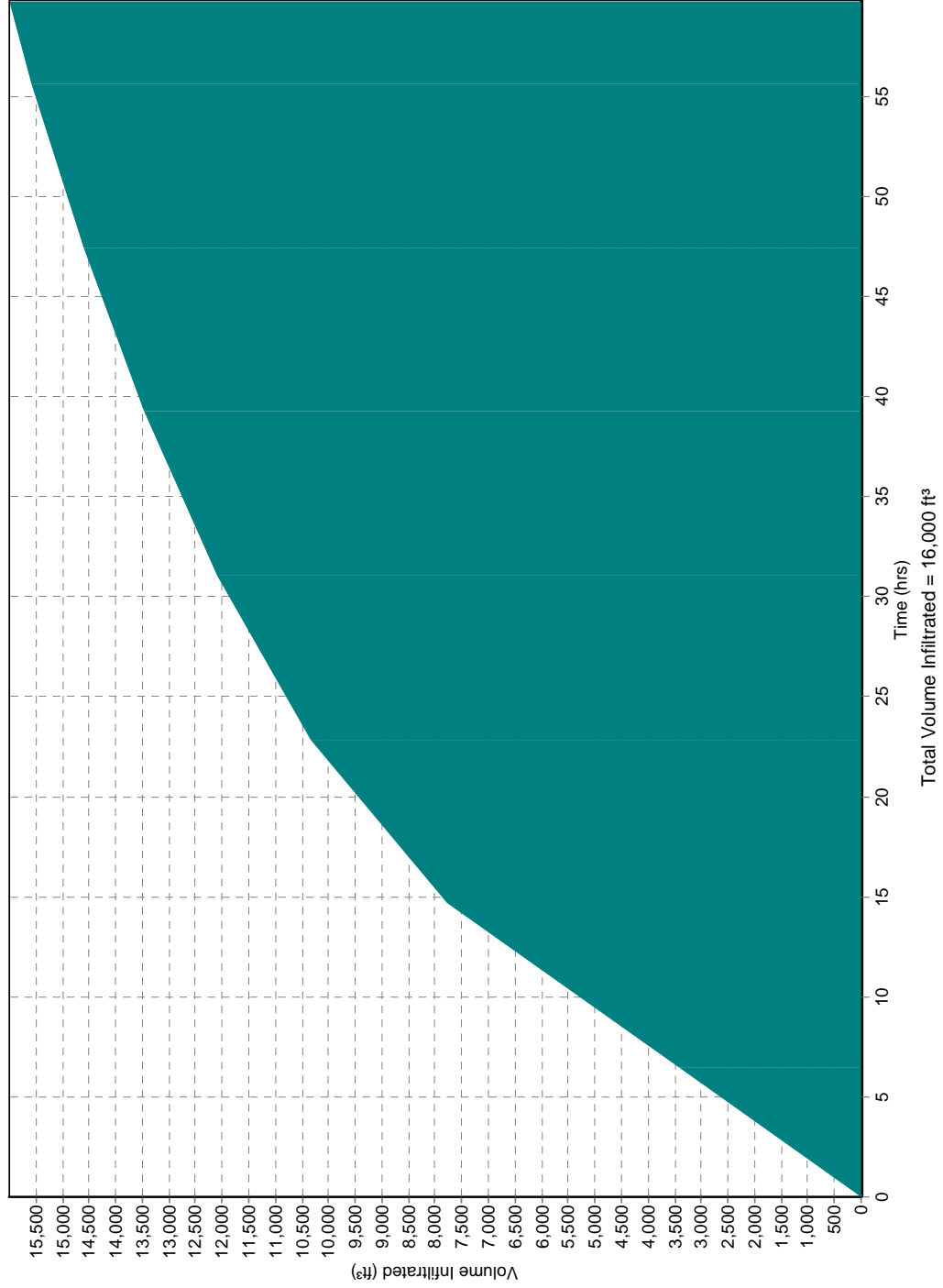
Recovery @ 59.759 hours

* Time increment when there is no runoff

Maximum Infiltration Rate: 1.750 ft/day

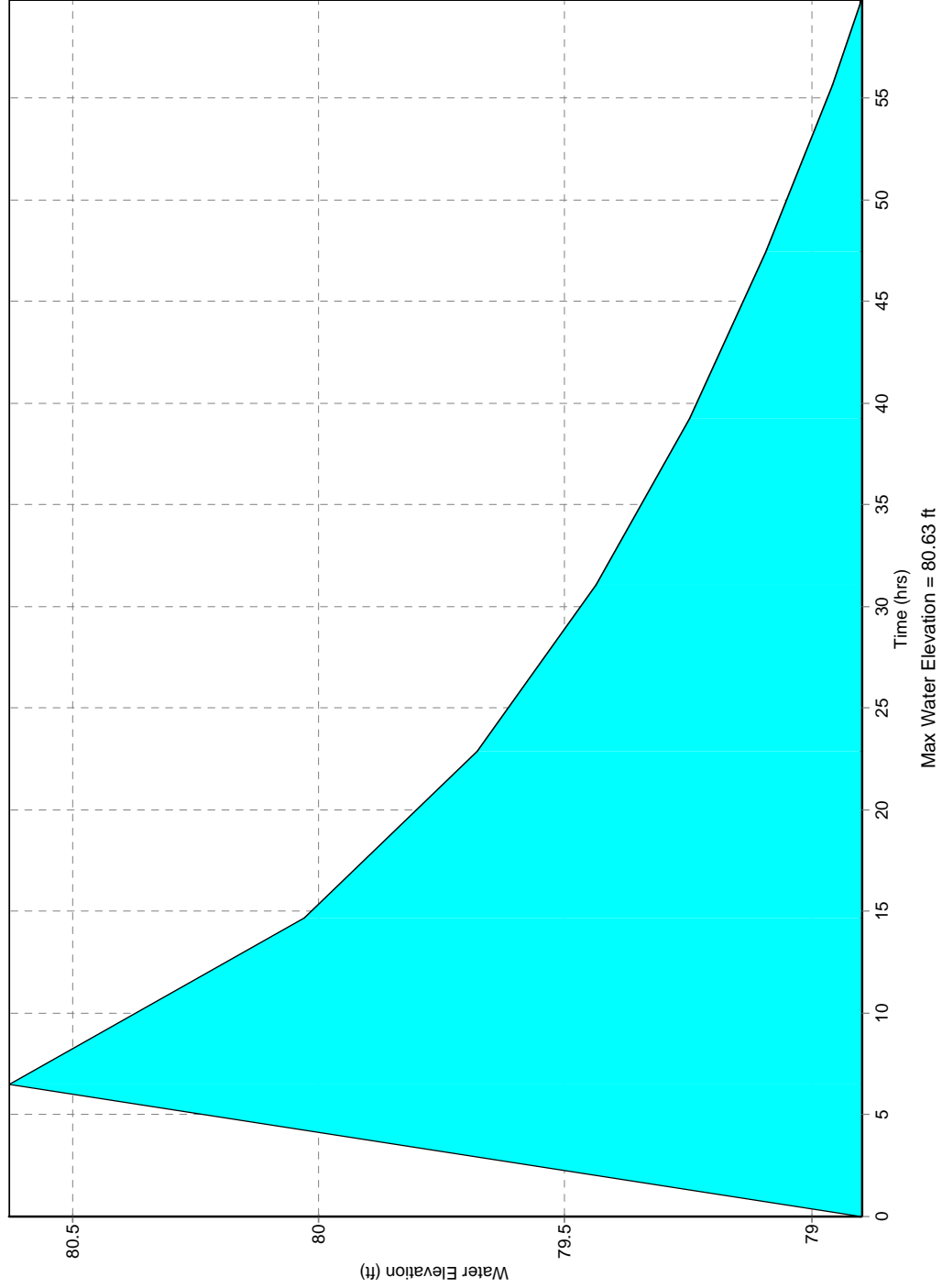
Analysis Date: 7/18/2021

INFILTRATION : FERN HILL BASIN 1P BASIN FULL VOLUME AN



Total Volume Infiltrated = 16,000 ft³

INFILTRATION : FERN HILL BASIN 1P BASIN FULL VOLUME AN



MODRET

SUMMARY OF UNSATURATED & SATURATED INPUT PARAMETERS

**PROJECT NAME : Fern Hill Basin 2P Basin Full Volume An
POLLUTION VOLUME RUNOFF DATA USED
UNSATURATED ANALYSIS INCLUDED**

Pond Bottom Area	1,766.00 ft ²
Pond Volume between Bottom & DHWL	1,739.00 ft ³
Pond Length to Width Ratio (L/W)	2.30
Elevation of Effective Aquifer Base	64.00 ft
Elevation of Seasonal High Groundwater Table	82.30 ft
Elevation of Starting Water Level	84.30 ft
Elevation of Pond Bottom	84.30 ft
Design High Water Level Elevation	85.10 ft
Avg. Effective Storage Coefficient of Soil for Unsaturated Analysis	0.20
Unsaturated Vertical Hydraulic Conductivity	1.72 ft/d
Factor of Safety	1.00
Saturated Horizontal Hydraulic Conductivity	17.20 ft/d
Avg. Effective Storage Coefficient of Soil for Saturated Analysis	0.20
Avg. Effective Storage Coefficient of Pond/Exfiltration Trench	1.00

