Robert G. Gerber
51 Woodland Road, Apt. 1
Cape Elizabeth, ME 04107-1245

March 8, 2018

Hancock "Griff" Fenton, Chairman
Lamoine Board of Appeals
Town of Lamoine
606 Douglas Highway
Lamoine, ME 04605

Re: Harold MacQuinn, Inc. –Peer Review
Kittredge Pit – Gravel Extraction Permit & Site Plan Review Permit

Dear Chair Fenton:

In 2013, while working for Ransom Consulting, Inc., I was asked by the Lamoine Planning Board to review and analyze a report by Summit Environmental Consultants, Inc. ("Summit") dated September 2012, a rebuttal by Dr. Willem Brutsaert ("Brutsaert") dated January 2013, and a surrebuttal by Summit to Brutsaert's testimony, dated February 2013. The task was to analyze the record, including tables, boring logs, groundwater elevations, maps, and other references and to identify, to the extent possible, the potential groundwater impact.

On April 16, 2013 I submitted a report to John S. Holt, Chair of the Planning Board. A copy of this report is attached as **Exhibit 1**. The report highlighted a number of questions that were raised following my review and laid out a proposed request for additional exploration that would assist with answering what I articulated as the two most important questions pertaining to the groundwater impact of the proposed expansion.

In August 2013, Summit collected a series of streamflow measurements in Archer's Brook and a tributary to Archer's Brook that originates near Cold Spring. These measurements, together with precipitation and geologic information, served as a basis for a Water Balance analysis that was conducted as a result of my recommendations.

In November 2013, a number of borings were installed in and around the proposed excavation site to gather geologic data. Seven of these borings were completed as monitoring wells. Five of the monitoring wells (PB-1, 2, 3, 4S and 4D) were installed at locations I recommended based on the study. Two of the monitoring wells (OW-2 and MW-4) were installed in order to obtain additional geologic data and to provide monitoring points in previously permitted portions of Kittridge Pit.

On March 15, 2014, after reviewing the report entitled "Supplemental Hydrogeologic Assessment" prepared by Michael Deyling of Summit, I sent a memorandum to Mr. Holt. In this memorandum I requested additional data and information that would allow me to answer some of the questions still remaining. A copy of this memorandum is attached as **Exhibit 2**.

On March 27, 2014, I submitted a memorandum to Mr. Holt regarding my review of the Summit report and additional exploration on the MacQuinn Pit and additional follow-up materials. At this time, I suggested a proposed permit condition that should protect the Cold Water Spring. As noted in this report, there are two separate and distinct water tables. The two water tables are not hydraulically connected upgradient of the spring or within the proposed pit area. Therefore, excavation of the proposed pit will not impact the spring hydraulically (i.e., dry up the spring) nor would the spring be impacted by any unanticipated release of petroleum product within the pit excavation area. A copy of this memorandum is attached as **Exhibit 3**.

I am presently working with the Cold Spring Water Company to develop a well head protection plan for Cold Spring. This study will not be completed until April and a report will be generated at that time. No data that I have reviewed in connection with this study, on behalf of Cold Water Spring Company, changes my findings and recommendations from the peer review conducted in 2014.

I regret being unable to join you in person to provide this testimony. An upcoming surgical procedure does not allow me to commit to attending so I provide this written summary to affirm my 2014 peer review.

Thank you.

Sincerely,

Robert G. Gerber

Digitally signed by Robert G. Gerber
Date: 2018.03.08 13:04:10 -05'00'

Robert G. Gerber, Certified Geologist #110

Enclosures: Exhibits 1-3

RANSOM Consulting, Inc.

Consulting Engineers and Scientists

April 16, 2013

R131.06049.001

Mr. John S. Holt, Chair
Lamoine Planning Board
606 Doughlas Highway
Lamoine, ME 04605

Re: Peer Review of MacQuinn Gravel Pit Expansion Application

Dear Mr. Holt:

In accordance with Ransom Consulting, Inc.'s (Ransom) proposal of March 14, 2013, and the Lamoine Planning Board's acceptance of that proposal in an April 3, 2013 email, Ransom has completed Task 1 of the work scope. This report summarizes our review of written documents submitted to the Board as part of its review of the proposal of Harold MacQuinn, Inc., to expand its gravel pit by moving into the area shown on the attached Figure 1 and apparently part of Lamoine Tax Map 3, Lots 31 and 33. Specifically, Ransom's work includes a review and analysis of a report by Summit Environmental Consultants, Inc. (Summit), of September 2012 (beginning on P. 74 of the Record), a rebuttal by Dr. Willem Brutsaert (Brutsaert) dated January 2013 (beginning on P. 228 of the Record), and a surrebuttal by Summit to Brutsaert's testimony, dated Feb. 1, 2013 (beginning on P. 221 of the record). These three reports contained tables, boring logs, groundwater elevations, maps, and other references and my analysis is based on the data contained in or referenced by these pieces of the record. Ransom's task was to analyze the record and identify, to the extent possible, the potential groundwater impact.

One of the first tasks that we undertook was to assemble all of the data into ArcGIS so that everything could be correctly georeferenced. We noticed that the November 2011 LiDAR GIS products were available from the Maine Office of GIS so we downloaded the new topographic maps and hillshade representations of topography. We georeferenced the data points contained in the three reports by aligning data with identifiable points on the 2003 orthophotograph or the USGS 7.5' topographic map of the area. Therefore, we transferred Summit's "site boundaries, cross section locations, and data points" from the various maps to the ArcGIS environment. A map in the Record that showed the proposed final topographic configuration of the completed pit was on P. 136 of the Record and was a map prepared by Summit called "Post Development Drainage Plan." We assume that this represents the final outcome of the project that is before the Board for approval.

400 Commercial Street, Suite 404, Portland, Maine 04101, Tel (207) 772-2891, Fax (207) 772-3248
Pease International Tradeport, 112 Corporate Drive, Portsmouth, New Hampshire 03801, Tel (603) 436-1490
12 Kent Way, Suite 100, Byfield, Massachusetts 01922, Tel (978) 465-1822
2127 Hamilton Avenue, Hamilton, New Jersey 08619, Tel (609) 584-0090
60 Valley Street, Building F, Suite 106, Providence, Rhode Island 02909, Tel (401) 433-2160

www.ransomenv.com

Using the LiDAR-determined ground surface, we estimated the ground elevation for each geologic data point, and then subtracted the depths to different features of interest to find the depths to such features as: 1) an upper, or perched water table in fine-grained glaciomarine sediments; 2) the position of the uppermost glaciomarine fine-grained sediment; 3) any deeper identified water table in the sand and gravel aquifer; and 4) the top of bedrock. Additional data points were added along the Jordan River, Archers Brook, Blunts Pond, and a few other small unnamed streams and tributaries that were obviously in glaciomarine fine-grained sediments. The purpose of these points was to add additional data points to the top of glaciomarine fine-grained sediments, and a perched water table elevation. Although most of the ground elevations that were surveyed at the Summit data points (after changing from NGVD29 to NAVD88 datum = 0.64' difference) were in close agreement with the LiDAR (95% of LiDAR points are supposed to be within +/- 0.5' of true ground surface), one point, MW-3-2012 has a difference in estimated ground elevation of about 27 feet, suggesting that either the survey data at MW-3-2012 are off either vertically or horizontally or MW-3-2012 was not plotted at the correct location on the Summit maps. We also note that on our maps we abbreviate the name for "glaciomarine fine-grained sediments" to "clay" simply for the purpose of fitting the text easily into the figures. We understand that the glaciomarine sequence is not all clay and that silty fine sands, silts, and clay-silts are stratified to form the unit and the texture is variable from place to place and one depth to another.

We put together all of the viable data for each of the four groups of data—shallow water table; deep water table; top of clay; and top of bedrock—in the program SURFER9 to contour the data using the minimum curvature algorithm, then blanked out large areas of the contour map where no data existed as we did not want to extrapolate far without data. By digitizing the location of the Summit Geologic Sections AA' and BB', we brought those into SURFER as *.bln files and used them to cut "slices" through the four data sets, giving us the elevation profiles of each data set along each of the two cross sections, in the general vicinity of where data existed. These data sets consist of sets of coordinates of distance from the beginning of the section and elevation of the data in NAVD88 feet. These data sets were then combined in EXCEL to show the estimated positions in cross section.

In reviewing the data and comparing the Summit interpretations to those of Brutsaert, the thing that struck us was that there are obviously two different water tables in the vicinity of the proposed gravel pit expansion. Cold Spring, which is located at the intersection of Geologic Cross Sections AA' and BB' and is the source of a small community water supply in Lamoine, is formed by springs that exit at the interface of a sand and gravel layer that pinches out over an underlying glaciomarine fine-grained sediment layer, which we will call "clay" for short, but understand the caveat we gave in the previous paragraph. All indications are that this water table that supplies Cold Spring is a perched or "shallow" water table. Boring logs and monitoring wells MW-1 and MW-3-2012 suggest a deeper water table in sand and gravel underlies the "clay" layer. In other words, the clay layer is sandwiched into the sand and gravel and a monitoring well that has a screen set deep into the clay layer shows up as "dry". Monitoring well OW-1 (the one in the existing Kittridge Pit) finds a groundwater table at about elevation 25' NAVD88. Given the knowledge and approximate inclination and distribution of the "clay" layer in the sand and gravel, the question is how important this clay

layer is to diverting precipitation recharge going down through the gravel pit area from the surface sands and gravels towards the Cold Spring area. As described below, it appears that the clay layer is sloped upward from Cold Springs into the pit area and it is not a stretch to conclude that Cold Spring is recharged by groundwater that percolates into the sand and gravel of the pit area, travels downward and hits the clay layer that slopes toward Cold Spring, and then flows down along this clay layer, concentrating and developing a more defined perched water table as it nears the Spring. How much of this clay layer can be removed before Cold Spring has a "significant impact"?

Figure 1 shows the proposed pit expansion area, the locations of Geologic Cross Sections AA' and BB' (the same as used by Summit), and a contour map of the top of the "clay" unit inferred from a few boring logs, and data points located along streams in obvious glaciomarine sediment terrain. Notice how the clay layer is interpreted to slope upward from the Cold Spring area (at the juncture of the two cross sections) toward the middle of the pit expansion area but remain well below the ground surface**.** **Figure 2** is a color-coded digital terrain model that accentuates with color the differences in the ground surface elevation. Otherwise, the information is the same as on **Figure 1**. **Figure 3** is a shaded relief model developed from the LiDAR data that is quite informative as to what is happening geologically. Notice the rather smoothed ground surface on the southeast side of the large raised mound of sand and gravel on the western end of Cross Section AA'. We interpret this rounded shoulder to be beach deposits in sand and gravel on top of the clay unit. The beach was formed immediately after deglaciation when the relative sea level dropped fairly rapidly from Elevation 240' at the time of deglaciation toward where it is today at 0'.

The important difference between the Summit interpretation and the Brutsaert interpretation has to do with whether or not the clay layer under the beach deposits extends into the gravel pit area and is important to the hydrology of Cold Spring. Summit's Geologic Cross Section AA' as shown on P. 231 of the Record (**Attachment 1**) suggests that the clay layer just laps up on the side of the esker, but does not penetrate into it. Summit's written analysis does not seem to put any weight on a clay layer penetrating into the gravel pit, either, despite boring log descriptions (**Attachment 2**) that suggest some type of fine-grained glaciomarine deposits being encountered at depth in borings near the expansion area. We have attached several pages from a well-known reference on glacial geomorphology by Embleton & King (**Attachment 3**). If you look at pages 475 and 476 of that reference and the figure on page 475, you can see how having an inclined clayey layer embedded in an esker is certainly possible.

It is easier to see what we are talking about by looking at our renditions of Geologic Cross Sections AA' and BB'. In Section AA' (**Figure 4**) we have drawn the topography of the ground surface with great precision, based on the November 2011 LiDAR. Notice that there is a lot of vertical exaggeration, so slopes look much steeper than they would be in a 1:1 scale. The green line is the inferred top of "clay" or the fine-grained glaciomarine sediments that we believe are important to the recharge capability of the springs to the east of the pit. The blue line is the shallow water table that would occur near the top of the "clay" unit. The orange line is the water table in the lower sand and gravel (beneath the "clay" unit under the eastern half

of the pit expansion area). Notice it is annotated within the pit expansion area itself as being a maximum because no water table was found in borings that were terminated at that depth. The estimated top of bedrock is shown by the lower red line. Because of the scarcity of the data points and the broad brush contouring, some of the lines fall above the ground surface lines in places but that is only an artifact of the methodology we have had to use to interpret widely-scattered data points. We know the lines are above ground surface in places but it is not important to the overall point to try to force them down to the ground surface. Cold Spring is located at the distance of about 6250' from the start of the AA' line. Section BB' (**Figure 5**) is not nearly as important to the issue as Section AA', so although we have provided Section BB' here to be complete, we do not need to discuss it here.

On Cross Section AA' we have sketched in the approximate sideways projected position of the bottom of the pit expansion in a black dashed line. The important thing to note here is that if the pit is developed as suggested by P. 136 of the Record, that a lot of the glaciomarine unit that is inferred to slope upward from Cold Spring into the pit area will be removed. If this unit is removed, the effect of this low permeability layer in encouraging downward percolating recharge to flow toward Cold Springs could be lost. If that happens, the flow of the spring could be greatly reduced.

With all of the foregoing in mind, and feeling that there should be some requirement for the applicant to prove as part of the approval process that he can really excavate the pit to the elevations shown on the plan on P. 136 of the Record and maintain 5' of separation to the average seasonal high water table, we have developed a proposed plan of additional exploration that will assist the Board in answering the most important questions pertaining to the groundwater impact of this proposed expansion: 1) where are the shallow and deep water tables within this pit; and 2) would excavation in the eastern half of the pit expansion area significantly affect the recharge for Cold Spring?

Figure 6 shows the location of 4 proposed exploration points. To try to capture the essential information at each point, two monitoring wells may be necessary. The idea would be to advance a boring at each location that would go at least 5 feet into the permanent (deep) water table in sand and gravel beneath any glaciomarine fine-grained sediment units. The boring should be logged continuously as it is advanced. It may be possible to do this through air rotary drilling methods, as we have found that this is a reliable means of drilling through thick esker sediments with boulders in a relatively quick and cheap fashion, provided the driller is experienced in logging surficial material in an air rotary hole and can differentiate the fine-grained units from the glaciofluvial sand and gravel. A monitoring well can then be completed in the hole and the casing either partially or totally withdrawn. Having determined the depth to the glaciomarine unit (if one is encountered), a separate hole should be drilled 10 feet away from the first that penetrates only 5' into that unit and a well installed in that hole. Since the existing data suggest that any glaciomarine units are likely to be relatively shallow, those wells should be installed with hollow-stem auger and continuous split-spoon samples taken as the augers are advanced, then the well installed inside the augers.

At the proposed locations on **Figure 6**, we expect that the glaciomarine unit may only be encountered in PB-3 and PB-4. Regardless of what is found in drilling deep at each of the locations, shallow holes should be drilled at PB-3 and PB-4 with auger borings and wells installed into the top 5 feet of any fine-grained glaciomarine units encountered down to elevation 150'. Shallow wells only need to be installed at PB-1 and PB-2 if glaciomarine units are encountered in those holes above the elevation of the deep water table. The hole locations and elevations should be surveyed upon completion by survey-grade GPS equipment. After completing the borings and taking at least 2 separate water level readings a week apart, the geologic consultant for the Applicant should summarize the new geologic data and water levels and write a report that focuses on whether there is a glaciomarine layer in the eastern part of the gravel pit expansion area that is contributing to Cold Spring recharge, and whether, if that unit were removed, the Cold Spring flow would decrease and the approximate magnitude of that decrease. The exploration program we have suggested here is an absolute minimum. Depending on what is found in the field, the Applicant may want to acquire additional data to support whatever findings his consultants will ultimately make. This work would be better done now at the time of seasonal high water table, than in late summer at time of low water table, because there may not be any measurable water in the top of the clay layer then, although there may be water there at other times of the year. The Applicant's geologist should take into account the time of year the water level data are acquired and adjust for conditions that may occur in other seasons.

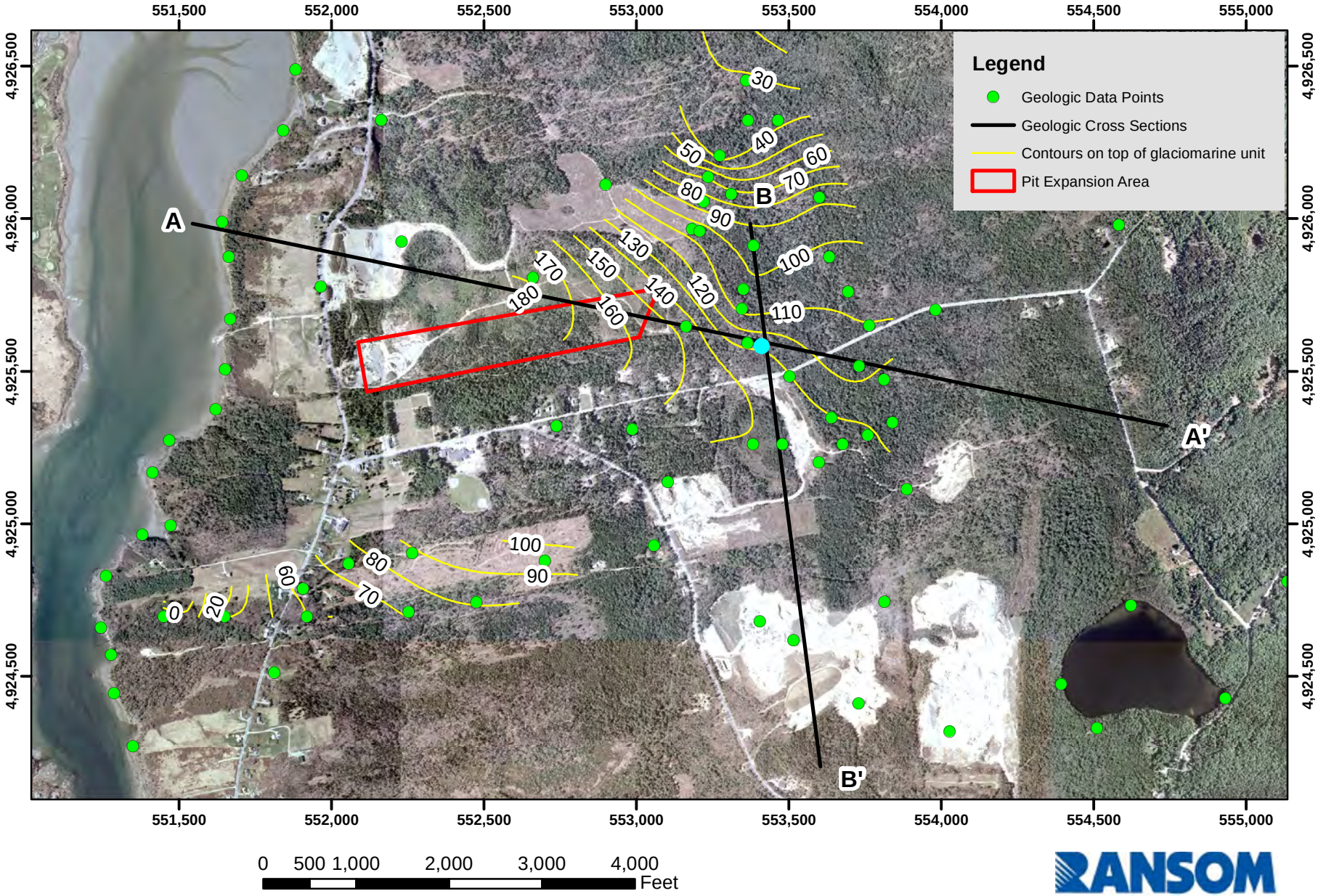
Sincerely,

Ransom Consulting, Inc.