Hydraulic Control Features:

Groundwater Control Features - Y/N

	Top	Bottom	Left	Right
Distance to Edge of Pond	N	N	N	N
Elevation of Water Level	0.00	0.00	0.00	0.00

Impervious Barrier - Y/N

	Top	Bottom	Left	Right
Elevation of Barrier Bottom	N	N	N	N
	0.00	0.00	0.00	0.00

MODRET

TIME - RUNOFF INPUT DATA

PROJECT NAME: FERN HILL BASIN 2P BASIN FULL VOLUME AN

STRESS PERIOD NUMBER	INCREMENT OF TIME (hrs)	VOLUME OF RUNOFF (ft³)
Unsat	5.58	706.40
1	1.00	1,032.60
2	0.57	0.00
3	0.57	0.00
4	0.57	0.00
5	0.57	0.00
6	0.57	0.00
7	0.57	0.00
8	0.57	0.00
9	0.57	0.00

MODRET

SUMMARY OF RESULTS

PROJECT NAME : Fern Hill Basin 2P Basin Full Volume An

CUMULATIVE TIME (hrs)	WATER ELEVATION (feet)	INSTANTANEOUS INFILTRATION RATE (cfs)	AVERAGE INFILTRATION RATE (cfs)	CUMULATIVE OVERFLOW (ft ³)
00.00 - 0.00	82.300	0.000 *		
			0.00000	
0.00	82.300	0.04327		
			0.04327	
6.58	84.628	0.04327		0.00
			0.04327	
7.15	84.587	0.04327		0.00
			0.04327	
7.73	84.546	0.04327		0.00
			0.04327	
8.30	84.505	0.04327		0.00
			0.04327	
8.87	84.464	0.04327		0.00
			0.04327	
9.44	84.423	0.04327		0.00
			0.04327	
10.02	84.382	0.04327		0.00
			0.04327	
10.59	84.341	0.04327		0.00
			0.04327	
11.16	84.300			0.00

Maximum Water Elevation: 84.628 feet @ 6.58 hours

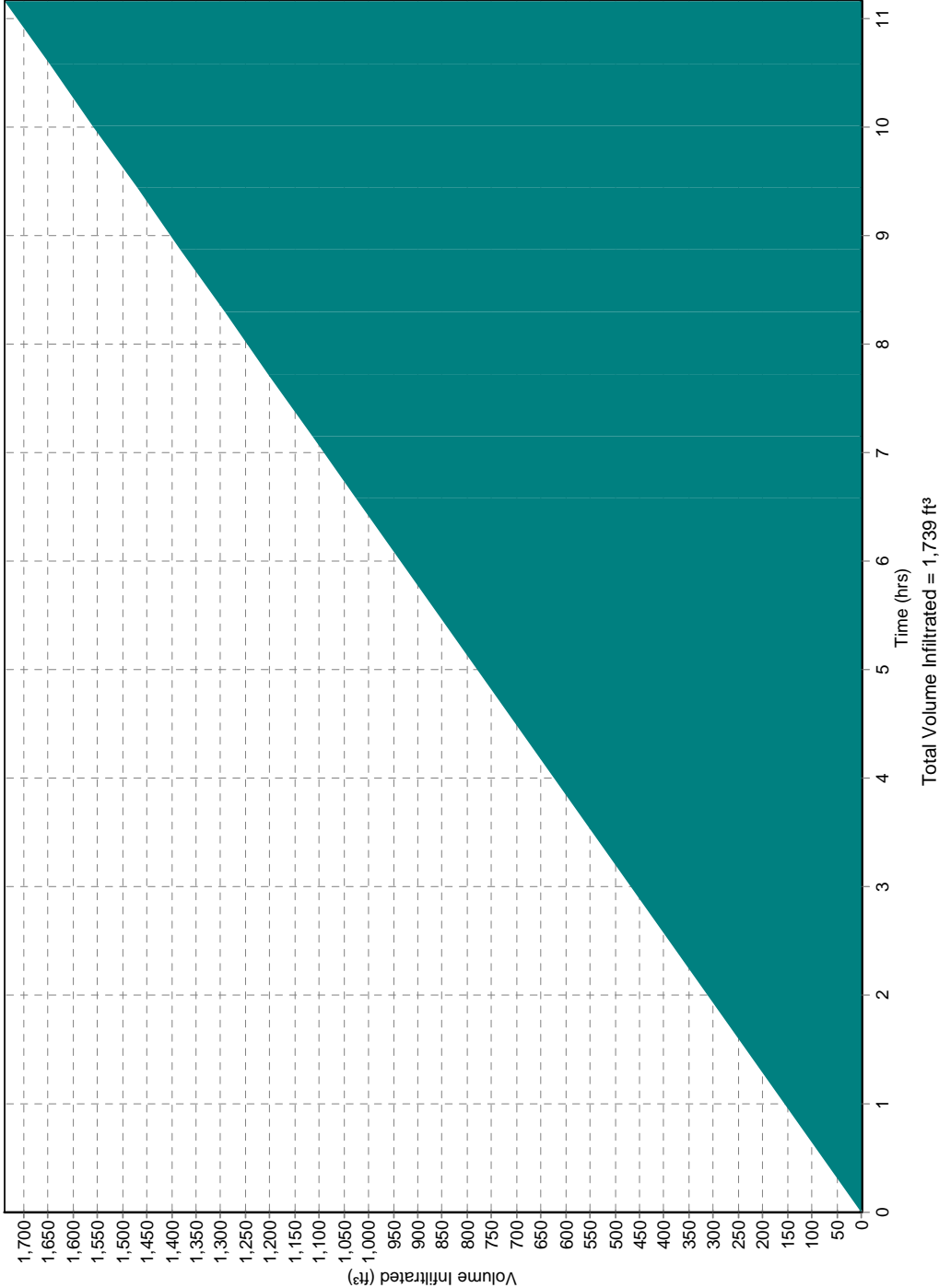
Recovery @ > 11.160 hours

* Time increment when there is no runoff

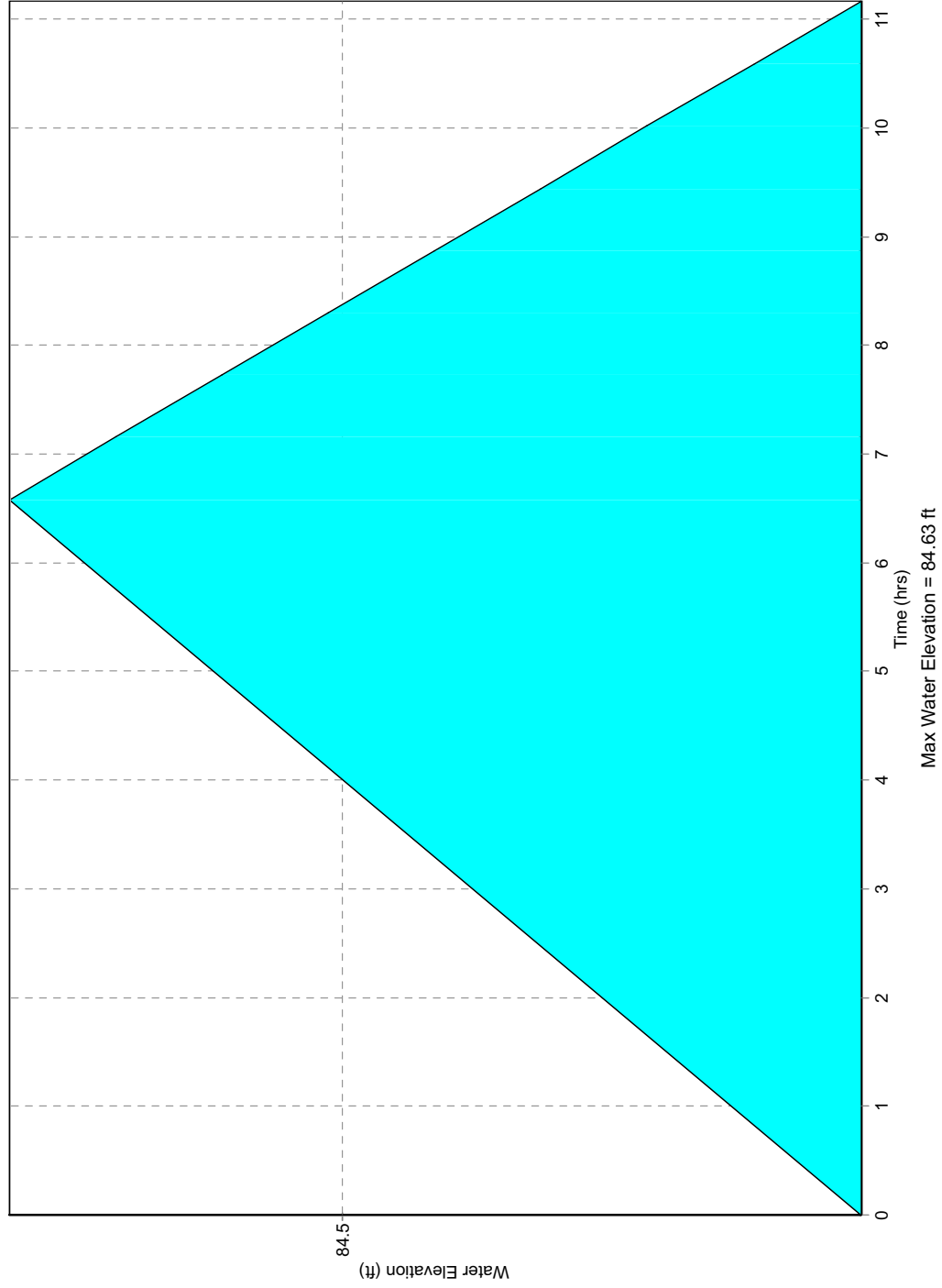
Maximum Infiltration Rate: 1.720 ft/day

Analysis Date: 7/19/2021

INFILTRATION : FERN HILL BASIN 2P BASIN FULL VOLUME AN



INFILTRATION : FERN HILL BASIN 2P BASIN FULL VOLUME AN



MODRET 6.1

INTRODUCTION

MODRET (Computer **MODEL** to Design **RETENTION** Ponds) was originally developed in 1990, by Nicolas E. Andreyev, P.E. as a complement to a research and development project for the Southwest Florida Water Management District (SWFWMD), Brooksville, Florida. The scope of this project was to develop a practical design manual for site investigation criteria, laboratory and field testing requirements, and guidelines to calculate infiltration losses from stormwater retention ponds in unconfined shallow aquifers. Since 1990 there have been several revisions to the original model, consisting of more options and greater flexibility. For this revision, the model was once again totally re-designed and greatly improved. MODRET Version 6.1, *For Windows 98/NT/XP*, allows generation of runoff hydrographs with various methods, calculation of infiltration losses from a retention pond, discharge (overflow) through various types of weirs and orifices, and generation of graphical results that are suitable for inclusion in final design reports for presentation and permitting. **In addition, this version includes a pond routing module**, which allows routing runoff through a pond, allowing for infiltration losses and determination of **peak discharge rate and peak water elevation**. This version