STATE OF MAINE
ROBERT
GRAHAM
GERBER
110
CERTIFIED
GEOLOGIST

Robert G. Gerber, Certified Geologist #110
Senior Engineer & Geologist

Attachments: Figures 1-6; Attachments 1-3

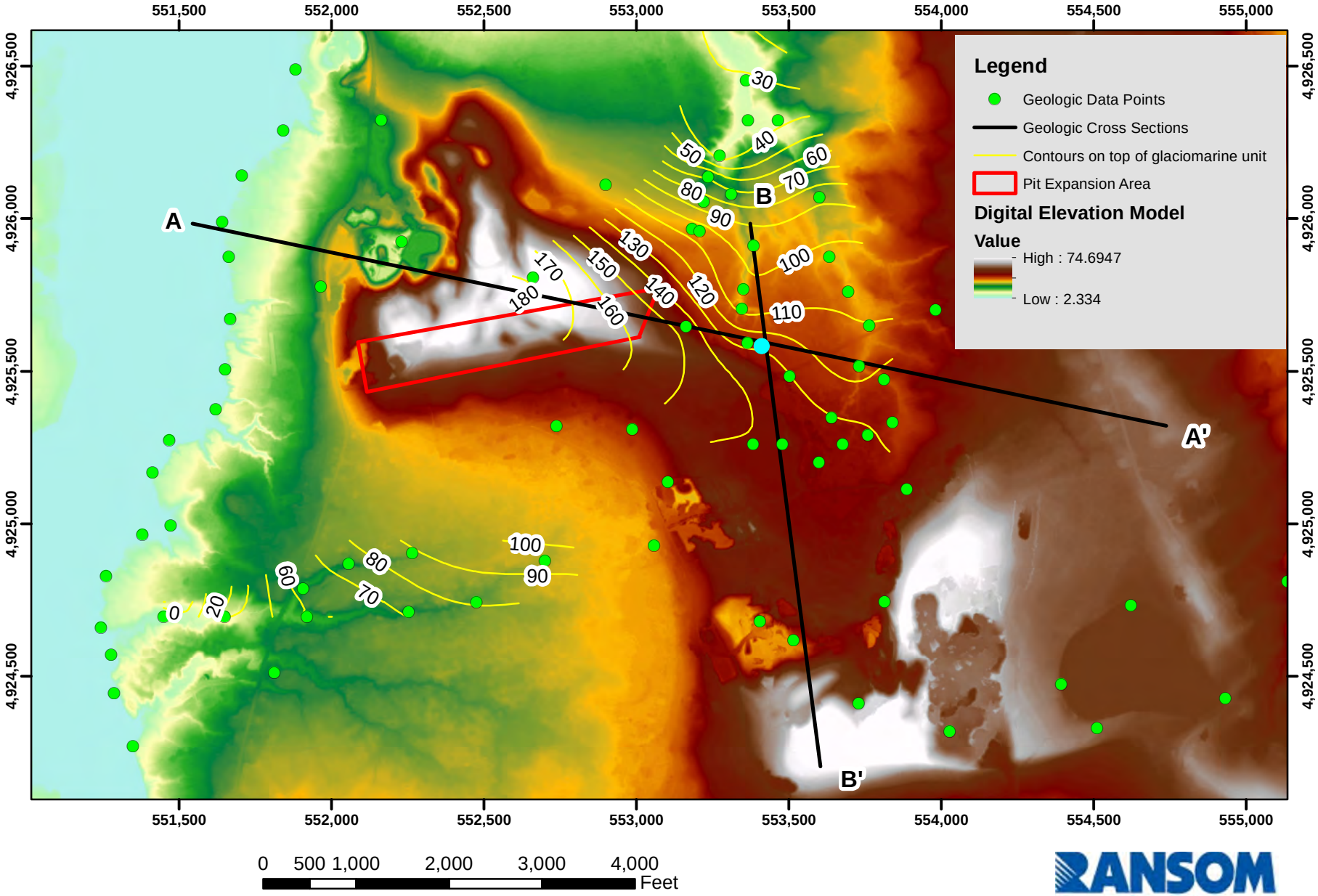


0 500 1,000 2,000 3,000 4,000 Feet

Elevation Contours on Top of Glaciomarine Unit
Town of Lamoine, MacQuinn Gravel Pit Expansion Review
Orthophoto is 2003 2-ft pixel density
Grid is UTM, NAD83, 19N, meters
RGG 4-15-13 131.06066

RANSOM Consulting, Inc.

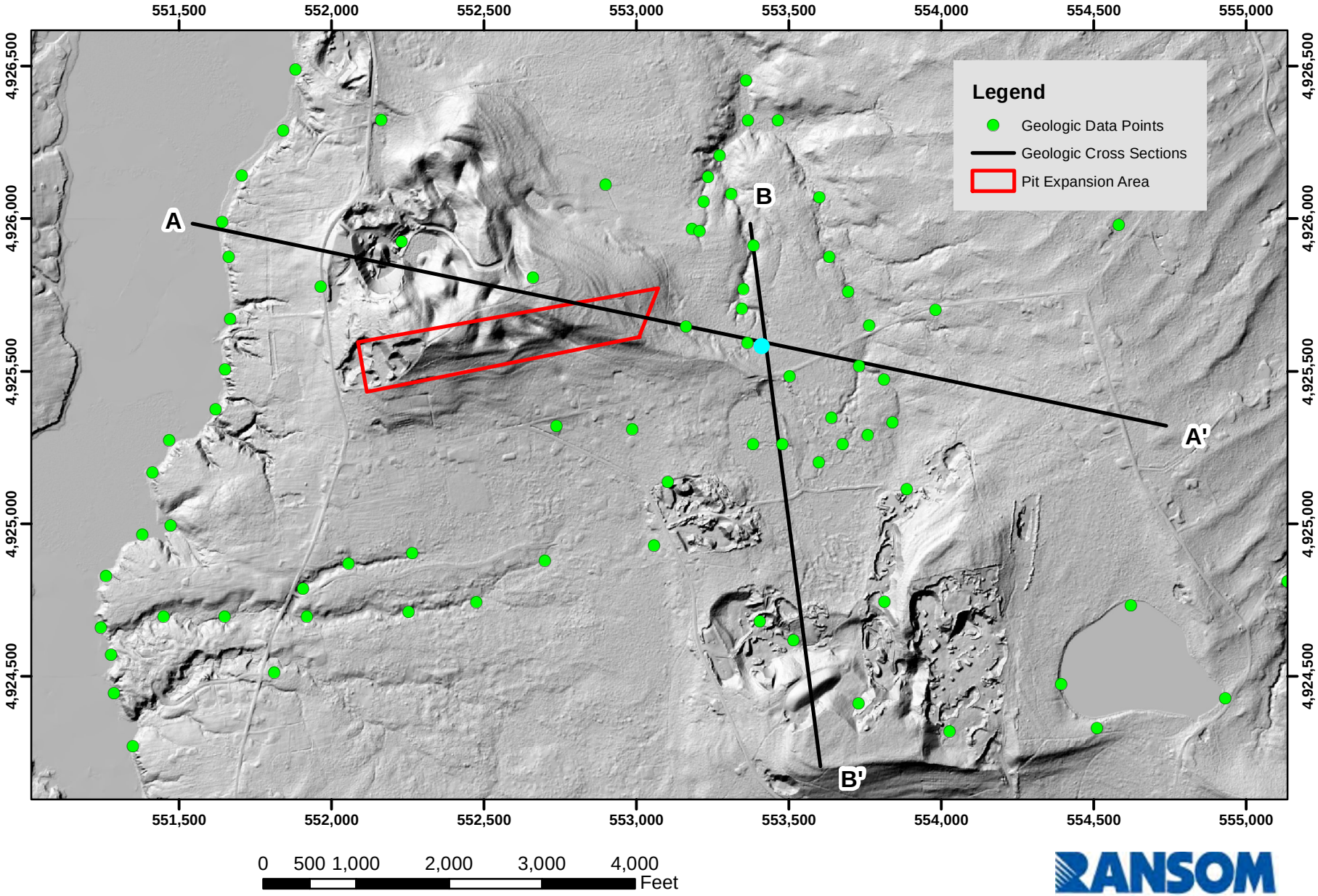
Figure 1



Elevation Contours on Top of Glaciomarine Unit
Town of Lamoine, MacQuinn Gravel Pit Expansion Review
Digital Elevation Model Developed from 2-m LiDAR
Grid is UTM, NAD83, 19N, meters
RGG 4-15-13 131.06066

RANSOM Consulting, Inc.

Figure 2



Elevation Contours on Top of Glaciomarine Unit
Town of Lamoine, MacQuinn Gravel Pit Expansion Review
2-meter Hillshade from LiDAR taken November 2011
Grid is UTM, NAD83, 19N, meters
RGG 4-15-13 131.06066

RANSOM Consulting, Inc.

Figure 3

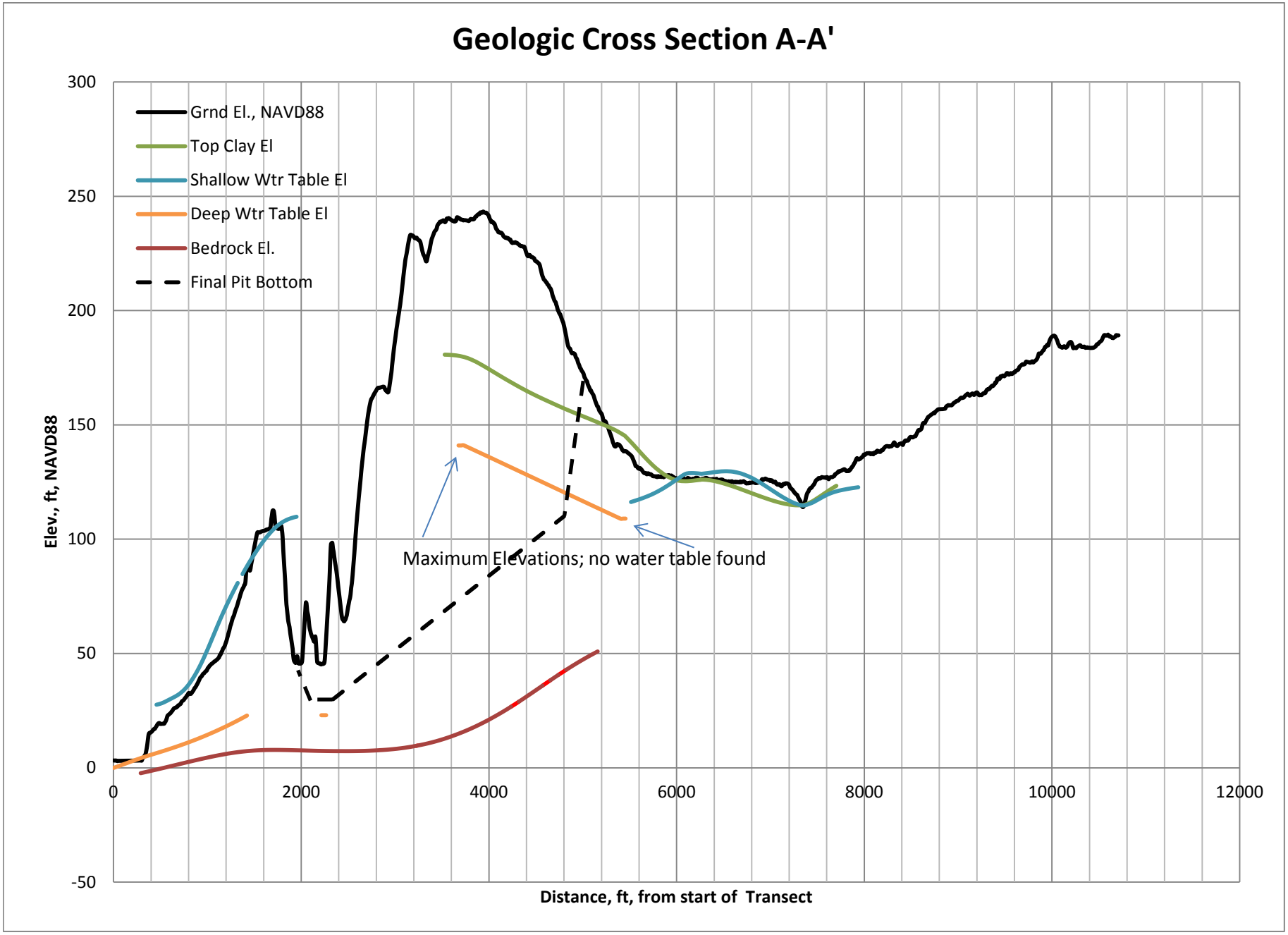

Geologic Cross Section A-A'
Grnd El., NAVD88
Top Clay El
Shallow Wtr Table El
Deep Wtr Table El
Bedrock El.
Final Pit Bottom
Maximum Elevations; no water table found
Elev., ft, NAVD88
Distance, ft, from start of Transect
300
250
200
150
100
50
0
-50
0
2000
4000
6000
8000
10000
12000

Figure 4

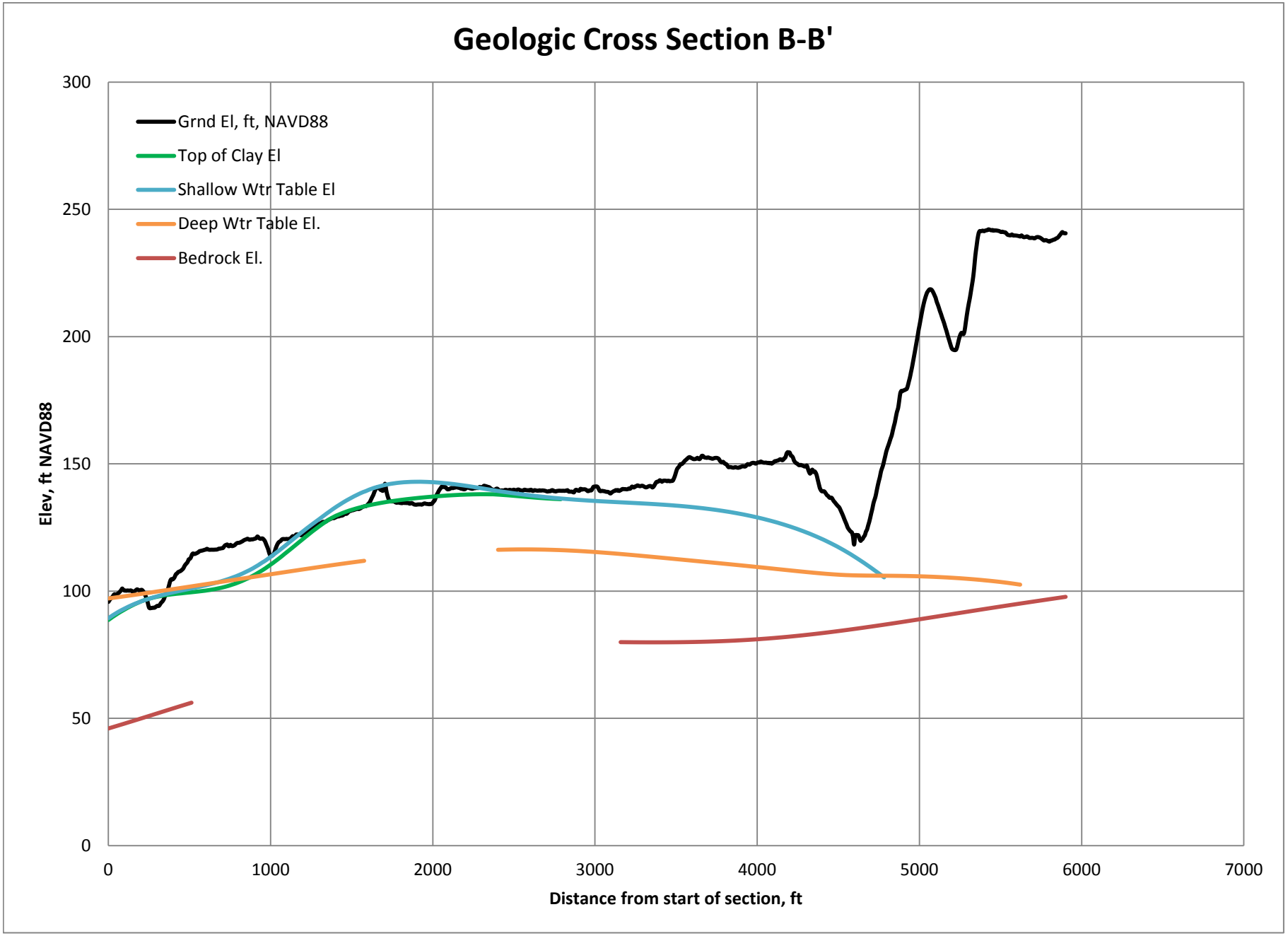
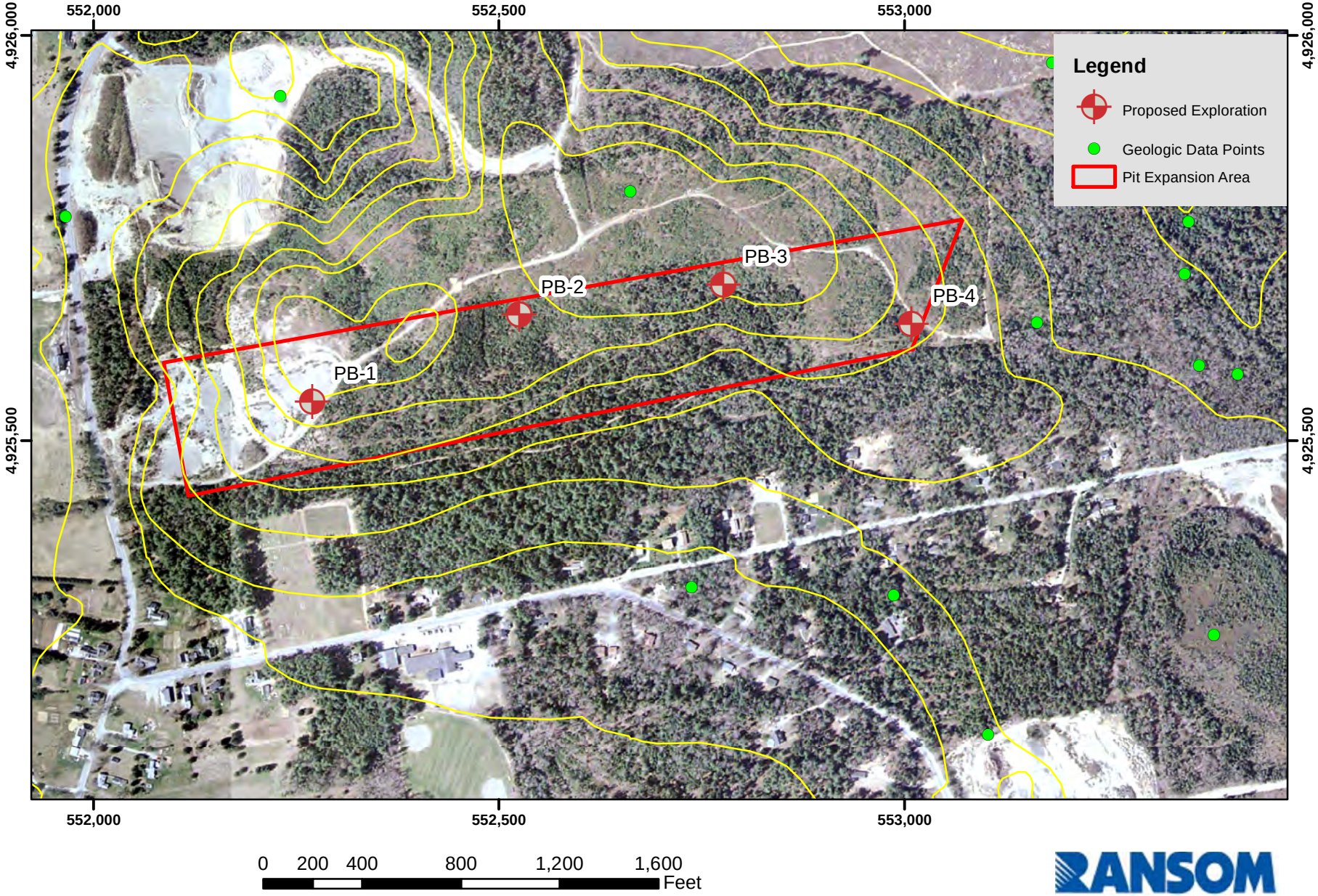

Geologic Cross Section B-B'
Grnd El, ft, NAVD88
Top of Clay El
Shallow Wtr Table El
Deep Wtr Table El.
Bedrock El.
Elev, ft NAVD88
300
250
200
150
100
50
0
0
1000
2000
3000
4000
5000
6000
7000
Distance from start of section, ft

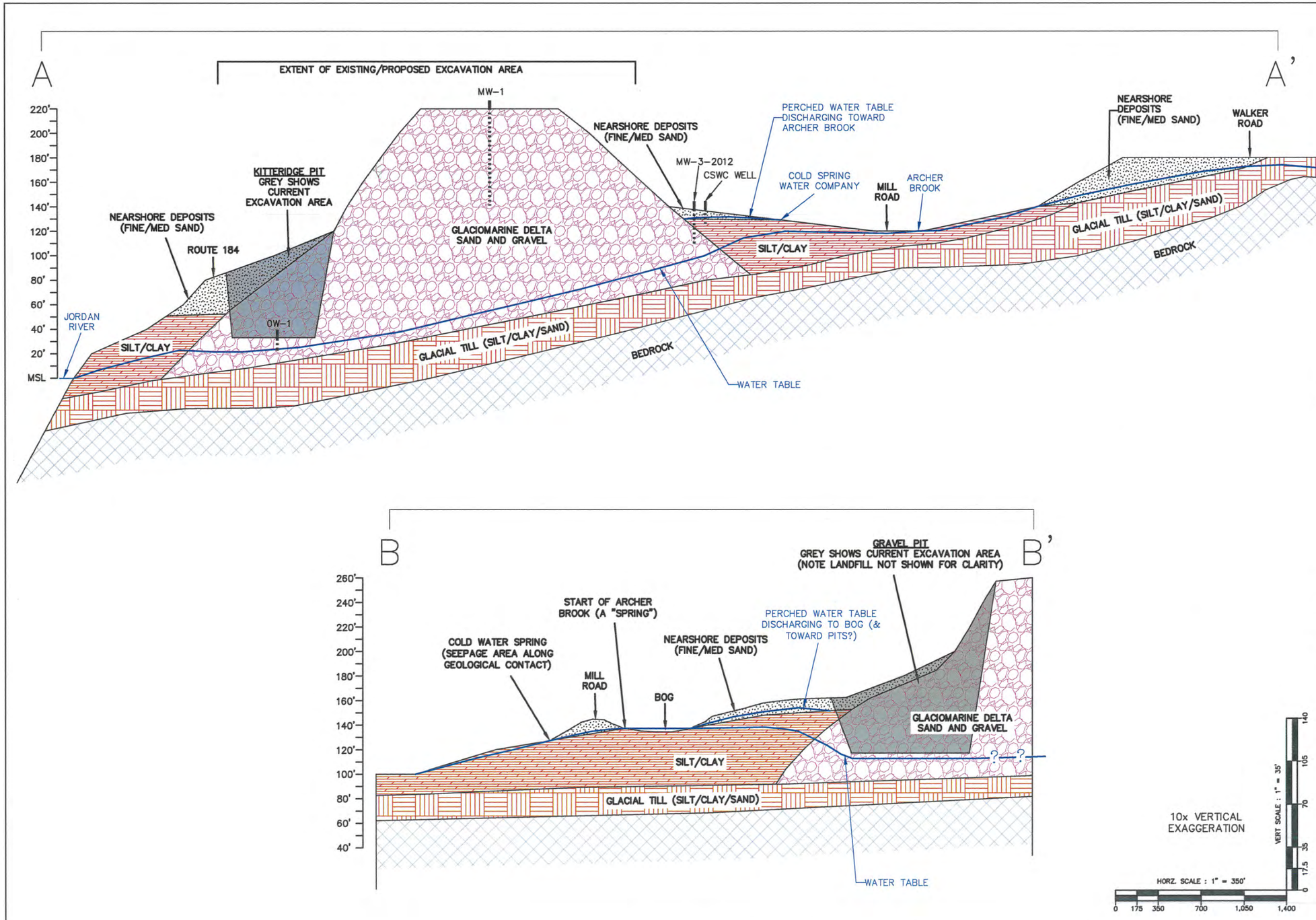
Figure 5



Proposed Additional Exploration Points
Town of Lamoine, MacQuinn Gravel Pit Expansion Review
Orthophoto is 2003 2-ft pixel density
Grid is UTM, NAD83, 19N, meters
RGG 4-15-13 131.06066

RANSOM Consulting, Inc.