is fully compatible with all **Windows Environments**, which allows flexibility in data management as well as text and graph generation on any compatible printing or plotting device. MODRET Version 6.1, *For Windows 98/NT/XP*, is used for permit reviews by the SWFWMD, SJRWMD, FDOT, FDEP, numerous counties in Florida and other regulatory agencies.

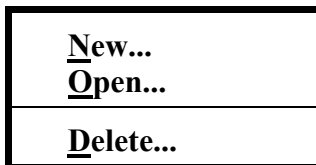
The new model capabilities, data entry, and output formats were developed based on many comments and recommendations submitted by the users of previous versions of MODRET.

This user's guide was developed to allow detailed explanations of the model menu screen prompts to assist the "first time" user in understanding the conventions and functions of each prompt. The user's guide was designed in a graphical/schematic format to allow quick access to the material and find the answers to questions. The Infiltration module of the program uses a modified Green & Ampt infiltration equation to calculate unsaturated infiltration and a modified USGS model "A Modular Three Dimensional Finite Difference Ground Water Flow Model", McDonald & Harbaugh, 1984, to calculate saturated infiltration.

The user is assumed to be a professional with a background in hydrology and/or hydrogeology, and has a good command in surface runoff and groundwater flow modeling. It is assumed that the user has read the *"Stormwater Retention Pond Infiltration Analysis in Unconfined Aquifers"*, manual (Andreyev, Wiseman, 1989) and understands the applicability and limitations of the MODRET program. It is also assumed that the user is familiar with the use of personal computers, Microsoft Windows operating system and its environment.