Figure 6



NO.	REVISION	DATE
1	ADDED MONITORING WELLS	2/1/13

SHEET TITLE: SCHEMATIC GEOLOGICAL CROSS SECTIONS

SCALE: AS NOTED
DATE: DEC. 2012
DRAWN BY: SBM
CHECKED BY: MAD

PROJECT: KITTRIDGE PIT
ROUTE 184
LAMOINE, MAINE

CLIENT: HAROLD MACQUINN, INC.
PO BOX 789, ELLSWORTH, ME 04605

640 MAIN ST.
LEWISTON, MAINE 04240
Tel.: (207) 795-6009
Fax: (207) 795-6128
www.summitenv.com
Summit Environmental Consultants,

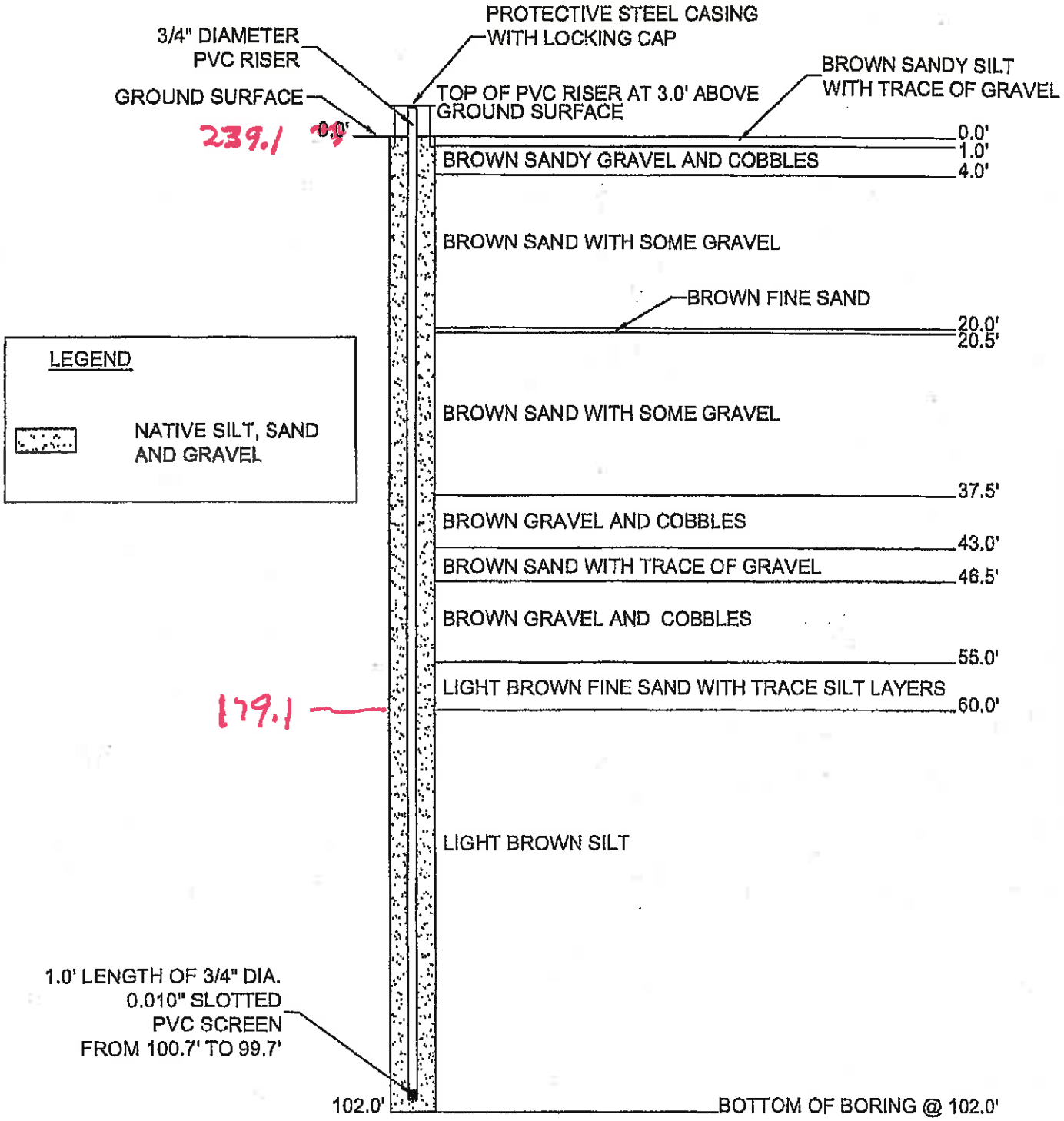
JOB NO: 11-3240.5

FOR PLANNING
BOARD PRESENTATION

Attachment 1

S.W.COLE ENGINEERING, INC.

MW-1
WATER LEVEL MONITORING WELL INSTALLATION DETAIL



SCALE

VERTICAL: 1" = 15'
HORIZONTAL: NOT TO SCALE

Job No : 04-0421 G

Sheet 8

SUMMIT

ENVIRONMENTAL CONSULTANTS, INC.
640 Main Street
Lewiston, Maine 04240

SOIL BORING LOG

Boring #: MW-3-2012
Project #: 11-3240.5
Sheet: 1 of 1
Chkd by: MAD

Project: MacQuinn - Miro Lot
Location: Lamoine, Maine

Drilling Co: Maine Test Borings
Personnel: Mike Porter
Summit Staff: Steve Marcotte, CG

Boring Location: see location map
Top of PVC Casing Elevation: 167.87
Date started: 8/27/2012

DRILLING METHOD		SAMPLER	
Vehicle:	Skidder	Type:	Not Functioning
Model:	CME	Hammer:	
Method:	4.25" HSA	Fall:	

ESTIMATED GROUND WATER DEPTH

Date	Depth (ft)	Reference	Groundwater Elevation (ft)
See Report			

Depth (ft.)	No.	Pen/Rec (in)	Depth (ft)	Blows/6 in.	SAMPLE DESCRIPTION	Stratum
164.9					0 to 2.5 ft bgs - Brown Sand and Gravel	Sand and Gravel Marine Near-shore
					2.5 to 10 ft bgs - Yellow Brown Medium Sand	
10					10 to 11 ft bgs - Gravel lense	
					11 to 20 ft bgs - Yellow Brown Medium Sand	
144.9' 20						
					20 to 23 ft bgs - Moist Olive Silty Sand	Marine Silt and Clay
					23 to 26 ft bgs - Olive Clayey Sand	
30					26 to 36.5 ft bgs - Olive Silty Clay Moist (balling)	
40					36.5 to 65 ft bgs Olive to Brown Silty Very Fine Sand to Silt	Silty Very Fine Sand To Silt Marine Delta
					Dry	
50						
60						
70					Bottom of boring at 65 ft bgs	
80						
90						
100						

Granular Soils		Cohesive Soils		% Composition	
Blows/ft.	Density	Blows/ft.	Consistency		
0-4	V. Loose	<2	V. soft		
4-10	Loose	2-4	Soft	<5%	trace
10-30	Compact	4-8	Firm	5-15	little
30-50	Dense	8-15	Stiff	15-25	some
>50	V. Dense	15-30	V. Stiff	>25	and
		>30	Hard		

NOTES:
1. bgs = below ground surface
2. bottom 15 feet of augers were left in the hole due to driller error
   MW-3-2012 was installed in second boring to 55 ft located 3 ft from this boring
3. split spoon sampler was not functioning. Materials were classified based upon cuttings and inspection of cutting bit every 10 ft

Attachment 2

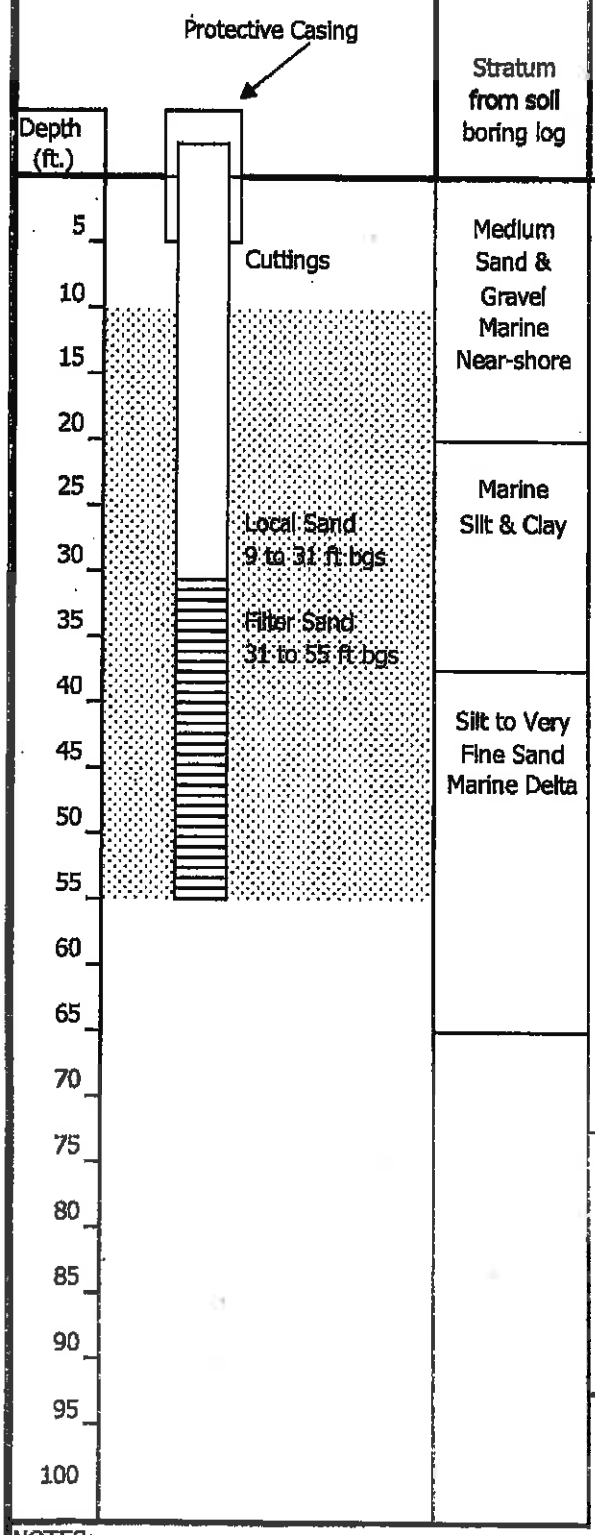
SUMMIT

ENVIRONMENTAL CONSULTANTS, INC.
640 Main Street
lewiston, Maine 04240

WELL COMPLETION LOG

Project:	MacQuinn - Miro Lot	Well #:	MW-3-2012
Location:	Lamoine, Maine	Project #:	11-3240.5
		Sheet:	1 of 1
		Chkd by:	MAD

Drilling Co:	Maine Test Borings	Well Location:	See Location Map
Foreman:	Mike Porter		
Summit Staff:	Steve Marcotte, CG	Date started: 8/28/2012	Date Completed: 8/28/2012



Stratum from soil boring log
Medium Sand & Gravel Marine Near-shore
Marine Silt & Clay
Silt to Very Fine Sand Marine Delta

REFERENCE ELEVATIONS

Surveyor:	Herrick and Salsbury
Reference (MSL or TBM):	NGVD 29
Top of Protective Casing:	
Top of inner casing:	167.87
Ground Surface:	164.9

GW ELEVATIONS

Date	Elevation
8/28/2012	<109.9
9/7/2012	**<109.9**

WELL CONSTRUCTION DETAILS

PROTECTIVE CASING

Type (Standpipe or roadbox):	Standpipe
Diameter (in.):	1 inch
Length (in.):	5 foot
Concrete Seal (gal):	N/A

WELL CASING AND SCREEN

	Riser	Screen
Material:	PVC	PVC
Schedule:	10	10
Diameter (in.):	1 inch	1 inch
Length (ft):	33.0	25.0
Interval below ground surface (ft):	+3 - 30	30 to 55
Slot size (in.):		0.01

FILTER AND SEAL MATERIALS

	Filter	Seal
Type:	Sand	None
Size:	#1	
Quantity (lbs.):	500	
Interval below ground surface (ft):	31-55	

GROUT

Type (filter sand, bentonite, etc.):	
Quantity (gal. or lbs.):	
Interval below ground surface (ft.):	

WELL DEVELOPMENT DETAILS

Water level from measuring point (ft):	
Depth of well from measuring point (ft):	
Total feet of water:	
Volume of water (gal):	
Volume of water evacuated:	
Method of development:	Not Developed

NOTES:

Attachment 2

flow law
p. 126

Glacial Geomorphology

Clifford Embleton

Reader in Geography, University of London King's College

Cuchlaine A. M. King

Professor of Physical Geography, University of Nottingham

A HALSTED PRESS BOOK

John Wiley & Sons
New York

Attachment 3

© Clifford Embleton and Cuchlaine A. M. King, 1975

First published 1975 by
Edward Arnold (Publishers) Ltd
London

This book is a fully revised edition of Parts I–III of
Glacial and Periglacial Geomorphology first published 1968 by
Edward Arnold (Publishers) Ltd
Reprinted 1969, 1971, 1974

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2.3 *Descriptions of eskers in different areas*

R. J. Price (1965) has described eskers left in front of the retreating Casement glacier in Alaska, some of which have been revealed since the glacier became land-ending about 1907. A complex set has been exposed from the retreating ice since 1935. The eskers are ridges 3–9 m high, formed of well-rounded gravel, cobbles and boulders. They occur on ground that slopes both away from and towards the glacier. Those formed on the slope down towards the glacier must either have been formed by subglacial streams under hydrostatic pressure or by englacial streams. In the latter event they must have been let down subsequently on to the reverse slope. A complex series of ridges is thought to have developed supraglacially in lakes, which have since drained, leaving shoreline features on the ridges. The largest ridges were probably on the site of meltwater streams and they appear to be true eskers which were underlain by ice at one time. Some near the glacier have ice cores, and photographs showed them extending on to the ice in places. They could either have formed in englacial tunnels or on the ice. Subsequent melting must have produced the uneven crest line. The lakes must have formed after the ice melted out beneath and around the eskers. Some of the eskers were 40 m high and 33 m wide at their base when they were still on the ice. These eskers have been destroyed by meltwater streams subsequently.

Hoppe (1961) has described some of the eskers of northern Sweden. These eskers occur both above and below the highest marine limit. They often extend for 5 to 10 km between breaks, which normally occur where the relief is highest. The largest eskers have rather flat, broad crests, supporting the view that the deposits were built up in successive layers in subglacial or englacial meltwater channels. Hoppe agrees with V. Tanner (1932) that the sharp-crested narrow variety of esker is the result of subsequent collapse of the sides when the supporting ice walls melt away. The eskers formed above the water-level consist mainly of stratified sand and gravel. Sometimes silt occurs within the esker or on its surface, and occasionally heaps of boulders are found.

One particular esker, Hammesharju, shows some unusual features. It is situated south-east of Gällivare and is over 4 km long, 50 to 80 m wide and up to 16 m high, although its crest is broken by gaps. The esker was formed probably in a subglacial or englacial tunnel; later, a supraglacial stream was let down across it and eroded the gaps that occur along it. Ridges of till flank the esker on either side. These ridges contain stones preferentially orientated transverse to the ridge elongation. It is thought that they were formed by the squeezing of water-soaked till into the area on either side of the tunnel. There are also examples of a similar type of feature that forms when the till is pressed beneath and into the central core of the esker rather than alongside it.

Another interesting example is the Vessö esker in southern Finland. It is in part a continuous ridge, but in places it is broken into separate mounds. It is situated about 50 km east of Helsinki, is 8 km long and varies in width from 300 m to 2 km, with a maximum height of 38 m (Fig. 16.7). It runs south-east to north-west radially to the large Salpausselka moraines to which it is linked. Its outer part consists of several islands, while it has been modified by the sea as it has risen isostatically since its emergence from the ice. The esker as a whole is asymmetrical and has a steeper eastern slope with a stony surface, continuing in places below sea level. In places, there are depressions,

which are steep and circular, along the ridge. Along part of its length, the esker forms a broad ridge with associated boulder-covered mounds. Elsewhere, the esker spreads out and merges into an even, sandy plain. The fluvioglacial material of which the esker is composed lies directly on the rock with no intervening till. The bedrock, an easily weathered granite, was eroded to form a depression along which the esker is situated.

The structure of the esker has been revealed in cuttings at a point where the eastern slope is 13° and the western only 3°. The esker is covered with boulders and its internal structure is shown in Fig. 16.7. The sloping layer of clay (4), with a dip of 8°, runs

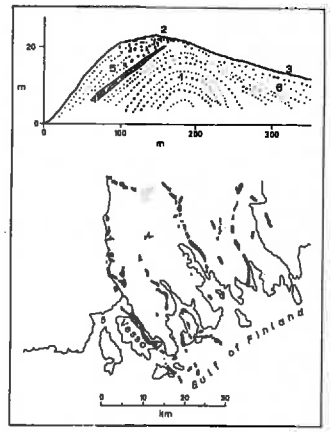

Fig. 16.7
The Vessö esker, Finland (O. Granö, *Fennia*, 1958, by permission of the Johnson Reprint Corporation)

almost parallel to the steeper eastern side. This layer probably formed the original esker surface, and the overlying sand and stones (5) consist of later marine additions. Beneath the clay and silt, sand (1) occurs in alternating layers of finer and coarser particles, showing cross-bedding. In the centre, the material is coarser. Some large angular boulders occur in the silt layer and on the upper surface (2), where the gravel and stone layer is 1–3 m thick.

The form of the esker and its constituent material give indications of its mode of formation. O. Granö (1958) suggests that the fluvioglacial material of the esker was deposited close to the ice margin in deep water. He considers that the character of the esker, particularly its core, agrees with the views of De Geer concerning esker formation in submarine environments. The original core was probably deposited as a small delta at the mouth of a subglacial stream emptying into the sea. A clay and silt layer represents a remnant of the covering of fine material deposited when the esker was still in deep water. It includes large ice-rafted angular blocks. The boulders covering the clay could have been derived from a covering of stony till from which the fine

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material has since been washed away. The sand (6) above the unconformity on the western side of the esker was deposited by the waves as the esker emerged above the sea. The steeper eastern slope is the result of movement of material to the lee side by the waves whose maximum fetch lay to the west. The feature has been considerably modified by the sea since its formation at the edge of the retreating Scandinavian ice sheet.

The Lammi esker, described by E. Wisniewski (1973) stretches north-west from the Salpausselka I moraines. It consists of a series of proglacial deltas linked by short ridges, and lies in a bedrock trough. The deltas formed successively in the Baltic Ice Lake. In places, the esker ridge is 200 m wide and 35 m high, and is composed of gravel and pebbles up to 30 cm in size. Its sides slope at 25° to 30°. Some boulders up to 2 m in size indicate an ice-contact position; they overlie bedded material whose stratification is deltaic. Deformation of the finer layers in places has resulted from melting of buried ice, and there are also kettle holes. The esker now has the form of hillocks of varying size, formed during deglaciation in a sub-aqueous environment. Each delta marks a pause in the retreat of the ice front, and the esker deposits accumulated in crevasses or channels along which fluvioglacial transport was taking place. It is a classic example of a De Geer-type esker. Most of it was submerged on deglaciation, resulting in some loss of fines and abrasion through wave action.

P. Fogelberg (1970) analyses the features of deglaciation associated with the Salpausselka II moraine in an area of southern Finland. In the moraine foreland, there are eskers whose southern ends rise to ridges or hills 135 to 140 m above sea level, northwards from which a lower tail continues at 100 to 110 m. The steep hillock at the southern end was deposited between ice walls where the ice-channelled stream or tunnel opened into a lake. The tail is part of the feeding esker formed in the ice tunnel. In the moraine hinterland, the fluvioglacial deposits include more continuous eskers. No De Geer-type eskers occur either in the foreland or the hinterland of this area.

Farther north in Finland, the deglacial history of the Tana valley provides further illustration of the complex environments with which esker systems are associated. The ice sheet melted rapidly from this area, its margin melting back at an average rate of 230 m/year until it became ice-free in 9500 BP (H. Mansikkaniemi, 1970). Subglacial sedimentation was extensive during this phase, and bottom eskers and subglacial valley trains formed. The largest eskers occur where the valley is narrow and deep; these include bottom eskers 10 to 40 m high that follow the valley floor and that were formed in ice tunnels. They have been trimmed by later marine incursion. During deglaciation, short-lived lakes formed in the narrow parts of the valley and these were filled with fine sediments, at a level above that of the river deposits. The sorted sediments attain thicknesses of 20 to 70 m on the valley floor. There are also 'slope eskers' descending the valley sides, which are smaller and less than 10 m high, the infillings of subglacial chutes (p. 346). Some of the large bottom eskers are continuous for 7 km. Their width varies from 100 to 300 m—25 to 50 per cent of the width of the valley bottom. Deep kettle holes are associated with them. The finest deposits in the eskers are well-sorted, and the stones rounded, having travelled 25 to 35 km. Coarse sediments, on the other hand, are poorly sorted and only slightly stratified. Some of the bedding in the bottom eskers is nearly horizontal. The eskers probably formed under dead ice 100 to 200 m thick, whose downwasting led to the plateaux and uplands being exposed while ice

remained in the valleys. Fine sediments accumulated as melting ice caused blockages in the valley at some places. Coarse sediments were deposited when the flow was rapid in subglacial or englacial tunnels. These were enlarged by melting until the marginal ice walls collapsed, together with the roof, and the fallen blocks of ice were then covered by further sediment. The slope eskers are less numerous because rapid flow of water down the subglacial chutes tended to prevent deposition.

The deglaciation of the Holy Cross Mountain area west of the Vistula in Poland has been discussed by C. Radłowska (1969). The Tarłow esker is associated with the Vistula ice lobe of Riss age. Its roots lie, in part, in a valley, although not at the lowest point. Its crest reaches 192 m where the plateau level is 210 m, and its course is sinuous, consisting of long hillocks and mounds, whose irregular relief is said to be partly the result of subsequent erosion. Coarse material occurs in the esker core, overlain by bands of gravel-pebble mixture and some sand. The structure is complex and in places disturbed, particularly where the material is coarsest in the north. Boulders up to 0·5 m across are tightly packed at the esker base. Material is more uniform towards the south. The lower eastern slope is thinly mantled with till up to 5 m from the crest, suggesting that the esker was formed in a tunnel. Large soft-rock boulders indicate short distances of transport, and there is little sign of sorting. Strong cross-bedding occurs and there are lenses of sand and silt. Three stages of deglaciation are inferred:

1 the esker developed in a subglacial tunnel and was then partially covered by till and ablation moraine as the ice decayed
2 a free space developed between the esker and the dead-ice wall, and water flowing along this channel added a kame terrace to the esker
3 after the dead ice decayed, a valley formed adjacent to the kame-esker, followed by settling and gelifluction on the slopes. Eolian activity finally added some sand dunes.

In central Poland, Z. Michalska (1969) differentiates true eskers from crevasse fillings. Esker materials are well washed but vary in particle size and bedding. Accumulation occurred in a marginal tunnel or, more rarely, in a decay crack near a tunnel outlet. There were probably short breaks in sedimentation, a series of layers representing separate depositional episodes with different sources. Till layers several metres thick are found near the bases of some eskers; at some later stage, channels up to 30 m deep were cut in the till. Following channel erosion, up to 30 m of fluvioglacial sediments were deposited in several episodes, to be overlain in turn by sandy deposits laid down in continuously flowing water. The tunnel then increased in size and deposits 15 m thick accumulated along the channel axis. Finally, the tunnel roof melted, letting down a mantle of till 1–2 m thick.

Mention should be made of some of the eskers of Ireland, as it was from this country that the name 'esker' originated. An interesting series of eskers and associated features has been described by F. M. Synge (1950) in the area around Trim, north-west of Dublin. The area lies in the drainage basin of the River Boyne, which flows north-eastward to the north of the main esker area. The area is drained by streams flowing north-westward to join the Boyne (Fig. 16.8). When the ice sheet associated with the eskers lay over the area, its margin ran roughly from north-east to south-west and was

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Memo

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Date: March 15, 2014
To: John Holt, Lamoine Planning Board Chair
From: Robert Gerber, C.G.
Subject: Review of Summit Report on additional exploration at MacQuinn Pit

I reviewed the report entitled "Supplemental Hydrogeologic Assessment" prepared by Michael Deyling of Summit Environmental Consultants in December 2013. This report was prepared in response to a Planning Board request that the applicant, Harold MacQuinn, Inc., for a gravel pit expansion of the Kittridge Pit into Lot 31 provide additional geologic information. The specifications for the acquisition of additional geologic data originally came from a report I wrote to the Planning Board on April 16, 2013, which was a peer review of the original Summit report on the geology of the site.

I believe the Planning Board actually passed a written motion that directed the applicant to do this additional work, but I don't know the exact wording of it. Therefore, I do not know if all of the things that I requested to be done were incorporated into motion.

The work and resulting report by Summit has gone a long way to answering some of the fundamental questions that bear on the potential impact of the proposed pit on Cold Spring and where the deep groundwater table lies beneath the proposed pit expansion. Before I finish my peer review of this latest report, I ask the Planning Board to consider asking the applicant for the following information to enhance the report and make it easier for me to complete my report:

1) I requested two rounds of water level data after the wells were installed. I only see one round of data summarized for PB-1, -2, and -3 in Table 1 of the report. It would be helpful to have another complete synoptic (acquired at the same time) round of water level readings. For the shallow wells, the water level readings should be taken within the next month. For the deeper wells, it is hard to tell when the "seasonal high water table" condition may be reached. I have monitored wells in deep sand and gravel and had a continuous stream gage on Libby Brook for the past 13 years in TD19 as part of my monitoring of blueberry barren irrigation for the Passmaquoddy Indians. The median peak in streamflow for Libby Brook, which drains a large glaciomarine delta, has occurred around April 1st. However, the wells, which typically penetrate 50 to 60 feet of unsaturated

sand and gravel above the water table, peak about 4 to 6 weeks later. In the MacQuinn case where the unsaturated zone is on the order of 3 times this amount, the time of the annual peak could be late summer into fall. However, the annual variation in water table is usually only a few feet, so the timing of water level measurements is not so important due to the low variability. But I still think it would be helpful to have another round of water levels taken before April 15th in all the new wells on the site plus MW-2, -3, and -4.

2) In the portion of the new report that discusses the water balance, I do not see a discussion of how the measured flows relate to any statistical measure of what those flows represent in terms of whether they are baseflows only (what was the antecedent precipitation history?) and whether these flows represent "average annual" base flows, fall high baseflows, etc. By comparison with a USGS gaged stream (Libby Brook might be similar) of similar properties and precipitation regime, one should be able to put the flow rates into some perspective.
3) For the comparison of the measured base flows with estimated flows from recharge area, it is clear that not all of the recharge area is of uniform recharge capability. I suggest dividing the recharge area into units of similar recharge capability and multiplying these sub-units by a representative recharge rate for the respective units and summing those to make the comparison. I have attached a paper that I co-authored with Dr. Charles Hebson that provides one way to do this calculation.
4) Page 7 of the PB-4 boring log is missing from the electronic file that I downloaded from the Town of Lamoine website. Can you please provide this?
5) In my recommendation for this study I specifically asked that the elevations and *locations* be surveyed with survey-grade GPS equipment. I see the elevation data attached to the new exploration points, but I saw no coordinate data. I have already spent a lot of time trying to georeference plans from the first report so that I could construct a good database in ArcGIS. I would rather not have to georeference these PDF plans to make them fit what I already have, as I did not include the time to do that in my estimate for this phase of work. Therefore, I ask for a table of x,y,z coordinates and elevations of all the new geologic explorations. As long as I know what horizontal and vertical datums are used, I can quickly add these to my database.
6) I see on Figure 1 of the new study a string of six "CSW" well locations. I have not seen drilling logs or groundwater elevations for these wells presented in either the original report or this report. I also am not aware that anyone else has entered that data into the record of this proceeding. Can this information be made available and put in the record? It would help to clarify the geologic interpretation. Were the locations of these wells surveyed by the applicant? If not, where did the applicant get the location data?
7) Michael Deyling should put his CG stamp on the report and sign it. Perhaps he did this on a cover letter or other page I do not have, but this is a standard requirement of the Board of Certification for Geologists and Soil Scientists for information provided in a regulatory proceeding.

If the Planning Board can request these clarifications then I can proceed in short order to wrap up my review of the hydrogeologic aspects of this application. If the Planning Board wants me to proceed on the basis of what data I already have, I can do that except that the margin of certainty of the meaning of the data will be less.

Attachment: Gerber and Hebson recharge reference

Geological Society of Maine

Bulletin 4

Selected Papers on the Hydrogeology of Maine

edited by

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1996

GROUND WATER RECHARGE RATES FOR MAINE SOILS AND BEDROCK

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ABSTRACT

This paper reviews methods and results of estimating recharge rates for Maine soils and bedrock. The percentage of precipitation that ultimately recharges soil and bedrock is an important variable in water supply safe yield evaluations and ground water contamination studies in Maine. The recharge rate is, for practical purposes, impossible to measure directly. Recharge rate varies seasonally and is related to features such as soil permeability and anisotropy, land slope, land cover, and location relative to ground water divide. Temperature variation as it affects snowmelt and evapotranspiration is also a governing factor. Recharge rates are examined for five basic geologic terrains: 1) ice contact and outwash sand and gravel; 2) glaciomarine and glaciolacustrine clay-silt; 3) thick fine-grained lodgment till; 4) thick sandy (granitic derived) till and diamicton; and 5) thin sandy widely-graded soil over bedrock. Recharge rates for bedrock overlain by these surficial materials are also examined. Historical safe yield data, baseflow as determined from stream gaging, and recharge calibrated for models of these types of aquifer systems are summarized. The results can be applied to a wide variety of ground water problems in Maine and hydrogeologically similar locales.

INTRODUCTION

The percentage of precipitation that ultimately recharges soil and bedrock is an important variable to many hydrogeological evaluations in Maine. For example, water supply safe yield evaluations and ground water contamination studies require a knowledge of net flux through the geologic formation of interest. Predictions of the highest and lowest positions of water tables also require a knowledge of response to precipitation. Recharge rate is almost impossible to measure directly, although the response of water wells as a function of precipitation is easy to measure. Unfortunately, mass balance models that compute water table rise from specific yield are overly simplistic. Even if one knows how much net recharge reaches a shallow soil water table, it is much more difficult to determine how much of that recharge will pass through to a fractured bedrock aquifer.

This paper considers several topics related to recharge rates for Maine soils and bedrock and similar hydrogeologic settings:

- a systems framework for considering recharge to ground water;
- methods for estimating net recharge to a geologic formation of interest;

- estimates by Robert G. Gerber, Inc. (RGGI), Freeport, Maine, and the U.S. Geological Survey (USGS).

From these studies, generalizations on regional average net recharge rates for different types of geologic formations are presented. In closing, further research efforts that would refine these estimates are suggested.

A SYSTEMS DESCRIPTION OF RECHARGE AND GROUND WATER FLOW

An exhaustive review of the literature on estimating recharge to ground water is beyond the scope of this article. For all practical purposes, the preferred method of direct observation and measurement is rarely feasible. Therefore, recharge must be calculated from those relevant variables that are observable or can be estimated independently. The very act of calculating recharge implies a particular model of recharge as related to other hydrogeologic variables. Modeling, whether simple or complex, plays an essential role in the estimation of recharge. The models can range from simple water balance analysis to sophisticated three-dimensional variably saturated numerical simulation. Most requirements for a realistic recharge estimate can be met by using a method intermediate in accuracy, complexity, and cost.

Given that some kind of modeling is generally required to estimate recharge, it is helpful to establish the systems nature of ground water flow. Precipitation recharge is usually the single most important natural input to a hydrogeologic system, while discharge to surface water is the ultimate system output. Piezometric head describes the state or condition of the system. The system parameters (hydraulic conductivity, storativity, fracture characteristics) and configuration (topography, stratification, bedding, types of rocks and soils) are fundamentally geologic. Important external forcing functions include pumping and artificial recharge, climate, water extraction by vegetative evapotranspiration (ET), and connections to adjacent aquifers and surface water bodies. There is essentially one physical process of interest, porous media flow as described by Darcy's law in saturated and variably saturated systems. The entire system must obey fundamental mass balance constraints.

Even though recharge is formally a system input in this context, it also is frequently referred to as a model parameter. This semantic distinction, while real, need not be an obstacle in this discussion. Even though recharge is an input, it also is unknown, and therefore must be estimated. Following conventional usage, recharge estimation will be referred to as a problem of parameter estimation in this paper.

The important factors affecting recharge can now be given within the systems context described above. Recharge rate varies seasonally in Maine and is complexly related to landscape, climatic, and hydrogeologic characteristics, including:

- hydraulic conductivity and anisotropy
- specific yield
- unsaturated flow behavior
- topography: slope and relief
- surface location relative to ground water divide

- soil thickness
- vegetative land cover type
- precipitation distribution in time and space
- temperature as it affects snowmelt and ET

METHODS FOR ESTIMATING RECHARGE

The extent to which all of the above factors are included in an analysis, i.e. the extent to which the system is modeled, will dictate the complexity of the method for estimating recharge. Four general approaches to estimating recharge are considered here:

- traditional water balance analysis
- parameter estimation from observations on measurable quantities,(e.g. ground water levels and stream flow), in conjunction with ground water flow models
- direct estimation based on conceptual and/or physically-based models of hydrologic processes
- indirect estimation by saturated and variably saturated flow modeling

Water balance analysis as applied to ground water systems is the simplest approach. Beyond that, it is difficult to assign a scale of difficulty to the other three approaches. Within each category, there is a range of complexity from which to choose.

The principle of mass balance is fundamental to all of these approaches. Water balance analysis is nothing more than hydrologic bookkeeping. Both automatic and trial-and-error parameter estimation may use numerical methods, statistics, and mathematical optimization in conjunction with flow modeling. Direct estimation by modeling the component hydrometeorological and vadose zone processes is a mechanistic approach that models the hydrologic cycle from initial precipitation down to percolation (recharge) at the water table. Indirect estimation uses fully saturated or variably saturated flow models with boundary conditions such that the models implicitly calculate recharge to the aquifer. Variably saturated flow modeling avoids the need for explicitly identifying ground water recharge rates, but does require estimates of the various hydrologic abstractions at the surface and in the unsaturated zone.

Water Balance Analysis

Water balance analysis is based on applying the principle of mass conservation to the ground water system of interest. The aquifer is treated as a lumped system, with fluxes integrated over the system. All fluxes besides recharge must somehow be estimated, with recharge to ground water given as the remainder in the mass balance equation. In essence, it is a form of bookkeeping applied to the various fluxes in the hydrologic system.

Water balance methods have several advantages:

- (potential) simplicity
- conceptually appealing

- physically consistent
- a long history of application in hydrology

Water balance analysis, though well-suited for application over large systems at steady state, is not without some limitations:

- estimation of the component fluxes can sometimes be a problem, especially evapotranspiration (ET)
- water balance analysis may be too coarse for smaller systems where a higher degree of resolution is required

The water balance equation can be written as

$$P = RO + R + ET$$

where P = total precipitation, RO = runoff, R = recharge, and ET = evapotranspiration. Given measurements for P and independent estimates of RO and ET, R can be calculated.

Runoff is simply understood to be the fraction of precipitation that runs off the land and is not available for infiltration and eventual recharge. The best estimates of runoff are derived from actual stream gaging and precipitation data. In the absence of data, runoff is frequently calculated in practice with the Soil Conservation Service (SCS) Runoff Curve Number (RCN) method (Mockus, 1964). The RCN is a function of soil type, soil drainage condition, and land cover type. Evapotranspiration can be estimated with, among other techniques, one of the Penman vapor diffusion/energy balance methods (e.g., Eagleson, 1970, pp. 211-242), a site-specific empirical method, or Morton's (1983) complementary relationship. Johnson (1977) concluded that the hybrid "Goldschmidt-Thornthwaite" theory was most appropriate for temperate continental areas such as New York state. On a watershed-wide basis, averaged over a year, analysis of the U.S. Geological Survey stream gaging data from Maine shows that 50% to 65% of precipitation passes through the watersheds. By simple water balance calculation, therefore, the average net ET in Maine is in the range of 35% to 50% of precipitation. Complex empirical formulas are unlikely to estimate the ET component much more accurately over an average year. However the formulas should provide insight as to how the ET can vary as a function of season and unique site-specific conditions. A limited amount of spatial and temporal distribution of fluxes can be handled by applying mass balance over smaller subareas. However, if local resolution, spatial variation, or seasonal effects are of primary interest then some of the other methods discussed here may be more appropriate. Alternatively, more detailed watershed models might be considered (e.g., Leavesley and others, 1983; Famiglietti and others, 1992). This kind of detail is probably most important in shallow, unconfined aquifers; flow in deeper bedrock aquifers is likely less affected by flux variability at the surface.

Parameter Estimation and Inverse Methods

The problem of estimating aquifer properties from water level observations has been called the "inverse problem" of ground water modeling. Formal parameter estimation utilizes

sophisticated methods of optimization, statistics, and systems theory in conjunction with numerical models of ground water flow. These methods are called "inverse methods" or "automatic calibration". Yeh (1986) gives a review of parameter estimation in ground water hydrology. Model parameters (e.g., transmissivity, recharge) are estimated such that a specified error criterion (e.g., sum of squared deviations between observations and simulation) is minimized. Prior to the development of formal algorithms for parameter estimation, models were typically calibrated by systematic trial-and-error (as opposed to "automatic") adjustment of parameters. The goal of manual calibration is also one of minimization, often the root mean square error (rmse) or the mean absolute error calculated from differences between simulated and measured water levels. Calibration and recharge estimation are improved if streamflow gain/loss data are also available, in addition to water level data. Inverse methods are potentially very powerful and in the right hands may be preferable to other methods for recharge estimation in typical Maine applications.