Infiltration



Clicking on the **New** option allows setting up a new infiltration input data set, or opening and editing an existing infiltration data set, print the input data set with the **Print** button, run the MODFLOW model with the **Run** button, and save the new or modified data set with the **Save** or **Save As** buttons. **Note that the MODFLOW model is a modified version, only applicable to the MODRET application, since the original DRAIN package of MODFLOW has been modified to allow specification of WEIR/ORIFICE overflow.** See INTRODUCTION section of this User's Manual (What's New in MODRET Version 6.1) for more details of weir/orifice overflow options.

New

Clicking on the **New** button, the following screen will appear allowing input of new infiltration data. If an existing infiltration data is desired to be imported for review and/or modification, it can be achieved by clicking on the **Open** button and selecting a desired file name:

Saturated and Unsaturated Data Input

Project Name: _____

Unsaturated Analysis: ☒ Yes ☐ No

Runoff Data: Overflow:

Design High Water Elevation:

Area at Starting Water Level (ft ²):	<input type="text" value="1.00"/>
Volume Between Starting Water Level & Estimated High Water Level (ft ³):	<input type="text" value="2.00"/>
Pond Length to Width Ratio (L/W):	<input type="text" value="1.00"/>
Elevation of Effective Aquifer Base (ft):	<input type="text" value="0.00"/>
Elevation of Seasonal High Groundwater Table (ft):	<input type="text" value="1.00"/>
Elevation of Starting Water Level (ft):	<input type="text" value="2.00"/>
Elevation of Pond Bottom (ft):	<input type="text" value="2.00"/>
Average Effective Storage Coefficient of Soil for Unsaturated Analysis:	<input type="text" value="0.10"/>
Unsaturated Vertical Hydraulic Conductivity (ft/d):	<input type="text" value="5.00"/>
Factor of Safety for Kvu (typically 2.0):	<input type="text" value="2.00"/>
Saturated Horizontal Hydraulic Conductivity (ft/d):	<input type="text" value="10.00"/>
Average Effective Storage Coefficient of Soil for Saturated Analysis:	<input type="text" value="0.20"/>
Average Effective Storage Coefficient of Pond (typically 1.0):	<input type="text" value="1.00"/>

Run Open Save... Save As.. Print Cancel

Input View Volume Infiltrated Elevation of Water Level

The **Project/Pond Name or Number** line requires specification of a name for the infiltration input data. This is for identification purposes only (**it is not a file name**). This **Name** will appear on the tabular and graphical printouts and on graphical view screens.

Unsaturated Analysis

The **Unsaturated Analysis** box allows specification to include unsaturated analysis in this simulation "Y" or exclude it "N". If "Y" is specified, MODRET automatically calculates unsaturated infiltration at the beginning of the saturated analysis and incorporates it into the overall water balance analysis. With the pollution abatement runoff volume option, the unsaturated infiltration volume and the corresponding time are calculated and used to subtract from the specified total runoff and recovery time. With the manual runoff input option, the unsaturated infiltration volume and the corresponding time are calculated and displayed for review and use as appropriate. With the runoff hydrograph data file option, the unsaturated volume and the effective time on the hydrograph curve is automatically calculated by MODRET and the starting time for saturated analysis is adjusted accordingly.

*The **Runoff Data** option is not activated until the required pond and aquifer parameters have been specified. Similarly, the **Overflow** option is not activated until the required pond and aquifer parameters have been specified. Details for these two options will be presented later in this section of the manual.*

Infiltration Model Input Data

The following is a line by line explanation for the infiltration model input data:

The **Area at Starting Water Level** prompt allows specification of the actual area of the pond at the starting water level. For dry ponds this value would be the pond bottom area. This value is used by MODRET in combination with pond volume, design high water level and length to width ratio to calculate the equivalent average length and width of pond for modeling purposes.

The **Volume Between Starting Water Level & Estimated High Water Level** prompt allows specification of the actual **volume of the pond** to be modeled, as measured between the starting and ending water levels for a particular simulation. This value is used by MODRET to calculate the average length and width of pond for subsequent sizing of the finite difference grid system for MODFLOW. The specification of starting water level, volume between starting and ending water level and length to width ratio of the pond (instead of the actual average pond length and width) was incorporated into MODRET to minimize the need to hand measure and calculate the average length and width of ponds. Typically, the pond areas and stage-storage data are readily available, while the average pond length and width are not.

The **Pond Length to Width Ratio** prompt allows specification of the approximate ratio of the length of pond divided by the width of pond. This can be obtained from approximate measurement or approximation of the overall geometry of the pond. For irregular pond shapes, outline the overall area it occupies, and select the approximate length and width that a rectangular pond may occupy within the same area. Minor differences of the length to width ratio should not affect the results.

The **Elevation of Effective Aquifer Base** refers to the base of aquifer (permeable portion of soil strata hydraulically connected to the pond) located directly below and around the pond, and which is effectively connected to the pond with permeable soil strata. Typically, this will be the **TOP OF THE FIRST RESTRICTIVE SOIL** stratum below the pond (i.e., Hardpan, Clayey Sands, Clays, Organic Materials, Silts, Rock, etc.). Sometimes, if the bottom of pond is excavated to a depth below a shallow restrictive soil layer, the base of effective aquifer may be extended to the top of the next restrictive soil stratum. It is very important to carefully evaluate the value of this input data, as it can affect the results significantly, if it is not properly established. Based on the research by Bouwer (Groundwater Hydrology, Bouwer, 1978), the effective depth of an unconfined aquifer below an infiltration pond is equal to one (1) width of the pond. Therefore, the MODRET model checks this condition, and if the specified aquifer base is deeper than one width of pond, it automatically adjusts the aquifer base elevation and the new elevation is displayed on the input screen. A message will appear in a box indicating that the aquifer base has been adjusted to the minimum elevation allowed.