Advantages of inverse methods for estimation of recharge include:

- estimates are consistent with underlying conceptual and mathematical flow models
- temporal and regional spatial variability can be accommodated
- estimates are optimal according to a defined criterion
- knowledge of ET and soil water distribution not required

Despite these strong points, automatic inverse methods are not yet routinely used. This may be attributable to some of the following disadvantages:

- high level of analytical and computer expertise required
- physically unreasonable estimates possible (may indicate problem in conceptual model)
- optimal estimates may be non-unique
- independent estimates of transmissivity may be needed
- unknown parameters may not all be identifiable and observable
- calibrate only to heads or fluxes; unable to calibrate to specified gradients

The related problems of identifiabilty and observability bear special mention. In a prototype vertical cross-sectional model bounded by a divide (no-flow boundary) and a discharge point (fixed head boundary), aquifer parameters governing steady-state saturated flow are recharge and transmissivity. The flux through the aquifer and the predicted water table positions will be a function of the ratio of recharge and transmissivity. A reasonable match between predicted and observed head does not guarantee a unique recharge estimate, since it is the parameter ratio that is critical. Knowing in advance the approximate recharge rate narrows the possible range of transmissivities. These issues lead directly to the subtleties of singularity, identifiabilty, and observability in parameter estimation (e.g., Cooley and Naff, 1990, pp. 77-81).

Several parameter estimation computer programs are generally available, in addition to the larger number of research codes with limited circulation. Cooley and Naff (1990) of the USGS have developed a parameter estimation computer program based on linear and non-

linear regression in combination with a two-dimensional integrated finite difference ground water flow model. Doherty (1990) has developed a regression program, MODINV, for use with the USGS MODFLOW three-dimensional flow model (McDonald and Harbaugh, 1988). Hill (1992) recently published the MODFLOWP regression module for use with MODFLOW. MODFLOWP is quite flexible and can be configured to a wide variety of estimation problems, including recharge estimation. Despite the availability of these codes, trial-and-error calibration will continue to be widely used, especially in simpler applications.

One-Dimensional Direct Modeling of Recharge

Direct modeling uses a decoupled model of hydrologic processes in the soil column above the water table. Most of these models have come out of agricultural engineering and soils science, where the object is to model water and chemical fluxes through the unsaturated zone. However, it is just a small conceptual leap from flux through bottom of the column to ground water recharge. With modification, these models can be used to calculate recharge rates to ground water. These models are typically one-dimensional in the vertical. The major component physical processes are included (e.g., ET, actual water evaporation and consumption by plants, interception of precipitation, infiltration, runoff, and redistribution). Thus, these models may be thought of as detailed, physically-based water balance models. The treatment of the component submodels may be conceptual or physically-based, the latter usually at the cost of added complexity and data requirements. The models are decoupled from the ground water regime. The lower boundary condition may be set as the water table in the case of shallow systems or as a specified head gradient (commonly = 1) for steady gravity drainage at depth. These models are data-intensive and require continuous and/or event meteorologic data, detailed soils characterization, and crop/plant growth and water consumption parameters.

A significant limitation of these recharge models is that they are one-dimensional. Variables such as distances to ground water divides and land slope are not considered. It is intuitive that steeper land slopes will shed more water and allow less deep percolation than flat land, other things being equal. This effect is not quantified in any meaningful way in the one-dimensional vertical models. However, the form of the landscape and the relationship of points to the ground water divides and discharge areas can be taken into account where water tables are close to ground surface. A useful technique for analyzing this special case is presented in a later section of this paper.

Advantages of direct recharge calculation by vertical modeling can be summarized as:

- includes detailed temporal variability due to plant growth and climate
- reasonable computational burden, though a computer is required

Corresponding disadvantages are:

- moderately heavy data requirements
- cannot capture spatial effects of topography and location between divide and discharge boundaries

- moderate modeling expertise required

A number of fully-documented, public domain one-dimensional models of vertical flow above the water table are available:

- **CREAMS**
- **GLEAMS**
- **HELP**
- **DPM**

All of these models use simplified soil water routing to simulate vertical flow through the unsaturated zone. Such an approach works best in humid climates.

CREAMS (Knisel, 1980) and its extension, **GLEAMS** (Leonard and others, 1986) are perhaps the best known and most widely used models in this list. The name "**CREAMS**" is an acronym for "Chemicals, **R**unoff, and **E**rosion from **A**gricultural **M**anagement **S**ystems". The model uses SCS curve number hydrology for runoff calculations, a simple soil water storage routing model for vadose zone water movement, and Ritchie's (1972) potential evapotranspiration model. A crop growth/water demand component is also part of **CREAMS**. **CREAMS** was later extended to include aspects of hydraulic and chemical loading to ground water. The result was dubbed **GLEAMS**, for "**G**roundwater **L**oading **E**ffects of **A**gricultural **M**anagement **S**ystems". However, it has been reported that **GLEAMS** does not route water completely from the root zone to the water table (Shoemaker et al., 1990).

The EPA-sponsored **HELP** model (Schroeder and others, 1984a,b) is another offshoot of **CREAMS**. **HELP** (**H**ydrologic **E**valuation of **L**andfill **P**erformance) was developed by the U.S. Army Corps of Engineers for EPA using **CREAMS** as a starting point. HELP is intended for calculating leachate fluxes through landfill caps and liners. It is often used to calculate recharge to ground water beneath landfills. One of the major changes from **CREAMS** was the inclusion of modules for calculating flows through engineered landfill drains. Most of the component submodels are similar to **CREAMS**. Since **HELP** is designed specifically for landfill analysis and design, it is of limited use for estimating regional recharge.

The last model in this group is the U.S. Geological Survey **D**eep **P**ercolation **M**odel, or DPM (Bauer and Vaccaro, 1987). The model is conceptually similar to **CREAMS**, **GLEAMS**, and **HELP** in terms of the physical process that are included and the manner in which flow through the column is modeled. Just as **HELP** is specialized for landfill applications, **DPM** is specialized for calculating deep percolation rates. Therefore, of these four models it may be preferred for estimating regional recharge.

There may be occasions in Maine when the unsaturated zone is thick, or the unsaturated zone requires a more physically based treatment. Then a one-dimensional variably saturated flow model should be considered, e.g., **Opus** (Smith, 1992) or **RZWQM** (GPSR, 1992). Some of the multi-dimensional variably saturated flow models listed below can also be applied to vertical one-dimensional situations.

Indirect Estimation of Recharge: Saturated and Variably Saturated Flow Modeling

In both water balance analysis and one-dimensional vertical modeling, recharge (or vertical flux through the bottom of the soil column) appears as an explicit boundary flux. The models, however simple or complex, solve for the recharge quantity when all other terms are known. In contrast, recharge does not appear explicitly in indirect methods, but is calculated as an internal flux in the model. This usually means that some effort may be required in interpreting model results to extract the desired recharge estimates. The advantage of this approach is that the problem can be posed in terms of known information (e.g. water levels) and system boundary conditions. Provided the information is accurate and the model is conceptually correct, the resulting recharge estimates should be consistent with the known information.

Advantages of estimating recharge indirectly with a flow model include:

- problem is posed in terms of known and observable boundary conditions
- recharge is calculated implicitly
- recharge estimate is consistent with underlying conceptual model
- allows for spatial distribution of recharge

The disadvantages of this approach are closely related to the advantages listed above:

- boundary conditions must be known
- conceptual model must be consistent with the actual hydrogeology
- modeling expertise and supporting computer resources are required

Saturated Flow Modeling

Indirect estimation of recharge with saturated flow models can be approached with two-dimensional models in section or plan, or three-dimensional models. It is appropriate for steady or transient flow situations. The essence of this approach is to develop the flow model in terms of known third-type (Cauchy or "leaky") boundaries over part or all of the domain. This boundary condition is formally given in terms of hydraulic head in a "leaky adjacent aquifer" separated from the aquifer of interest by an aquitard. In practice, though, this method can be used even when a clearly defined aquitard is not present. The primary requirements are that the phreatic (or piezometric) surface and hydraulic conductivity are known or can be estimated over the entire domain.

In section models, the water table position (or reference head surface, for leaky connected aquifers or water bodies) is assumed known, and the goal is usually to determine the distribution of recharge across different strata in the aquifer of interest. Section models are quite useful in that the spatial distribution of recharge (and discharge) along the section is determined. This approach is best used at a local or small regional scale.

In plan models, recharge across a semi-confining layer into a lower unit is often of interest. The same kind of known information assumed in section models is also assumed in plan models. Two- or three-dimensional models can be used, though three-dimensional mod-

els are most representative of the physical flow system. As saturated flow modeling is now a mature subject that is widely applied, it is not necessary to tabulate the many available models. In passing, though, the popular three-dimensional finite-difference USGS **MODFLOW** model (McDonald and Harbaugh, 1988) and the flexible two-dimensional finite-element **AQUIFEM** model (Townley and Wilson, 1980) are considered by the authors to be among the best.

Variably Saturated Flow Modeling

The use of variably saturated flow models enables one to avoid the problems of specifying ground water recharge rates or calculating recharge as distinct from the ground water system. Instead, the effective recharge at the ground surface is specified. The model then determines the movement of water in the unsaturated and saturated zones, including some or all of the aquifer of interest. This has the advantage that the internal spatial distribution of flux across the water table (i.e. recharge) is automatically determined by the model. Variably saturated flow models may be most useful when the temporal distribution of recharge is required, the unsaturated zone is of significant thickness, and there is significant ET demand in the shallow (root) zone. Thick unsaturated zones often induce long lag times between application of precipitation at the surface and recharge at the water table. This effect cannot be captured by saturated flow models.

Much of the original work in variably saturated flow modeling was motivated by agricultural and soil physics needs, but more recently the unsaturated zone has received attention in studies of potential nuclear waste repositories and landfill failure analysis. Since much of the original work in unsaturated flow originated in agricultural work, many models include well-developed algorithms for including plants and evapotranspiration as moisture sinks. However, the effective precipitation at the ground surface must still be estimated, considering the surface processes of interception, runoff, infiltration, etc.

As with fully saturated section models, multi-dimensional variably saturated flow models produce a physically-based spatial distribution of recharge as a function of geology and topography. This is useful if a detailed understanding of recharge/discharge patterns is required. Inverse methods applied to regional flow models and one-dimensional recharge modeling cannot produce this level of detail.

A representative list of available public domain two-dimensional models follows:

- VS2D (Lappala et al., 1987) and VS2DT (Healy, 1990)
- UNSAT2 (Davis and Neuman, 1983)
- SUTRA (Voss, 1984)

Fully three-dimensional models are impractical for most problems, due to computational and parameter demands. The nature of unsaturated flow is such that even the one- and two-dimensional models should only be used by those experienced in the computational and theoretical aspects of unsaturated flow.

Choosing a Method

The most useful and general recommendation is to consider only those methods that address the important features in the problem under consideration. Anything less, and one is likely to obtain an inadequate model for estimating recharge. Anything more, and one is likely to expend scarce resources on a needlessly complex model. Furthermore, higher levels of complexity generally imply greater data requirements. It is difficult to justify a particular method if the supporting data is not available. For example, a transient three-dimensional variably saturated flow model is inappropriate if average annual regional recharge to a sand and gravel aquifer is of interest.

It is good practice to include a simple water balance analysis in any determination of recharge, even if more complicated methods are used. Water balance provides a check on the realism of results obtained by other methods. Part of basic water balance analysis is a determination of ET. Several methods for estimating ET have already been mentioned in the "Water Balance Analysis" section. ET calculations are subject to great error, and care must be exercised when interpreting the results of whichever method is used.

On a regional basis over large time scales the water balance method is probably sufficient. At smaller scales or for transient analysis, one of the other methods may be necessary. The other methods all have the drawback that they require higher degrees of sophistication and expertise on the part of the hydrologist. They also require significantly more data and computing resources. Confident, knowledgeable use of the more advanced methods presupposes experience as well as advanced study in theoretical and computational hydrology, as none of the methods are trouble-free. At a minimum, a basic understanding of the physical processes and hydrogeologic setting are required.

If a numerical ground water model is being applied, then automated inverse methods should be considered. They constitute a systematic approach to the difficult task of calibrating numerical flow models, and are useful for both transient and steady-state applications. The resultant recharge estimate is inherently consistent with the rest of the ground water model as well as the underlying conceptual model. Thus, automated inverse methods are also useful for evaluating the soundness of the conceptual model. Models so calibrated should be checked against hydrogeologic experience, suggested "rule of thumb" parameter values, and an independent water balance analysis. One weakness of currently available codes is that they only calibrate to heads or fluxes, and not specifically to horizontal or vertical gradients. Critical gradients should be checked carefully in models calibrated with automated methods. Recharge estimates from manual or automatic inverse methods are generally better if good independent estimates of transmissivity are available. Then transmissivity can be taken as "known" in the inverse modeling. There is usually more difficulty in estimating transmissivity than in estimating recharge rates. This is because transmissivity can easily vary over an order of magnitude while recharge is more tightly constrained. If automated methods are inappropri- ate, then trial-and-error can be used to estimate recharge by matching simulated heads and fluxes to available data. Examples are given later in this paper of trial-and-error and automated inverse methods for recharge estimation where the hydraulic conductivity distribution was known with some degree of confidence.

An alternative to inverse modeling is to use one of the direct recharge calculation models. For typical ground water applications in Maine, DPM is probably the best choice since it was developed for ground water applications and the vertical flow component has been shown to be adequate for humid climates (Thompson and Tyler, 1984). If the unsaturated zone processes are of special concern, if there is a specific agricultural aspect of the problem, or transient behavior at the field scale is a problem, then one-dimensional variably saturated flow models might be considered. Multi-dimensional variably saturated flow models such as VS2D and UNSAT2 can also be used for one-dimensional applications. Variably saturated flow models are most useful when strong seasonal recharge variation (e.g., due to distinct growing seasons) or transient flow is an important feature, or when the unsaturated zone is thick. Their use is questionable when these factors are unimportant.

At local or small regional scales, indirect estimation with flow models may be useful for determining recharge. The chief advantage of multi-dimensional variably saturated flow models is that they produce a spatial distribution of recharge that is governed by the geology and topography in an integrated, physically based manner. When used in cross-section, these models are limited by their two-dimensional nature to a single flow path with no horizontal extent. Depending on the problem this may be acceptable. Along with automated inverse methods, these models may also be the most intimidating from theoretical, computational, and data requirement perspectives. Many of the variably saturated flow models include sophisticated treatments of plants as moisture sinks, especially useful for modeling seasonal behavior.

If flow in the unsaturated zone is unimportant, indirect estimation using saturated flow models should be considered. They are considerably easier to use than variably saturated models and yield much of the same information. Whereas variably saturated flow models only make sense in transient and seasonal applications, fully saturated flow models using leaky boundaries can be used effectively under steady or transient conditions. Transient behavior due to seasonal variation can often be modeled in a quasi-steady manner (i.e., model each season as a steady state, but vary the boundary conditions by season).

WATER TABLE RESPONSE TO RECHARGE

Before presenting ground water recharge rates for specific geologic terrains characteristic of Maine, it is useful to consider the general issue of water table response to recharge. The very notion of response implies some kind of transient behavior, as opposed to steady state conditions in which a long-term average water table position is of interest. Three problems commonly appear when interpreting the response of a phreatic aquifer to recharge.

Short-Term and Long-Term Specific Yield

A common and simplistic way of calculating the response of a water table to an increment of recharge is to divide the amount of recharge (units of length, [L]) by the specific yield. For example, one might assume that 0.25 inches of recharge on a phreatic aquifer with 0.25 specific yield will cause a 1 inch rise in the water table. Specific yield is a time-dependent variable and it is usually not the same for a drying condition as it is for a wetting condi-

tion during the transient state. A discussion of these aspects of unsaturated flow can be found in many textbooks, such as Bouwer (1978, pp. 29-31).

Pumping test analyses of wells in unconfined stratified sand and gravel aquifers will often produce a calculated specific yield of about 0.05, although the commonly accepted textbook value for these materials would be about 0.25. Over a typical year on Maine sand and gravel aquifers, with alternating wetting and drying cycles, an average value of specific yield of 0.1 seems to provide the best calibrated fit to regional models. Here the times between major change in volumetric-water content of the unsaturated zone and water table changes is longer than the duration of a typical pumping test, but shorter than the time required for complete drainage to a new "equilibrium" condition in the volumetric-water content of the unsaturated zone above the water table.

Lag Time between Recharge Application and Water Table Response

The next problem in predicting water table change from a given recharge distribution relates to the time between application of recharge and the response of the water table change. This only becomes an issue in transient evaluations. In the case of simple lumped-parameter models, the response time can be calculated explicitly. Sangrey et al. (1984) suggest that water table response is a linear function of recharge on the basis of empirical evidence. The parameters of the relation can be estimated by standard linear regression. This approach is somewhat simplistic, and due to its empirical basis the parameters lack meaningful physical interpretation.

Gelhar and Wilson (1974) used a simple water balance/linear reservoir conceptual model to study aquifer response to recharge. This same approach is used extensively in surface hydrology rainfall-runoff modeling (e.g. Dooge, 1973). In Gelhar and Wilson's application, the reservoir time constant (i.e. response time) is $T_c = SL^2/3T$, where S is specific yield (dimensionless), L is the distance [units of length] from ground water divide to discharge zone, and T [units of length^2/time] is the effective aquifer transmissivity. The response time T_c is the time required for the aquifer to complete 63% of the total change in storage induced by a step change in recharge. The value 63% is a consequence of the assumed linear reservoir conceptual model and the resultant exponential impulse response function. The time t^* to reach an arbitrary degree of completion c^* is $t^* = \{-T_c \ln(1-c^*)\}$, $(0<c^*<1)$, so that time to 95% completion is $t_{95} = 3T_c = SL^2/T$.

While these simple models may not be suitable for local site-specific applications, they are useful for developing a conceptual understanding of aquifer dynamics. For example, the response time of very large aquifers (such as the Raritan Formation in New Jersey) is much longer than those of small isolated New England glacial deposits. Most New England aquifers respond to seasonal changes in recharge pattern. Some are even small enough to respond to daily changes. However, large aquifers only respond to long-term geologic, climatic, and man- induced stresses.

Movement of Recharge Through the Unsaturated Zone

A final problem in evaluating the response of the water table to recharge is calculating the time for precipitation recharge to move through an unsaturated zone. This is different from the response time discussed above which relates solely to specific yield, transmissivity and aquifer length scale, and not to unsaturated thickness above the aquifer. The time required for flow through the unsaturated zone is small for most Maine aquifers. However, there are places in Maine, such as the sand and gravel aquifer near the McKin Chemical Superfund site in East Gray, where as much as 100 feet of unsaturated material overlies the aquifer. In order to simulate properly the response of the water table to recharge, a one-dimensional unsaturated flow model must be coupled to the saturated flow model. This had to be done, for example, in developing ground water management models for the Long Island, New York, aquifer (G. Pinder, personal communication., 1986).

RECHARGE RATES IN MAINE SAND AND GRAVEL

For sand and gravel aquifers, RGGI has identified a narrow range of recharge estimates based on results from modeling studies in Maine. Recharge values also exist for this soil type from Long Island, New York, and Cape Cod, Massachusetts, although recharge rates are somewhat less (16 to 18 inches per year according to Wilson, 1981) than for Maine. This difference is due to the higher average annual temperatures and therefore greater ET rates. Average annual precipitation in these hydrogeologically similar locales is on the order of 45 inches per year.

Surface water runoff appears to be insignificant on sand and gravel aquifers. In southern and mid-coastal Maine, stream gage analysis indicates that ET accounts for about 35% to 40% of average annual precipitation loss. It stands to reason, therefore, that in sand and gravel aquifers with no runoff that the remainder of the precipitation is ground water recharge. Cervione et al. (1972) found that only 5% of total runoff from precipitation on Connecticut stratified drift aquifers is surface runoff; the remainder is ground water discharge. Vechiolli and Miller (1973) concluded that surface water runoff was insignificant in the Ramapo River Valley aquifer, a stratified-drift valley fill aquifer in northern New Jersey.

Recharge Estimates from Ground Water Models by Robert G. Gerber, Inc.

RGGI (1984) calibrated a two-dimensional finite-element flow model of the outwash sands of the Branch Brook aquifer in Kennebunk and Wells to base flow of the brook as measured at the Kennebunk, Kennebunkport & Wells Water District (KKWWD) pumping station. The best fit was obtained with an average annual recharge rate of 55% of precipitation.

Similar recharge estimates resulted when RGGI (1987a) evaluated the long-term safe yield of the Estabrook and Stevens well field in a well-defined sand and gravel aquifer in North Yarmouth. This well field has a proven safe yield of 475 gpm. RGGI calibrated a one-dimensional model (Wilson, 1981) to this aquifer. When the pumping rate exceeds the safe yield, static water levels decline. Based on areal mapping of contributing area, the average annual recharge rate must be on the order of 60% to 65% of precipitation to produce this yield.

Recharge Estimates from Ground Water Models by U.S. Geological Survey

Computer modeling studies by the U.S. Geological Survey have developed estimates of recharge rates on sand and gravel in valley-fill stratified drift and outwash glacial aquifers. Morrisey's (1983) study of the Little Androscoggin River valley gave a recharge estimate of 45% of precipitation in water year 1981. Undoubtedly there were other soil types and urbanized areas within this large study area that would tend to reduce the recharge rate estimate from a more representative range of 50% to 55% for pure sand and gravel.

An important point in the Morrissey (1983) study is the necessity of adding the recharge contribution from adjacent till-covered uplands to the edge of the stratified drift. Based on flow model calibration, he suggests that one can estimate lateral inflow across a given edge length of sand and gravel aquifer by taking 60% of the precipitation falling on the surface watershed above the edge of the sand and gravel aquifer. This lateral influx takes the form of ground water flow as well as surface runoff that subsequently infiltrates the sand and gravel.

Tepper et al. (1990) developed a model of the Saco River Valley glacial aquifer between Bartlett, New Hampshire and Fryeburg, Maine. They cite a recharge estimate of 24 inches per year for stratified drift aquifers in the glaciated northeast United States, or approximately half of total annual precipitation. They accepted this as a "known" value and did not calibrate their model by adjusting recharge. Average annual precipitation in the study area is approximately 44 inches per year.

Recharge estimates from studies of other glaciated terrains in the northeast United States can also be used to make inferences for Maine sand and gravels. Vecchioli and Miller (1973) estimated long-term average annual recharge to the 4.5 square mile Ramapo River valley-fill stratified drift aquifer in northern New Jersey as 25 inches per year, with average annual precipitation of 45 inches per year. This estimate was based on water balance and assumed no significant surface runoff. Getzen (1977) cites a gross estimate of 23 inches per year recharge for Long Island, New York, as given by Cohen et al. (1968). He suggested that it is probably too high for the entire island, as it ignores several important factors, including spatial differences in precipitation, the distribution of morainal and outwash soils, thickness of the unsaturated zone, and local relief. He therefore developed a spatial distribution of average annual recharge for his analog flow model of Long Island, with recharge ranging from 16.9 inches per year to 21.7 inches per year. Average annual precipitation on Long Island is on the order of 45 inches per year.

In a later modeling study of the Ramapo aquifer, Hill et al. (1992) calibrated a two- dimensional **MODFLOW** application by trial-and-error adjustment of recharge and several other parameters. They obtained acceptable fits to observed water levels and measured streamflow gains and losses with a range of recharge values, from 8.8 inches per year (0.002 feet per day) to 19 inches per year (0.0042 feet per day), with a recommended compromise value of 12.4 inches per year (0.0032 feet per day). This apparently low value is due to the fact that they calibrated to seasonal low water level conditions on October 13, 1982, and is therefore not representative of long-term average annual recharge. This highlights the impor-

tance of using recharge estimates that are consistent with the available calibration data. If the goal is to estimate long-term average annual recharge, then the calibration data must reflect long-term average conditions, and not seasonal and/or other cyclical lows or highs.

Seasonal Variation of Recharge and Drought

Although average annual recharge values are used for long-term contaminant transport studies (where the time scale is on the order of tens of years or more), seasonally variable recharge values may be more appropriate for some studies. As part of the Branch Brook watershed ground water model (RGGI, 1984), a detailed water balance was performed on data recorded during a one-year test period (10/81 to 10/82). The available data included monthly water levels from USGS-installed monitoring wells within the model area and partial stream gaging of the Branch Brook watershed (D'Amore, 1983). Average monthly rates derived from the RGGI (1984) Branch Brook study are summarized in Figure 1 for sand and gravel in south-coastal Maine. The range of values reported above for Hill et al. (1992) is consistent with the recommended September and October recharge values for Southern Maine in Figure 1.

Note the net removal of water indicated by Figure 1 in June, July, and August. This would only apply on those phreatic aquifers where the water table is close enough to ground surface to be affected by ET. The removal of water by ET is included in most ground water models, e.g., McDonald and Harbaugh (1988), Prickett and Lonnquist (1971), and Trescott et al. (1976). It is typically treated as a truncated linear depth function, such that ET is a maximum when the water table is at the ground surface, and it decreases linearly to zero with the water table at a defined depth below ground surface below which ET ceases to function. The values in Figure 1 were derived from the trial-and-error inverse procedure of calibrating the Branch Brook aquifer model (RGGI, 1984) to measured water table fluctuations in a number of USGS monitoring wells spaced throughout the aquifer. Actual precipitation and calculated potential ET from measured meteorologic conditions were used to guide the calibration. The water table in much of the upper section of the aquifer is close to ground surface.

The Branch Brook study also yielded insight into the effect of drought on ground water levels and discharge. The 1965 drought in the Branch Brook aquifer was simulated such that the minimum monthly flow in Branch Brook matched the recorded yield at the KKWWD pumping station. The estimated monthly recharge and ET values for that year are somewhat site-specific and also depend upon the choice of specific yield. Subject to these qualifications, it was observed that in severe drought years precipitation is only about 60% of average annual precipitation. It is reasonable, therefore, to simulate a severe drought by multiplying average recharge rates by 60%. Surface water reference head values at first- and third-type boundaries should also be adjusted for drought.

Figure 1 includes some recharge during the winter months of December, January and February. During this period most precipitation is in the form of snow. The snow does not actually recharge the aquifer until March and April when the recharge rates are much greater due to snow melt. Recharge will occur during winter when precipitation is in the form of rain or when average daily temperature is above freezing under forested watersheds (Gerber,

1978). The distribution of recharge throughout the year will shift as one goes from southern to northern Maine. As one goes further north, relatively more water is stored during the winter months in the snow pack. This snow pack water creates a larger spring recharge event that begins later and lasts longer.

RECHARGE RATES IN SANDY GLACIAL TILL

Sandy glacial till and diamicton is located on and in the down-glacier direction from granitic rock masses in Maine. The till commonly has from 15% to 25% passing a #200 sieve (in the silt and clay range) and has a typical hydraulic conductivity of 0.15 to 1.5 feet per day (ft/day). Morrissey (1983) used a hydrograph separation method to evaluate the baseflow from the Little Androscoggin River above South Paris. The watershed is covered primarily by a sandy till derived from granitic rock. Stream baseflow varies seasonally. When an "average" baseflow figure is cited in the literature, it is an average of the values across the seasons. Morrissey (1983) found that for water year 1981, which had 39.4 inches of precipitation at West Paris, the till produced an average baseflow of 19% of precipitation or 7.4 inches. This is interpreted as the ground water recharge rate of the sandy glacial till.

During the period 1987 to 1989, a major geologic and hydrogeologic investigation was conducted in Township 30, Washington County, for a special waste landfill. This study generated useful data pertaining to recharge in glacial tills (RGGI et al., 1988). The site is situated on a granitic pluton, but metasedimentary rocks are located about 2 miles up-glacier. The fines content of the till and diamicton on the site was quite variable and ranged from 15% to 55%. Because of intermixing of some metasedimentary-derived sediments in the till matrix, the geometric mean insitu horizontal hydraulic conductivity is about 0.1 feet per day in the upper 20 feet and 0.04 feet per day below 20 feet depth, which is slightly lower than a till derived from only granitic rock. However, hydraulic conductivity varied over a wide range and a uniform horizontal hydraulic conductivity of 0.2 feet per day was used to represent the till in the final model.

A regional three-dimensional model was constructed using **MODFLOW** (McDonald and Harbaugh, 1988). This model was calibrated to 38 monitoring wells, including numerous clusters of wells measuring potentiometric levels at various depths. Forty-three in-situ permeability tests and 3 bedrock pumping tests provided information on hydraulic conductivity. The model was calibrated with a recharge rate of 5 inches per year applied over an area where till was prominent on the surface and 5.5 inches per year where ice disintegration deposits dominated. The recharge was applied uniformly over both recharge and discharge areas.

The model calibration, although good (arithmetic mean of residuals of 0.9 feet and mean absolute value of residuals of 4.9 feet), could have been improved by spatially distributing recharge while maintaining an overall average for the model area of 5 or 5.5 inches per year. Nonetheless, most modeling studies use a uniform recharge because of the difficulties of determining the spatial distribution of recharge.

Sensitivity analyses on the till and ice disintegration recharge rate using **MODFLOW** showed that multiplying the calibrated recharge by a factor of 1.5 caused an average poten-

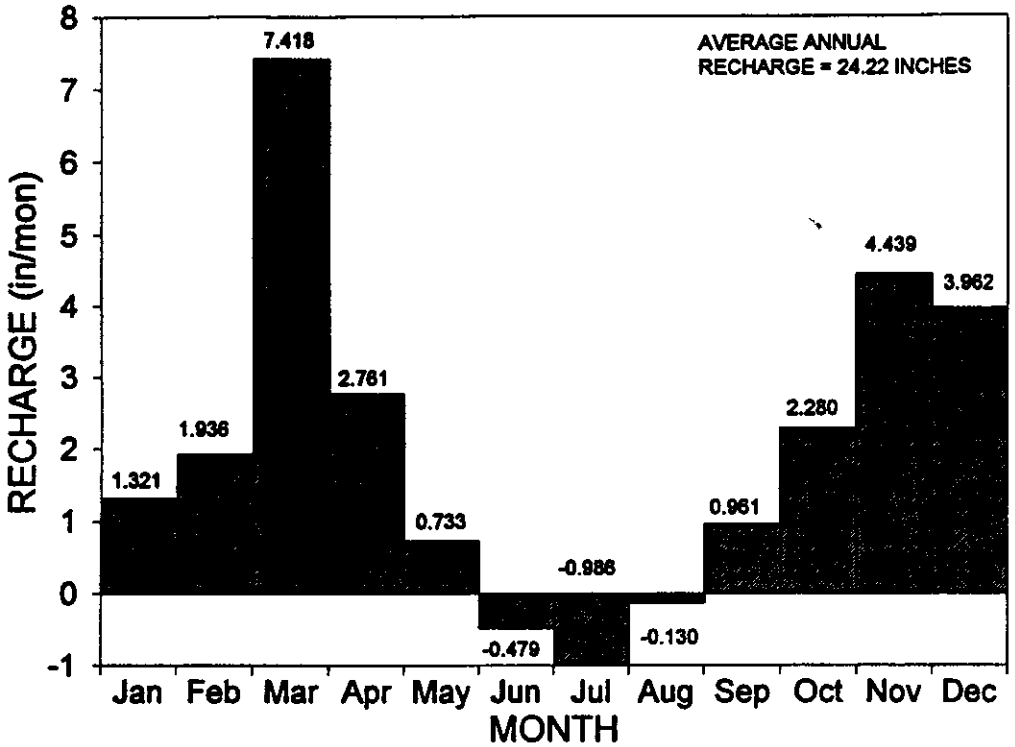

Figure 1. Average monthly recharge rates on sand and gravel deposits in Southern Maine.

tiometric head increase of 2.2 feet; multiplying calibrated recharge by a factor of 0.67 caused an average decrease of 1.5 feet in site area potentiometric heads. When all significant hydraulic parameters (such as till hydraulic conductivity) were varied one at a time by the same multiplication factors, the change in recharge rate caused the greatest change in site heads.

A final check on the recharge estimate was provided by measurements of vertical hydraulic conductivity. The Township 30 landfill site is on a local recharge area. With the large number of measurements of ground water vertical gradients on the site, it was possible to estimate the effective vertical hydraulic conductivity of the diamicton, which is approximately equal to the recharge rate divided by the average vertical gradient, or 0.04 feet per day.

RECHARGE RATE OF FINE-GRAINED LODGMENT TILL

If one knows the phreatic water table position and the hydraulic conductivities pertinent to a geologic cross section along a flow line with known boundary conditions at each end, the technique of specifying constant heads on the phreatic surface should provide the correct recharge into the section. Having a row of clustered multi-level piezometers on the section provides an important check on model calibration, particularly the hydraulic conductivity anisotropy which is one of the most sensitive parameters in cross section modeling. Large local fluxes can occur at sharp slope changes. In many field situations, a sharp change in slope

is often associated with a discharge point that is at least seasonal in nature. Many of the model-simulated fluxes are created by juxtaposition of two constant head nodes on a steep slope, which causes a "short-circuit". Examining the flux below the top row of elements eliminates misinterpretation of the recharge rate that reaches deeper soil and rock zones.

Georgia-Pacific Landfill Study

An indirect method was used to estimate recharge to a thick silty glacial lodgment till at the Georgia-Pacific secure landfill site (RGGI, 1983). This site, a drumlin, is on the west bank of the St. Croix River and upstream of Woodland, Maine. A two-dimensional finite element model of the bedrock aquifer was applied to the regional flow system. A detailed finite-element cross section model was projected along an approximate flow line through the site. The models were calibrated with data from multi-level piezometers and insitu hydraulic conductivity measurements. The water table position in the cross section was known quite closely, and the stratigraphy and hydraulic conductivity of the till and bedrock units were well-documented. The phreatic surface in the model was fixed as a specified head boundary. With this boundary condition, the model calculated the flux into the till.

This was an important exercise as it also illustrated how recharge rates vary with proportional distance between the ground water divide and the discharge area. The averaged recharge rate over the soil cross section was 7.6% of precipitation (about 3.2 inches per year) but the localized rate was significantly higher (up to 25% of precipitation) on the top of the hill, then decreased in the downhill direction. These rates are taken as representative of soils with vertical hydraulic conductivities in the 0.015 to 0.0015 ft/day range with 35% to 60% passing a #200 sieve.

To extend the cross section results to the local plan-view two-dimensional model, the slope was divided into sections running parallel to ground surface contours, then an average recharge rate was applied in the slope sections within the same general slope position as calculated from the cross-section model. Of course, near the bottom of the slope, recharge rate drops to zero and discharge begins in streams and wetland areas. These discharge areas should be treated as a discharge point in the plan-view modeling, but not necessarily as constant head boundaries, since the streams and wetlands are not usually fully penetrating. Methods for simulating these 3rd-type Cauchy boundary conditions are given in most standard modeling references, e.g. Townley and Wilson (1980), McDonald and Harbaugh (1988), and Anderson and Woessner (1992).

Bald Mountain Hydrologic Study

A recent detailed hydrologic study for the Bald Mountain area of Aroostook County by (Fontaine, 1989a & 1989b) provides a baseflow analysis for watersheds comprised of shallow bedrock and thick, fine-grained glacial till. The till has 35% to 55% passing a #200 sieve and is derived from basic to intermediate volcanic rocks and graphitic shales. Insitu hydraulic conductivity values were typically in the range of 0.03 to 0.2 feet per day. Fontaine (1989a) calibrated a rainfall-runoff model (PRMS, Leavesley et al., 1983) to the Bald Mountain data by automatically varying recharge and other parameters. In addition to detailed meteorologic

Table 1: Annual Water Balance of Fine-grained Till in Northern Maine

Water Balance Component	Volume Equivalent	Percentage of Observed Precipitation
Observed Precipitation (P)	44.00 inches	100.0%
Interception (INT)	2.08 inches	4.7%
Net Precipitation (PNET)	41.92 inches	95.3%
Potential ET (PET)	21.28 inches	48.4%
Actual ET (ET)	13.81 inches	31.4%
Observed total runoff (ORO)	28.06 inches	63.8%
Water Balance Error (ERR1)	0.05 inches	0.1%
Predicted total runoff (PRO)	28.82 inches	65.5%
Surface runoff (SAS)	3.99 inches	9.1%
Subsurface flow (RAS)	17.75 inches	40.3%
Ground water flow (BAS)	7.08 inches	16.1%
Runoff mass balance err (ERR2)	-0.76 inches	-1.7%
Ground water reservoir inflow (RCH)	6.43 inches	14.6%
Ground water flow out of system (SNK)	-0.65 inches	-1.5%

Water Balance Relations:

P = ET + INT + ORO + ERR1
ERR1 = PNET - ET - ORO
PRO = SAS + RAS + BAS
RCH = BAS + SNK (SNK < 0: water into system)

PNET = P - INT
ERR2 = ORO - PRO

Reference: Table 15, Fontaine (1989a, p. 33)

and water quality measurements, detailed stream gaging was done on two forested watersheds with areas of 1.73 and 1.15 square miles, respectively. The PRMS calculates the various components of the catchment water balance as shown on Table 1. Neither Fontaine (1989a), nor this paper goes into detail on the fundamental topic of hillslope hydrology. However, one should consult a text such as Kirkby (1978) to gain an appreciation for the complexity of water movement from precipitation falling on the land to its final destination.

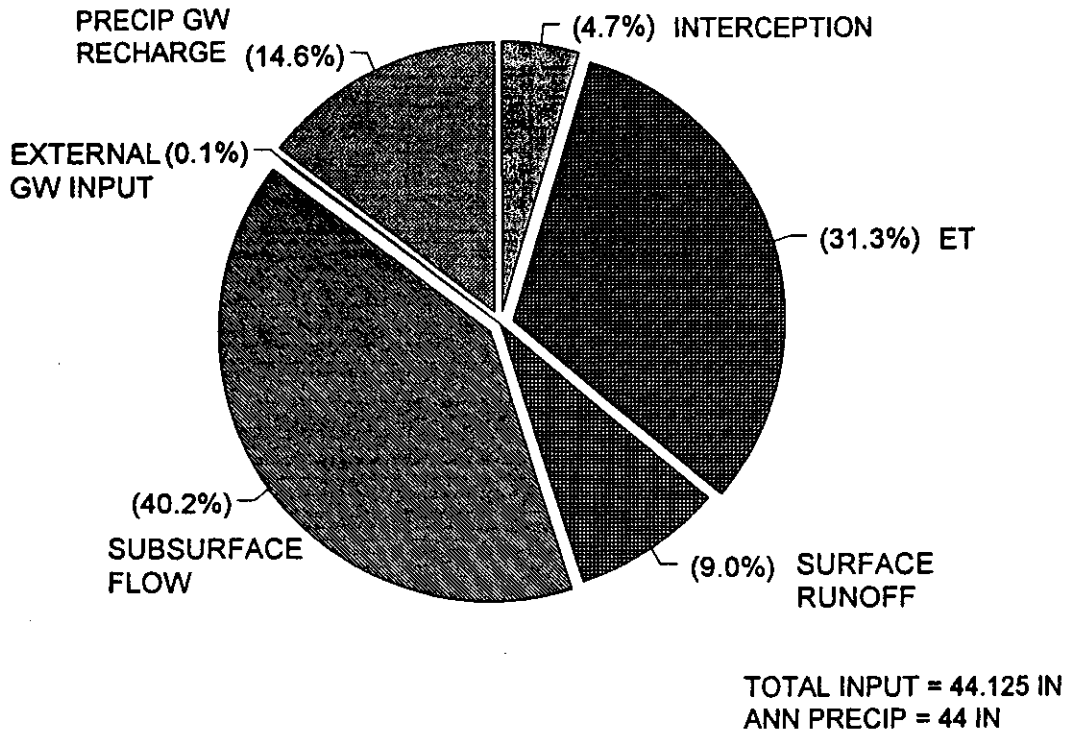

Figure 2. Annual water balance of fine-grained till in Northern Maine.

Fontaine (1989a) simulated the water year 1983 water balance with PRMS as given in Table 1. The same data is depicted graphically in Figure 2 (small discrepancies between percentages in Table 1 and Figure 2 are due to residual errors in the simulation). ET is a smaller percentage of precipitation than in the southern sections of Maine. The largest component of stream flow is the contribution from "subsurface flow" ("RAS" in Table 1), which is the shallow ground water flow taking place within a few feet of the ground surface. It is often a perched ground water table in the A- and B-horizons of the soil.

The ground water recharge rates discussed in this paper correspond to "ground water reservoir inflow", or "RCH", in Table 1. The deep ground water reservoir is below the zone of soil development and "subsurface flow". Twenty-seven percent of the Bald Mountain Brook watershed consists of steep slopes with thin soils, so the "ground water reservoir inflow" component, 6.43 inches per year, reflects a composite of both thick and thin till terrains. Simulated baseflow ("BAS"), or ground water discharge to surface water, is the sum of precipitation recharge to the ground water reservoir and any ground water exchanged directly with an external ground water system ("SNK"). Fontaine estimated a small (0.65 inches per year) net exogenous input to the ground water reservoir, for a baseflow of 7.08 inches.

Baseflow as estimated for Bald Mountain, 7.08 inches per year, is only slightly less than the estimated baseflow contribution for sandy till in Morrissey (1983) of 7.4 inches per

year (19% of precipitation). These data suggest that there is only a minor difference in recharge potential among the tills at this site and those in the Little Androscoggin Valley and at the Township 30 landfill site. This finding is consistent with the similar till hydraulic conductivities at Bald Mountain and the Township 30 landfill site. Contrast this with the horizontal hydraulic conductivity of the Georgia-Pacific landfill site in Woodland, 0.0085 feet per day in the unweathered zone. Recall that in Woodland average recharge was estimated as 7.6% of annual precipitation, or 3.2 inches per year.