The **Elevation of Seasonal High Groundwater Table**, **Elevation of Starting Water Level** and the **Elevation of Pond Bottom** are self explanatory. The seasonal high groundwater

table must be established by a qualified soil scientist or a geotechnical engineer, with local experience. The starting water level **was added in this version of MODRET** to eliminate confusion of pond bottom elevation of wet retention ponds. For this version, the starting water level is used to calculate pond dimensions, unsaturated infiltration and as starting level for saturated infiltration modeling. The elevation of pond bottom is used only to check the vertical effect of the pond on the aquifer and to print the actual value of the pond bottom for wet retention ponds.

The **Effective Storage Coefficient of Soil for Unsaturated and Saturated Analyses** prompt allows specification of the appropriate effective storage coefficient or **fillable porosity**. These values depend on the soil types, in-situ moisture content of the soil, and the average groundwater mounding during the model simulation. MODRET automatically calculates these two values, based on the South Florida Water Management District data of Soil Storage Curves (depth to water table vs cumulative available storage) and the elevations provided for the pond to be modeled (MODRET calculates these values using Table A-1 included in this document, for Uncompacted Soil). These calculated values can be accepted by the user or changed.

The **Unsaturated Vertical Hydraulic Conductivity** prompt allows specification of the average hydraulic conductivity or permeability of the soil **between starting water level and seasonal high groundwater table**. Typically, the reported hydraulic conductivity values are for saturated condition and need to be adjusted. The saturated vertical hydraulic conductivity should be multiplied by a factor of 2/3 to achieve an approximate value of unsaturated hydraulic conductivity (Andreyev & Wiseman, 1989).

The **Saturated Horizontal Hydraulic Conductivity** prompt allows specification of the average hydraulic conductivity or permeability of the soil **between design high water level and elevation of effective aquifer base**. Typically, the permeability tests provide values for portions of the effective aquifer system (specific soil strata) and it is necessary to calculate an average value by utilizing the measured data with estimated data to obtain a representative weighted average value. Refer to **Examples 1 and 2** for equations and procedures to calculate weighted average horizontal hydraulic conductivity.

The **Average Effective Storage Coefficient of Pond** prompt allows specification of an average fraction of pond volume that is unobstructed. Typically, an open pond will be completely unobstructed and a value of 1.0 should be specified for this prompt. However, in the case of underground exfiltration trenches, the gravel pack and solid portions of pipes are an abstraction and the effective storage coefficient could be in the range of 0.4 to 0.6.

The **Time Increment During Storm Event**, the **Time Increment After Storm Event** and the **Total Number of Increments after Storm Event** prompts will appear **only** if the option of **HYDROGRAPH** is specified in the Runoff Data box. Although MODRET will allow specification of shorter time increments, time increments during the storm event are recommended to be 0.25 hour or larger for infiltration losses modeling. Due to the method of calculation (3-dimensional groundwater flow model MODFLOW) short time increments, may result in some error of convergence of the finite difference equations. If small time

increments are used and MODFLOW fails to converge, MODRET will detect this error, during reading of output data, and will display an error message, indicating that MODFLOW failed to converge. This could happen with small time increment or when unrealistic (or wrong) data is entered. If this occurs, try changing time increments or correct input data and then re-run the program. The time increments after the storm event is typically specified to evaluate the rate of water level decline in the pond after the storm event and the increments could be relatively large (typically 6 to 12 hours).

Working Directory = C:\Program Files\Engineering Software\MODRET61\Files - [Infiltrat...

Setup Hydrograph Infiltration Routing Graphic Windows HELP

Saturated and Unsaturated Data Input

Project Name:

Unsaturated Analysis: ☒ Yes ☐ No

Runoff Data: **HYDROGRAPH** Overflow: **NONE**

Design High Water Elevation:

Elevation of Pond Bottom (ft):

Average Effective Storage Coefficient of Soil for Unsaturated Analysis:

Unsaturated Vertical Hydraulic Conductivity (ft/d):

Factor of Safety for Kvu (typically 2.0):

Saturated Horizontal Hydraulic Conductivity (ft/d):

Average Effective Storage Coefficient of Soil for Saturated Analysis:

Average Effective Storage Coefficient of Pond (typically 1.0):

Time Increment during Storm Event (hrs):

Time Increment after Storm Event (hrs):

Total Number of Increments after Storm Event:

Specify Hydraulic Control Features

Groundwater Control: ☐ Top ☐ Bottom ☐ Left ☐ Right

Distance to Edge of Pond:

Elevation of Water Level:

Impervious Barrier: ☐ Top ☐ Bottom ☐ Left ☐ Right

Elevation of Barrier Bottom:

Run Open Save.... Save As.. Print Cancel

Input View Volume Infiltrated Elevation of Water Level

The **Groundwater Control** prompt allows specification of ditches, canals, rivers or lakes in the vicinity of the pond that have a constant controlled water level, which could affect the performance of the retention system modeled. The MODRET convention of pond layout assumes that the **length of pond runs up and down along y-axis** and the **width of pond runs from left to right along the x-axis**, and the **origin of the x and y axes originate at the center of the pond**, see Figure A-1. For this prompt the user is allowed to flag the location of a groundwater control feature, if there is any, by clicking the box next to the appropriate designation (Top, Bottom, Left or Right). If a flag is set at any one or more than one of the locations, the user **must specify the Distance to Edge of Pond**, which is the average distance as measured from the edge (wetted edge) of pond to the edge of the water feature (canal, ditch, lake, etc.). The second prompt of the water feature is the **Elevation of Water Level**, which is the average water elevation in the water feature that will prevail throughout the pond infiltration model simulation.