RECHARGE RATE TO GLACIOMARINE CLAY-SILT

The Presumpscot Formation clay-silt covers a large portion of the state of Maine (Thompson and Borns, 1985). It acts as an aquitard for bedrock and sand and gravel aquifers. It lies at the base of many of Maine's wetlands. It protects the ground water under the large commercial landfill in Norridgewock, Maine. The facility was formerly known as the Consolidated Waste Services (CWS) landfill, and is now called the WMDSM Crossroads Landfill. A knowledge of how much recharge moves downward into the soft "gray clay" zone is critical to contaminant dilution calculations and to ground water travel time computations. RGGI has developed recharge estimates for this ground water system by indirect calculation (1985) and manual and automatic inverse methods (1987b and 1993, respectively), i.e. calibrating by recharge to observed heads.

The Presumpscot Formation clay-silt is typically composed of about 10 feet of desiccated brown or olive clay-silt overlying a softer "blue" or gray clay-silt. The desiccated zone is fissured into a subangular blocky pattern, more dense and closely spaced at the ground surface and diminishing with depth. The softer gray clay lies below the position of the permanent water table. Because the fissured clay acts like a double porosity medium, ground water can rise rapidly in the fissures and is often at or near the ground surface in the spring. The hydraulic conductivity of the fissured zone is determined by the fissure pattern and can be about 50 times greater than in the unfissured gray clay.

The Crossroads landfill site has been studied extensively over the years by RGGI. Exhaustive hydrogeology studies and associated three-dimensional ground water model applications have been documented (RGGI, 1985, 1987, 1993). One of the most difficult parameters to estimate was the recharge rate of the clay-silt. Extensive data on the distribution and hydraulic conductivity of the clay-silt, underlying sandy till and bedrock was assembled. There were many clusters of multi-level piezometers throughout the site. Hydraulic conductivities were measured by numerous variable head tests in the piezometer clusters and several pumping tests in the bedrock.

The initial approach to modeling the site (RGGI, 1985) assumed that hydraulic conductivity and all other physical parameters of each of the 5 layers in the three-dimensional model were known. Recharge was treated as the only unknown and it was estimated indirectly by fixing constant heads in the top layer of the model, based on the known position of the phreatic surface. The model output gave the fluxes through the bottom of each model cell. This treatment is analogous to the fixing of the phreatic surface in the Georgia-Pacific cross section model described earlier, only at Crossroads Landfill (formerly CWS) the model

was fully three dimensional. This approach indicated that an average recharge of 12.1 inches per year (29% of precipitation) entered the fissured clay, which was the top layer of the model. At Bald Mountain watershed in 1983 (Fontaine, 1989a), 24.1 inches of precipitation per year entered the silty till. Most of this recharge was presumably retained as shallow ground water flow.

The model was revisited in 1987 (RGGI, 1987). The hydraulic conductivities of the clay-silt, till, and rock were kriged according to hydrogeologic unit. The gridded data were used to develop spatially variable conductivity inputs for **MODFLOW**. Most of the constant head cells were removed from the model and instead direct recharge was applied to the model. The model was calibrated by trial-and-error, adjusting recharge until a good fit to observed water levels was obtained. Vertical hydraulic conductivity was also varied during this inverse procedure. After re-calibration of the three-dimensional model, it was determined that only 1.9 inches per year of precipitation (4.6%) moved down into the soft gray clay. This would be approximately equivalent to the mass flux vertically downward through a soil with a vertical hydraulic conductivity of 5 10-4 feet per day. This seems reasonable since the clay-silt hydraulic conductivities range from 3 10-5 to 3 10-3 feet per day, which is considerably lower than the values in the Bald Mountain till (horizontal Kh = 0.045 - 0.91 feet per day, vertical Kz = 0.5Kh, deep recharge 6.4 inches per year), and just slightly lower than the values in the till at the Georgia-Pacific landfill where deep precipitation recharge in the till (Kh = 8.5 10-3 feet per day, Kz = 1.4 10-3 feet per day) was 3.2 inches per year.

Further revision of the model was reported in 1993 (RGGI, 1993). The grid was expanded and recharge was estimated using the **MODINV** (Doherty, 1990) regression package for automatic estimation of **MODFLOW** parameters. The model was calibrated by fixing the hydraulic conductivity and varying the recharge. Considerable data on hydraulic conductivity were available: a total of 160 falling head tests, including 32 located in the bedrock, were available for estimation of hydraulic conductivity. Five bedrock pumping tests were also performed. Consequently, conductivity could be assumed known with some confidence. The computer program **MODINV** was used to perform the calibration by parameter optimization, which consisted of varying the recharge to minimize the RMSE head residual. Head observations from 201 individual piezometers comprised the calibration data set. There were two recharge zones: one representing areas with clay controlling the recharge, and the other representing areas with till controlling the recharge.

The calibrated recharge values derived using the optimization procedure were 0.53 inches per year (1.2 % of precipitation) for the clay zone, and 2.2 inches per year (5% of precipitation) for the till zone. These are total recharge values. Some of the recharge remains in the shallow flow zone and discharges locally through internal drainages, instead of passing through the gray clay to till and bedrock. The clay recharge is equivalent to the mass flux vertically downward through a soil with a vertical hydraulic conductivity of 1.2 10-4 feet per day (4.3 10-8 cm/sec). This agrees with the field hydraulic conductivity tests results, where the vertical hydraulic conductivity of the gray clay was also calculated to be 1.2 10-4 feet per day. These results are consistent with the 1987 results and are a refinement of that work.

A check on this work was provided by analysis using tritium age dating of water samples from the gray clay. To the authors' knowledge, this is the first application of age dating of ground water in Maine for the specific purpose of estimating recharge and vertical flux in overburden. Due to the lab method used (direct liquid scintillation counting), the data were not very precise (+/- 8 TU). The best results suggest a maximum recharge rate through the gray clay of 0.24 inches per year, assuming a porosity of 0.40. This value represents the portion of recharge that actually passes through the gray clay, and is therefore less than the total recharge value estimated by inverse modeling for the clay zone. This value is undoubtedly subject to some variation over the site, and also must be qualified by the fact that the precipitation tritium input function was developed using data from Ottawa, Canada. That said, the estimate is remarkably consistent with the results of automatic flow model calibration.

BEDROCK AQUIFER RECHARGE RATES

A more difficult problem is to estimate the rate of recharge to bedrock aquifers. Except for areas where bedrock is exposed at ground surface, all precipitation has to travel first through soil before penetrating into minute cracks in the bedrock surface. The relief of the land and the location of the point of interest with respect to ground water divides and discharge areas control the bedrock recharge rate. The thickness and effective vertical hydraulic

Table 2: Average Recharge Rates to Maine Bedrock

Project	Location	Rock Type/ Rock Name	Typical Transmissivity (ft2/day)	Recharge*
McKin Chemical	Gray	Sebago Pluton	100	7%
Sewage lagoons	Jackman	granite	40	4%
Aeration lagoons	Woodland	Cookson Formation (metasandstone) and granite	0.1 to 142	10%
Industrial landfill	Woodland	Cookson Formation	42	5%
Commercial landfill	Norridgewock	Sangerville Formation	150 NE to 50 NW	1-4%
Leaking gas tanks	Friendship	granite	15 ENE to 1.5 NNW	13%
CZM study	Portland Islands	metamorphic	43 NE to 4.3 NW	7.4-8.5%
Seawater intrusion	St. George	granite	0.6 to 200	10%
Seawater intrusion	York	Kittery Formation (quartzite)	75 to 400	5%

* expressed as a percentage of total average annual precipitation

conductivity of the soils are very important. Finally, the difference between the potentiometric surface in the bedrock versus the overlying soil aquifer controls the recharge/discharge rate. Local recharge rates can vary greatly depending upon all of these parameters. Nevertheless, some basic areally-averaged estimates that may be of use to hydrogeologists have been derived from detailed computer modeling studies performed by RGGI. These studies have involved three types of models:

- vertical cross section models along known or assumed flow paths in the bedrock aquifers;
- two-dimensional bedrock aquifer models that include the overlying soil as an "adjacent aquifer" with defined thicknesses, vertical hydraulic conductivities, and known water table positions;
- fully three-dimensional models.

In all of these studies model verification in the form of at least some bedrock water potentiometric surface data was available. In other cases pumping test data and/or insitu hydraulic conductivity tests were used to calibrate models by adjusting recharge. In all cases, field mapping of the density and orientation of bedrock fractures was performed.

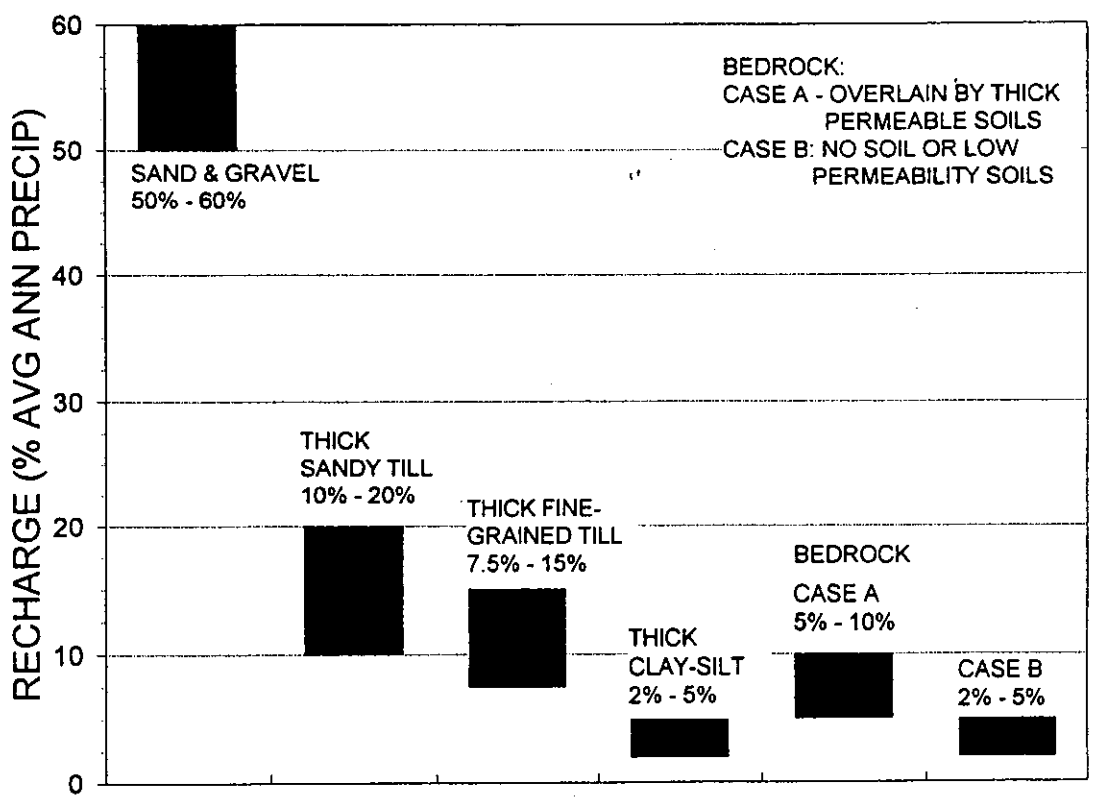

Figure 3. Suggested average ground water recharge rates according to geologic terrain.

Table 2 summarizes information from bedrock modeling studies by RGGI. In all cases, the results did not rely on a need to estimate the recharge rate to the soil, though other measured or estimated soil parameters were used (vertical hydraulic conductivity, soil thickness, and water table elevation in the soil). The sites listed on Table 2 with the lowest leakage factors (vertical hydraulic conductivity divided by thickness) in the overlying saturated soils generally have the lowest recharge rates. However, the site with one of the smallest recharge rates is the York site where there is almost no soil and therefore, no medium to hold water long enough for it to seep into cracks in the rock surface. In the York study (RGGI, 1988), a seawater intrusion model (Bear and Verruijt, 1987) was used which gave good agreement with historical saltwater intrusion in bedrock wells. The St. George model was also calibrated with many wells and much fracture data. The **AQUIFEM** model (Townley and Wilson, 1980) was used in that study, with the overlying soil treated as an adjacent leaky aquifer. The Friendship and Norridgewock models were calibrated partially through the use of pumping tests.

Although computer models are useful and indeed necessary to study bedrock recharge patterns in detail, the general recharge estimates given in Table 2 are probably representative of the range that exists in most Maine bedrock aquifers. Initial estimates for screening calculations and simple analytical models can be drawn from this compilation.

ADDITIONAL RESEARCH NEEDED

The modeling work by RGGI and the USGS has been time-consuming and costly, yet knowledge of effective recharge rates for many types of Maine geologic terrain is still incomplete. Additional detailed studies are needed on various surficial units to develop a broader recharge data base. One source of information might be other private-sector model applications that were unavailable to the authors. More detailed USGS water balance studies such as Fontaine (1989a,b) are needed on small watersheds of homogeneous surficial geology. To the authors' knowledge, the tritium dating at the Crossroads Landfill is the only age dating to have been performed in Maine for the specific purpose of estimating recharge. Age dating studies on different surficial units where downward gradients can be demonstrated are an important check on other estimation methods. More work is also needed on differentiating the change in recharge rate from ground water divide to discharge point. The seasonal variations in recharge for geologic units other than high water table sand and gravel aquifers need study. Finally, Maine-specific studies of hillslope hydrology are needed to analyze the division of water flow among the various types of flow within a slope. This would be particularly useful to the study of nitrate contamination from subsurface septic systems which are placed in the upper soil horizons.

SUMMARY

Ground water recharge rates cannot be measured directly through observation, and therefore it must be modeled in some fashion. Various methods of estimating ground water recharge have been reviewed. Examples have been presented of how these methods have been used in Maine to estimate ground water recharge at specific sites on different homogeneous geologic terrains. It is reasonable to believe that similar terrains within Maine have simi-

Ground water recharge rates cannot be measured directly through observation, and therefore it must be modeled in some fashion. Various methods of estimating ground water recharge have been reviewed. Examples have been presented of how these methods have been used in Maine to estimate ground water recharge at specific sites on different homogeneous geologic terrains. It is reasonable to believe that similar terrains within Maine have similar average annual recharge rates over large areas. Inverse and indirect modeling approaches are useful tools for estimating the distribution of recharge, but the models demand a good knowledge of hydraulic conductivity distribution, stratigraphic data, and bedrock fracture flow information. The detailed water balance studies coupled with models such as the USGS PRMS also offer promise, but are costly in terms of field data and data reduction requirements. Areas for investigation that would benefit all hydrogeologists have been suggested.

Studies with modest hydrogeologic budgets will not be able to estimate recharge independently. Therefore, recommendations for averaged annual recharge rates for the most common geologic terrains found in Maine are given in Figure 3. Some error will be involved in applying these uniformly over large regions, but the judicious use of 3rd-type boundary conditions can provide avenues of ground water discharge where appropriate. With some care, the monthly recharge rate distribution given in Figure 1 can also be adapted to other geologic terrains. Severe droughts can be approximated by applying 60% of the average annual recharge rates. In the absence of better data, enough information on the variables involved has been presented so that an informed hydrogeologist can adapt these estimates to most situations.

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Memo

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Byfield, Massachusetts □ Portsmouth, New Hampshire □ Hamilton, New Jersey □ East Providence, Rhode Island
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Date: March 27, 2014
To: John Holt, Lamoine Planning Board Chair
From: Robert Gerber, C.G.
Subject: Review of Summit Report on additional exploration at MacQuinn Pit and additional follow-up materials

I reviewed the report entitled "Supplemental Hydrogeologic Assessment" prepared by Michael Deyling of Summit Environmental Consultants in December 2013. This report was prepared in response to a Planning Board request that the applicant, Harold MacQuinn, Inc., provide additional geologic information for a gravel pit expansion of the Kittridge Pit into Lot 31. The specifications for the acquisition of additional geologic data originally came from a report I wrote to the Planning Board on April 16, 2013, which was a peer review of the original Summit report on the geology of the site.

Status of Additional Information Requests

I made an initial review of the December 2013 report and requested additional information in a memo I wrote to you on March 15, 2014. The applicant gathered information and submitted this and their supplemental analyses and opinions through a series of emails to me through their agent, Stephen Salsbury. Some, but not all of these emails were copied to you. Apparently he was concerned about your internet bandwidth not being able to handle the size of some of the documents. The following describes what was submitted in response to my requests.

1) *Another complete synoptic (acquired at the same time) round of water level readings in the new monitoring wells and four older monitoring wells*. All water levels were lower than the November 2013 readings.
2) *A discussion of how the timing of the stream flow measurements used in the water balance computations related to whether they are baseflows only and whether these flows represent "average annual" base flows, fall high baseflows, etc.* A discussion was provided comparing antecedent precipitation readings to the time of the stream flow measurements. The measurements were taken August 26, 2013, when flow in a small watershed in sand and gravel in Washington County was 6.3 cfs (see **Attachment 1**), which was about the lowest flow of the summer

in that watershed. Over the 13 years of stream gaging in Libby Brook, the lowest flows have typically been in August and September. So I think we can conclude that the measurements at the time of flow were less than the average baseflow for the year.

3) *Divide the recharge area into units of similar recharge capability and multiplying these sub-units by a representative recharge rate for the respective units and summing those to make the comparison*. Summit did a more elaborate and complete estimate of the recharge rate to the Cold Spring aquifer system. It appears to be a reasonable evaluation of the type I have done many times.
4) *Supply page 7 of the PB-4 boring log*. It turns out there there were only 6 pages to that particular boring log and the indication that there were 7 pages was an error in the report.
5) *Provide a table of elevations and locations of geologic data points with survey-grade GPS equipment*. Salsbury provided a table of the xyz values for the geologic data points and also provided a CAD drawing that was georeferenced that I was able to pull into ArcGIS.
6) *Provide data on the string of six "CSW" wells*. I received an email from you saying you would put data on the wells into the record and that you had sent the data previously to Summit. I have not been able to find the data on the town website record of this proceeding, but I did get a list of water level readings taken in the wells from Salsbury and a plan of the locations and the x-y-z table of the well locations and elevations. I did not receive any boring logs for these wells.
7) *Michael Deyling should put his CG stamp on the report and sign it*. I was told by Salsbury that a hardcopy page with Mr. Deyling's stamp and signature was submitted directly to the Board.

In my opinion, the additional data requested has been provided and are sufficient to allow my review.

Review of New Information Provided Since My March 15, 2013, Report

There were several major issues outstanding when I wrote my March 15, 2013, review:

A) The westward extent of the clay layer that held up a perched water table that supplied Cold Spring was uncertain and therefore the proposed plan to excavate the pit in that area could have a deleterious effect on the Cold Spring yield and quality
B) The position of the deep water table in the sand and gravel within which the pit would be excavated was largely unknown and the proposed excavation plan might therefore turn out to be too ambitious.

The additional information I requested was designed to fill in the information gaps and permit the Planning Board to make an informed decision as to whether the Application met the Board requirements.

In my opinion the Applicant has fairly complied with my information requests and supplied sufficient data for the Board to be able to review and decide whether the groundwater impact part of the application meets their requirements. The new deep monitoring wells in and near the proposed pit expansion area define the approximate position of the water table under the pit. The Applicant has provided a modified pit development plan that shows in cross section the depths and extent of the proposed gravel mining. Given the great depth to the deep water table and the long time it will take to excavate gravel out to get close to that water table, *a reasonable condition of the permit would be to require that when the pit bottom is excavated to within 15 feet of the currently-estimated groundwater table position that new monitoring wells be installed over a wider area and that one year of monthly water levels be taken in those new wells (except biweekly during March, April, and May) to determine the final position for purposes of determining the final allowable bottom elevation of the pit*.

The new borings along the eastern side of the proposed pit expansion found that the westward extent of the clay layer that supports the perched water table feeding Cold Springs does not extend as far as I speculated originally that it might extend. I think we have a reasonable understanding of the extent and depth of that clay layer now. The Applicant has modified the mining plan to show protection of this clay layer and has offset the proposed mining area to the west to accommodate it. Again, *a reasonable condition of the permit would be to require that in the event the clay layer of interest (the one that forms the perched water table flowing toward Cold Spring) is intercepted farther west than currently known, then the mining plan shall be altered to stop any further mining in this area to depth and the edge of any deeper excavations be shifted westward to beyond the edge of the clay layer*.

Although we do not know everything there is to know about the recharge area of Cold Spring, we now know a lot more than previously known. I am convinced that there are indeed two separate water tables in this area: a perched water table supported by a clay layer that is embedded in the eastern flank of the esker and dips to the east; and a deep water table in sand and gravel in the core of the esker. These water tables are separated—at least along the eastern edge of the proposed pit expansion—by an unsaturated zone between the bottom of the clay and where the deeper water table is intercepted by MW-2 and PB-4D. These water tables likely merge about a quarter mile north-northeast of Cold Spring.