The **Impervious Barrier** prompt allows specification of concrete walls, clay liners, plastic liners, building footings and other features that obstruct lateral flow of groundwater away from the pond. For this prompt the user is allowed to flag the location of a impervious barrier feature, if there is any, by clicking the box next to the appropriate designation (Top, Bottom, Left or Right). If a flag is set at any one or more than one of the locations, the user **must specify** the **Elevation of the Barrier Bottom**, which is the average elevation of the obstruction located along the edge of pond. Impervious barriers located at significant distances (2 to 3 times the width of pond) from the edge of pond may not hydraulically affect the pond and may not need to be included in the analysis. MODRET accounts for the impervious barrier by reducing the weighted average horizontal hydraulic conductivity for the effective aquifer along the entire length or width of the pond, on the specified side of the pond. If the impervious barrier bottom is below the bottom of aquifer base, then the horizontal hydraulic conductivity is set to zero and no flow occurs on the specified side of the pond.

Runoff Data

Clicking the down-arrow of the runoff data box allows specification of the type of runoff data to be used for the specific infiltration modeling, i.e., **HYDROGRAPH, POLLUTION OR MANUAL**. If a specific storm event is being modeled where a runoff hydrograph data file can be specified, then the **HYDROGRAPH** option should be selected and a corresponding hydrograph file name must be picked from the list of hydrograph files or as specified by the user. Otherwise, a prompt will appear during MODFLOW run, requesting the name of the hydrograph file name.

In the case of pollution abatement recovery analysis, click on the **POLLUTION** option and on the subsequent prompts specify the total runoff volume and the corresponding total recovery period. MODRET will subtract the unsaturated infiltration volume from the total runoff volume, recharge the pond with the remaining volume in a period of **1 hour** and divide the remaining time of recovery into **8 equal time increments**.

If the runoff data consist of several runoff volume increments or some unusual runoff conditions, then the **MANUAL** option could be selected and the data can be entered manually by specifying increments of time with the corresponding increments of volume. The following input screen will appear for the **MANUAL** option:

Stress Period Number	Increment of Time (hrs)	Volume of Runoff (ft ³)	Stress Period Number	Increment of Time (hrs)	Volume of Runoff (ft ³)
Unsat	0.48	0.05	15		
1			16		
2			17		
3			18		
4			19		
5			20		
6			21		
7			22		
8			23		
9			24		
10			25		
11			26		
12			27		
13			28		
14			29		

On the first line prompt the program displays the calculated unsaturated infiltration time and volume, if applicable, for review (in this case 1.67 hours and 243.4 ft³). The next 29 line prompts are available for input of incremental time (hrs) vs runoff volume (ft³). The user can specify as many data pairs as necessary, but not more than a total of 29. For example, if the user desires to specify only 3 or 4 points, the rest of the entry lines **need not** be filled in. Click on the OK button after input is completed. To create a graph for the model results, a minimum of two data points must be specified for this option.

Overflow

Clicking the **Overflow** down-arrow allows selection of one of three options for overflow devices of the pond, i.e., **NONE**, **WEIR/ORIFICE & MANUAL**. To select, click on the desired option. If **NONE** is selected, then the pond is modeled without overflow option. When **WEIR/ORIFICE** option is selected, the model allows selection of **only weir, only orifice or both**. If **WEIR** option is selected, it is necessary to select one of three types of typical weirs; **V-notch, Sharp Crested and Broad Crested**. If **ORIFICE** option is selected, it is possible to specify any number of symmetrically identical orifices. The **MANUAL** option is provided to specify an overflow rating data set for overflow devices that do not fall into one of the other options. The manual specification can also be used when a combination of different overflow devices are present.

The following weir data input screen prompt appears when **WEIR - V_NOTCH** option is specified:

The **Crest Elevation** prompt allows specification of the actual elevation of the Vortex of the V_Notch weir. The **Angle of “V”** prompt allows specification of the angle (in degrees) of the v-notch of the weir. The **Coefficient of Discharge "C"** and the **Weir Flow Exponent "a"** prompts refer to parameters of the following weir equation:

$$Q = C \tan(1/2) H^a$$

Where,

- Q = Flow rate (cfs)
- C = Coefficient of Discharge
- 1 = Angle of V-Notch (degrees)
- H = Head on the weir (feet)
- a = Weir flow exponent

The **Design High Water Elevation** prompt appears here or below the **Overflow** selection prompt, if NONE is selected. This prompt allows specification of the actual design high water level or an estimated value (best guess). The purpose of specifying this value is to allow MODRET to develop a rating curve (to be used by MODFLOW) between the weir crest elevation and the design high water level (must always be > crest elevation). **NOTE:** This design high water level data is also utilized by MODRET to calculate the average length and width of pond. This is done in combination with pond area of starting water level, pond volume and length to width ratio data. Therefore, it is important to specify this value as accurately as possible. This elevation should **always** be correlated with the **pond volume between starting water level and estimated high water level**.

Once all weir input data prompts are answered, MODRET returns to the main data input screen and the Overflow option box is displayed with the selected overflow device. If a new weir device is selected at this point, the previously selected data will be ignored and prompts for a new set of data will appear.

The following weir data input screen prompt appears when **WEIR - SHARP CRESTED** or **BROAD CRESTED** option is selected:

The input prompts of **Structure Type**, **Crest Elevation**, **Coefficient of Discharge**, **Weir Flow Exponent** and **Design High Water Elevation** are the same as presented for the V-Notch weir option above.

The **Crest Length** prompt allows specification of the actual length of a rectangular sharp crested or broad crested weir.

The **Number of Contractions** prompt allows specification of the number of weir end contractions (i.e., 0, 1 or 2). The following equation is used to calculate overflow over a sharp crested or broad crested weir:

$$Q = C (L - 0.1Hn)H^a$$

Where,

- Q = Flow rate (cfs)
- C = Coefficient of Discharge
- L = Crest length (feet)
- H = Head on the weir (feet)
- n = Number of weir end contractions
- a = Weir flow exponent

General Conditions and Assumptions for Weir Flow Calculations

For **ALL** weir flow calculations it is assumed that the discharge is free flowing and **is not** submerged. It is assumed that the upstream water depth below the weir crest level is at least 2 times the maximum head on the weir. For weir flows with end contractions it is assumed that the horizontal distance from the end of the weir crest to the side wall of the channel is at least 2 times the maximum head on the weir.

The screen prompt for orifice option appears together with the weir option, as shown above. The input parameters of **Coefficient of Discharge, Orifice Flow Exponent, and Design High Water Elevation** are the same as presented for the Weir flow options above. However, the coefficient of discharge in this equation **is not the same** as the coefficient of **typical** orifice equation. For MODRET the coefficient $C = C_o * (2g)^{0.5}$. The **Centerline Elevation of Orifice** prompt allows specification of the actual elevation of the centerline of a **circular or symmetrical** orifice to be modeled. The orifice is assumed to be **unobstructed and without tailwater condition**. The **Area of Orifice** prompt allows specification of the total area (**in inches squared**) of individual orifice being specified. The **Number of Identical Orifices** prompt allows specification of the total number of identical orifices to be modeled, which must exist at the same elevation and have the exact same size and flow conditions. The following equation is used to calculate flow through the orifice:

$$Q = n C A H^a$$

Where,

Q = Flow rate (cfs)

n = Number of identical orifices

C = Coefficient of Discharge [$C = C_o * (2g)^{0.5}$, where $C_o = 0.6$ to 0.9 , typ.]

A = Area of Orifice (ft^2)

H = Head over the centerline of orifice (feet)

a = Orifice flow exponent

The following data input screen appears when **MANUAL** option is specified for the Overflow device:

Manual - Elevation vs Overflow Relationship [X]

Data Point	Elevation (ft)	Total Overflow (cfd)	Data Point	Elevation (ft)	Total Overflow (cfd)
1	2.00	0.00	13		
2			14		
3			15		
4			16		
5			17		
6			18		
7			19		
8			20		
9			21		
10			22		
11			23		
12			24		

The data input for this option is typically referred to as the overflow rating curve method. The first data point line prompts the user to specify only the elevation and a zero (0) is automatically assigned to the **Total Overflow** column. This indicates that the first entry must be the starting point of overflow (i.e, crest elevation of weir). Subsequent data point inputs have no restriction of any kind. The user can specify as many data points as necessary, **but not more than a total of 24**. For example, if the user only desires to specify 6 points, the rest of the entry lines **need not** be filled in. The user must simply click on **OK** button after the 6th point data has been specified. When previously saved data is recalled for editing, the saved rating curve data will be displayed. To edit, simply over-write or add as needed. Elevation above the last input line will be assumed equal to the last line entry.

File Management Control & Model Execution

On the top-right side of the infiltration input data screen, several command button are displayed. These include **Run, Open, Save, Save As, Print and Cancel**. Once all the input data has been specified, the data should be saved by clicking on the **Save** or the **Save As** button. At this point the input data can be printed by clicking on the **PRINT** button. The **PRINT** command allows significant amount of print customization, such as orientation, paper size, margins, color, printer selection, etc.. The **Open** option allows loading of an existing infiltration input data file from the available list or a file name that can be specified by the user.

Once all the input data is specified and saved, the infiltration analysis can be executed by clicking on the **Run** button. The **Run** option allows creation of the MODFLOW files and execution of the MODFLOW model from within the MODRET program. It may take some time to execute MODFLOW, depending on the computer and the number of stress periods. A message box will appear indicating that MODFLOW is running. When execution of MODFLOW is complete, a message will appear in the box, prompting the user to click **OK** to continue. If the MODFLOW model crashes during execution, an error message will appear in a message box.

Output

At the bottom-left corner of the infiltration input data screen four buttons appear, **Input, View, Volume Infiltrated and Elevation of Water Level**. *Prior to selecting one of these options, the infiltration analysis must be executed by clicking on the **Run** button.*

Clicking on the **Input** button allows input and editing of the infiltration model input data parameters. Clicking on the **View** button allows a tabular view of the infiltration model results and an option to print the tabular results by clicking on the **Print** button.

Clicking on the **Volume Infiltrated** button allows generation of a graphical view of the volume infiltrated vs time. Clicking on the **Elevation of Water Level** button allows generation of a graphical view of the water elevation in the pond vs time. All displays of graphical results are provided with a **Print** button to allow printing of the graphs.

Open...

Clicking on the **Open** button, will display a list of input data file names that were previously created by MODRET. These have the extension **ifl**, however, other file extension can be specified by the user. To bring the input data files on the screen for review and editing, simply double click on the desired file name.

Delete...

Clicking on the **Delete...** button will display all the infiltration input data files with the extension **ifl**. Double click on the file to be deleted and click on the **Yes** button. Other files with different extensions can also be deleted by selecting the desired extension and file name.