As to the contributing recharge area to Cold Spring, we have the revised Summit recharge area delineation from Summit's revised water balance analysis of March 20, 2014 (**Attachment 2**) which gives us a general interpretation of the recharge area and surficial geology of different portions of the recharge area. In addition, I have prepared a contour map of the shallow water (perched) table that seems to be related to Cold Spring as **Attachment 3**. **Attachment 3** was prepared by entering the x and y coordinates of all of the points of known (measured) and inferred (streams with approximate LiDAR elevations) water table, converted elevations to NAVD88 datum and contoured the data using a simple linear interpolation procedure. There are two groundwater "highs" that

seem to feed the Cold Spring, assuming groundwater flowlines are more or less perpendicular to the groundwater contours on **Attachment 3**. The smaller of the two watersheds seems to extend northwest from Cold Spring and extend along the northern side of the string of CSW monitoring wells, terminating near a small high in the water table identified as elevation 136' on the figure. One anomaly along this area is the significantly lower groundwater elevation at CSW-05. The other portion of the recharge area and the portion that is probably more likely to keep the relatively constant level in the spring is the large recharge area suggested by the closed contour of elevation 136 to the south of Cold Spring, which includes a bog area. There is a suggestion that along the western edge of this closed contour there is a connection and shallow groundwater flow to the north that passes through the area of CSW-02 and CSW-03, entering gravel where the ground surface is almost 30 feet higher than the water table elevation, and passing through the Cold Spring area. There is sufficient watershed area to supply the 12 gpm withdrawal rate from Cold Spring.

Response to Dr. Brutsaert Concerns

Dr. Willem Brutsaert filed a memo dated January 2014 with the Planning Board called "Impressions of Summit's Supplemental Hydrogeologic Study, DEC 2013." Because Dr. Brutsaert is a credible professional in the matters that the Board has requested my assistance, I will attempt to address his concerns based on what I know and deduce from the information I have seen, but the Board may want to consider his comments further and request additional data from the Applicant if they feel that information is needed to assist in the decision-making process.

Bullet 1—*The supplemental data raises more questions than it answers on the distribution of the clay/silt layer*. I do not agree with this. I think we know more now, particularly within the proposed gravel expansion area. There are other questions remaining about the exact nature and distribution of the clay-silt layer beyond the Applicant's site, but those questions do not need to be answered to determine whether the mining plan is appropriate.

Bullet 2—*The topography of the land near Cold Spring suggests that the surficial soil is fine-grained and not sand and gravel*. I disagree. The stream pattern development as displayed on **Attachment 3** is suggestive of groundwater sapping within a material like sand, possibly underlain by clay-silt. A similar pattern can be observed, for example, in the upper reaches of Branch Brook in Kennebunk (**Attachment 4**) where a thick sand overlies clay and groundwater seeps out of the sand over the top of the clay.

Bullet 3—*The geochemistry of the Cold Spring water has not been examined*. I agree. There is none in the record that I could find and it would be helpful, for example, to determine whether my hypothesis that some of the water from the spring recharges from a bog to the south is valid. Again, although this would be helpful to a better understanding of the origin of the Cold Spring Water I do not think it is critical to a determination of the groundwater regime on the proposed expansion site.

Bullet 4—*Concerned why there is no water in MW3 and PB4*. My particular interpretation of PB-4S is that it is on top of the western edge of the clay-silt deposit and at this position, the well would only have water during a period following a major snowmelt or rainfall event when the downward rate of infiltration within the clay layer is less than the mass rate of the wetting front coming down from the ground surface as it reaches the clay layer. I think that a well placed at the top of the clay layer at MW3 would be likely to have water, at least much of the year, but the well was constructed in such a way that is screened largely below the clay layer, thus permitting any water flowing through the clay-silt to go down the well and dissipate as unsaturated flow into the sand and gravel beneath the clay layer. The bottom of the MW3 well should be no deeper than the approximate top of the clay layer in order to measure the state of a perched water table on top of the clay there.

Bullet 5—*The water balance study (December 2013) does not appear to include all parts of the watershed nor account for ET losses*. I agree that the first water balance study was not a good evaluation of the problem, which is why I suggested an approach used in the peer-reviewed paper that Dr. Hebson and I wrote. The revised Summit water balance study is a more comprehensive and better approach to the problem and I think that based on the available data it is a reasonable interpretation of what is currently known.

Bullet 6—*The recharge area of Cold Spring does not make sense based on Summit's December 2013 map*. This is a lengthy bullet that covers a lot of ground and offers opinion. Even the more recent March 2014 revised recharge area map that was submitted by Summit with their March 20, 2014, memo does look strange to the south of Cold Spring. But if you look at my **Attachment 3**, which is a contour map based on linear interpolation of the available shallow groundwater elevations, there does appear to be an avenue of groundwater flow from the south toward Cold Spring that makes sense hydraulically as I discuss on the bottom of page 3 and top of page 4 of this memo. Again, although it would nice to unravel all the secrets of Cold Spring, I do not think that the Applicant should be required to do that as we already know what we need to know to evaluate the proposed gravel pit expansion area.

Bullet 7—*The water table supplying Cold Spring is connected to the deeper water table to the west-northwest and excavating material from this area will cause Cold Spring to dry up*. I do not agree with this statement. Along the eastern edge of the MacQuinn property and east of the proposed expansion the data clearly support two distinct water tables, separated by many tens of feet. I think the two water tables converge about a quarter mile to the north about elevation 80' to 90' where the brook emanating from the Cold Spring area flows into the eastern panhandle of the MacQuinn property. The water tables would also converge east of this brook where the gravel thins and pinches out. We do not have enough information to know what happens with the deep water table south of Cold Spring. But as long as the applicant does not excavate into and drain the deep water table, regardless of how that interacts in detail with the perched water table there should not be an effect on Cold Spring.

Bullet 8—*A synoptic round of groundwater level measurements is needed and the data needs to be independently peer-reviewed.* This is an independent review of the data. A synoptic round of monitoring well measurements was taken on March 21, 2014. It was probably not equivalent to seasonal high in either the perched water table or deep water table. For the perched water table, the long string of water level measurements in the CSW monitoring wells since 2009 show the March 17, 2014, measurements were below the spring high water elevations measured in past years. This is undoubtedly due to the long cold snowy winter and the fact that the spring thaw had not really set in yet at the time of the measurements. For the deep water table, as I pointed out in my memo of March 15, 2014, the very large unsaturated zone from the gravel pit ground surface to the deep unsaturated zone will mean that large recharge events at the surface will take months to be expressed in the deep wells. In fact the Nov. 12, 2014, groundwater elevation in PB1-2013 was 33.31' on 3/21/14 versus 37.18' NGVD88 on 11/12/13, or almost 4 feet lower. Since both the perched and deep water tables would not be expected to vary by more than a few feet in this area, if the Board adopts my proposed permit condition relating to measuring water tables, there should be better data later to make final determinations on how deep the pit can be excavated.

Summary

As with anything dealing with the underground, we do not know everything possible to know. But I do believe that we do know enough now to understand reasonably well the extent of the clay that slopes up under the sand from Cold Spring into the proposed pit expansion area. The Applicant has defined that approximate limit and if the Board adopts the proposed permit condition I have suggested in moving the pit limits if the clay is found to extend farther west, then the spring should be protected.

There are two separate water tables and we have a better idea where the deep water table lies. The exact distribution of the seasonally high water table in the bottom of the proposed exploration will be better determined once a large amount of material is removed from the pit and the water table begins to respond more directly to precipitation and snowmelt events. I have suggested a permit condition to apply that will assist in this matter.

The Applicant has modified the expansion plan to move the eastern edge of the pit west to accommodate the clay layer and to adjust the bottom of the pit elevation to what we now know about the deep water table. From this point forward the Board needs to evaluate all the new information provided by the Applicant and by me and determine if the plan as revised meets they Planning Board criteria.

STATE OF MAINE
ROBERT GRAHAM GERBER
110
CERTIFIED GEOLOGIST

Robert G. Gerber, Certified Geologist #110
4 Attachments

Attachment 1

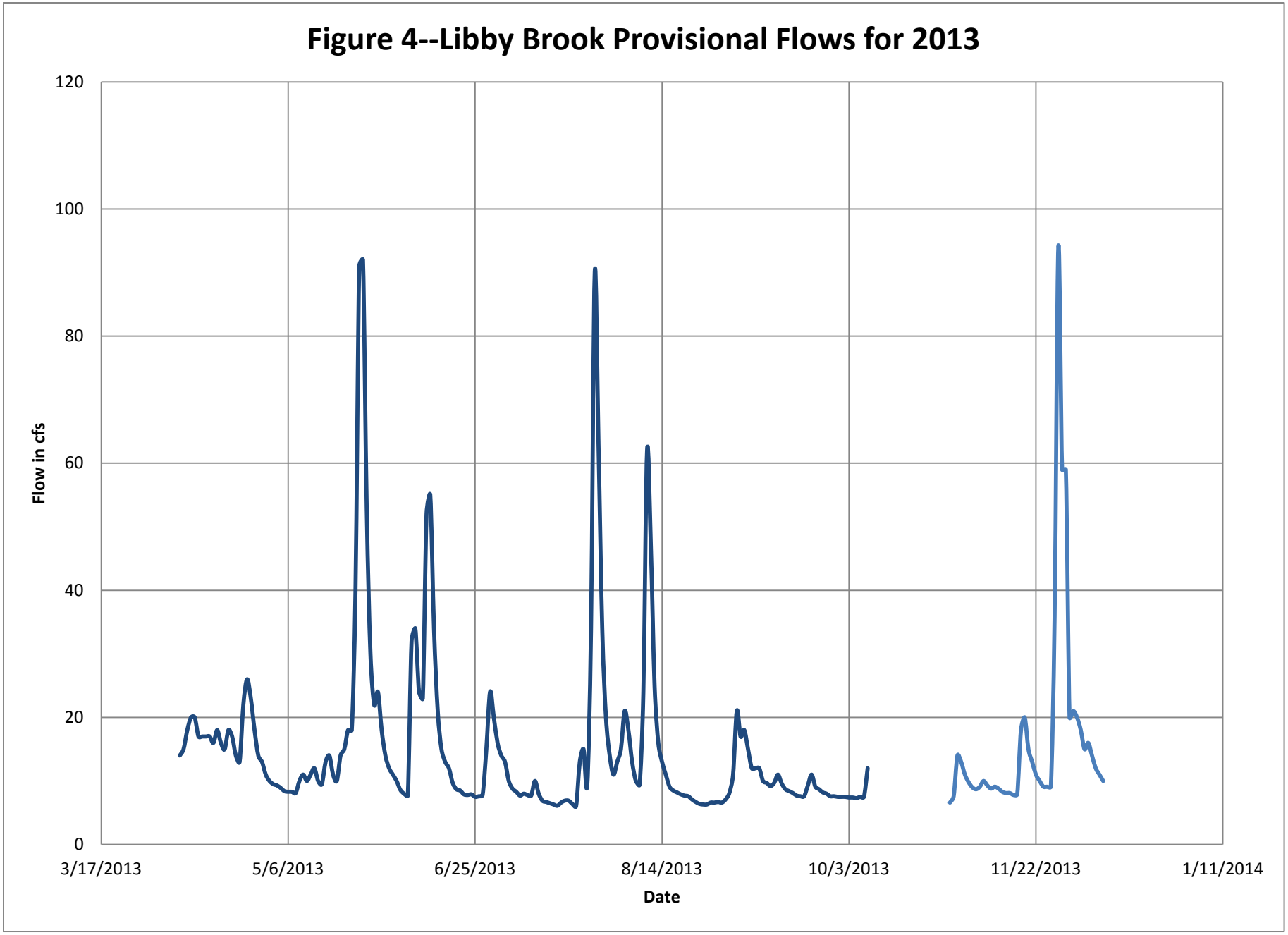
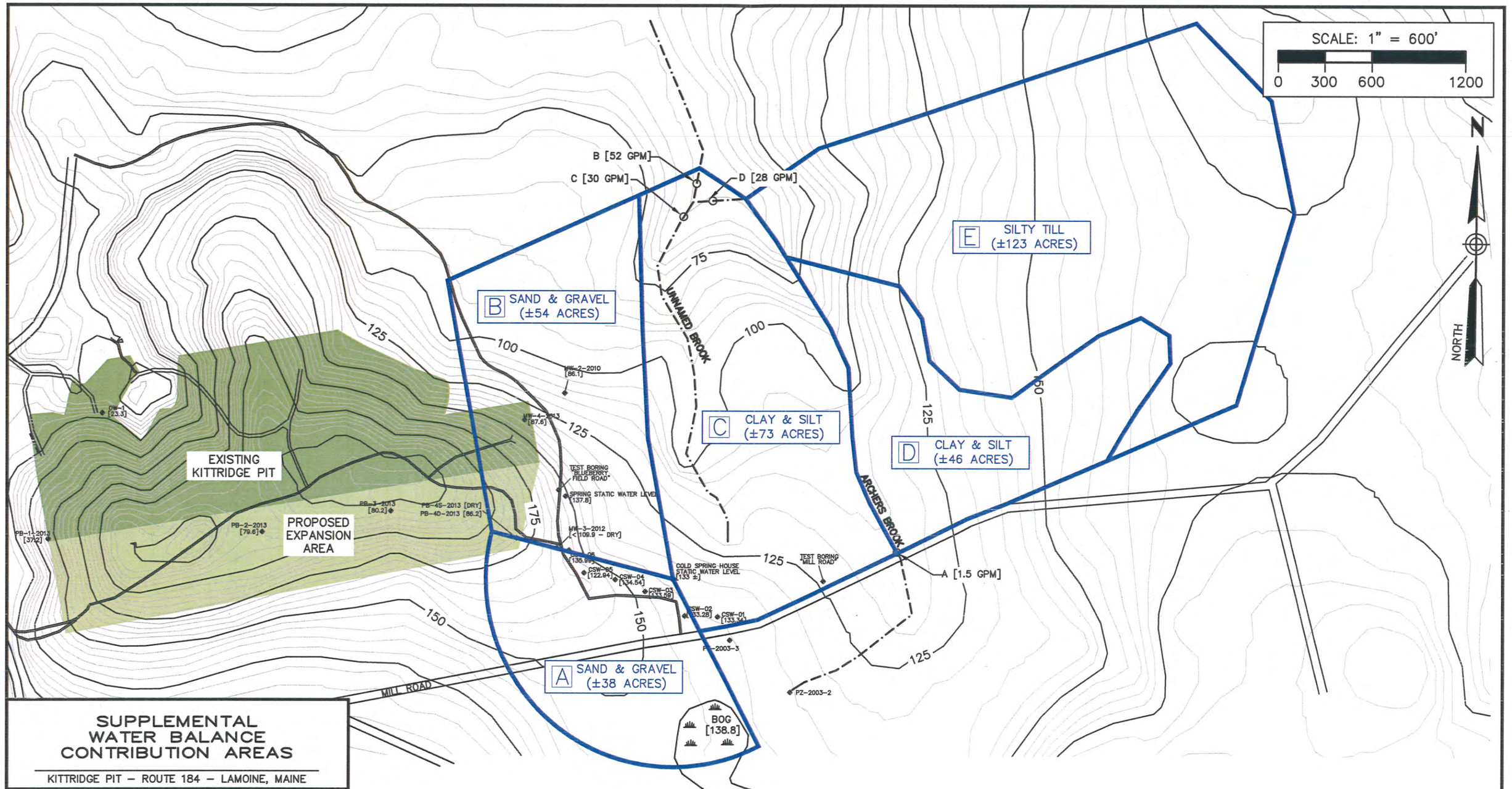


Figure 4--Libby Brook Provisional Flows for 2013
120
100
80
60
40
20
0
Flow in cfs
3/17/2013
5/6/2013
6/25/2013
8/14/2013
10/3/2013
11/22/2013
1/11/2014
Date

Attachment 2



SUPPLEMENTAL WATER BALANCE CONTRIBUTION AREAS

KITTRIDGE PIT – ROUTE 184 – LAMOINE, MAINE

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LEWISTON, ME 04240

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www.summitenv.com

Summit Environmental Consultants
A CES, Inc. Company

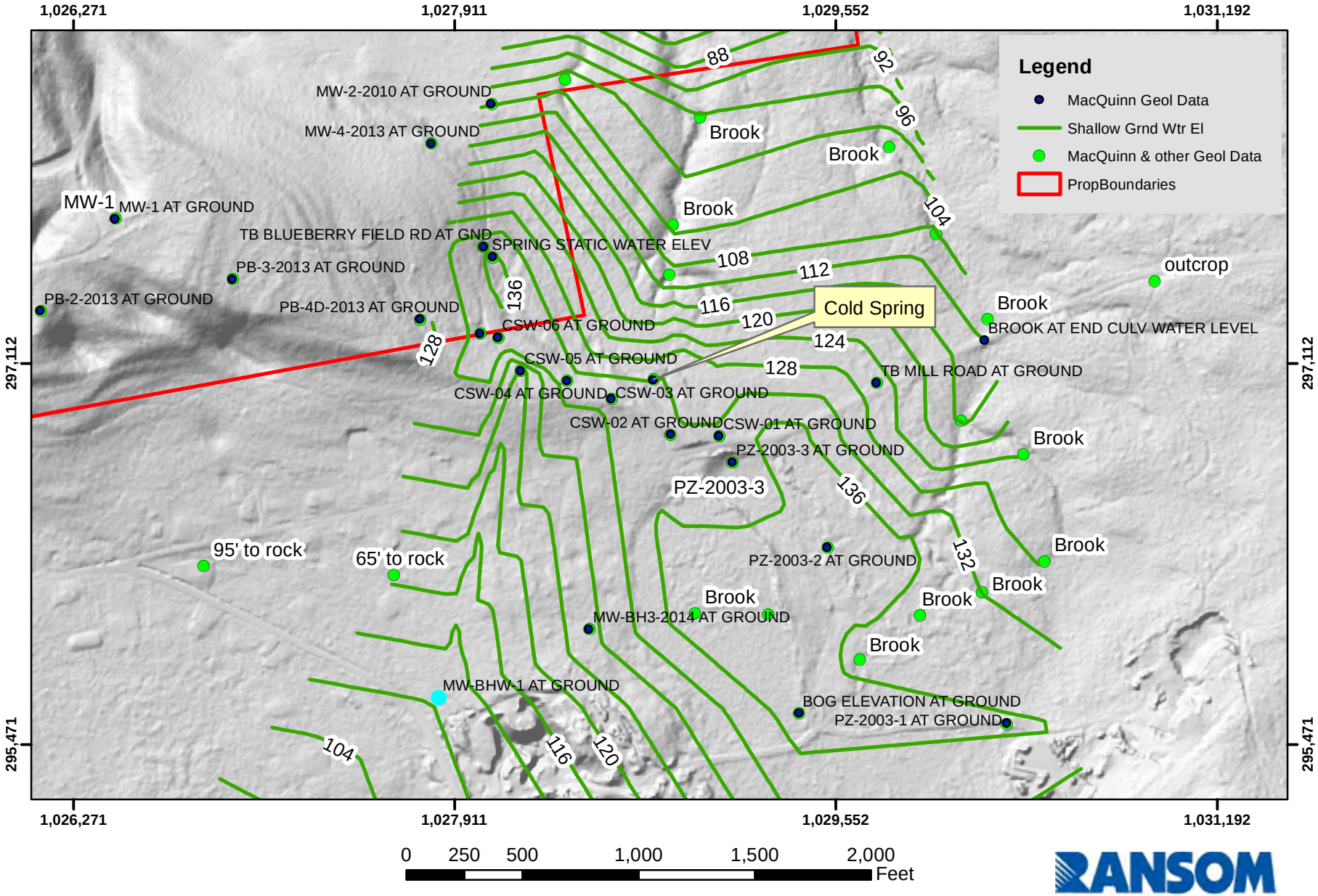
DATE: MAR. 2014	DRAWN BY: SBM	SCALE: AS NOTED
JOB NO.: 11-3240.5	CHECKED BY: MAD	CADD: N/A

NOTES

1) BASE PLAN AND TOPOGRAPHIC COUTOURS IN NGVD29 DATUM PROVIDE BY HERRICK & SALBURY, INC. ELEVATIONS BASED ON UNITED STATED GEOLOGICAL SURVEY (USGS) DATABASE. GENERAL STREAM LOCATIONS APPROXIMATED BASED ON USGS TOPOGRAPHIC MAP AND SURVEYED STREAM LOCATIONS NEAR STREAM FLOW MEASURING POINTS A, B, C & D.
2) CONTRIBUTION AREAS BASED ON SURFICIAL MATERIALS INFORMATION FROM ON-SITE BORINGS AND MAINE GEOLOGICAL SURVEY SURFICIAL GEOLOGY MAP.

A	GROUNDWATER CONTRIBUTION AREAS WITH AREA AND SURFICIAL MATERIAL INDICATED
O A [1.5 GPM]	BROOK FLOW MEASURING POINT & FLOW MEASURED ON AUGUST 26, 2013
—125—	TOPOGRAPHIC COUNTOUR (FEET)

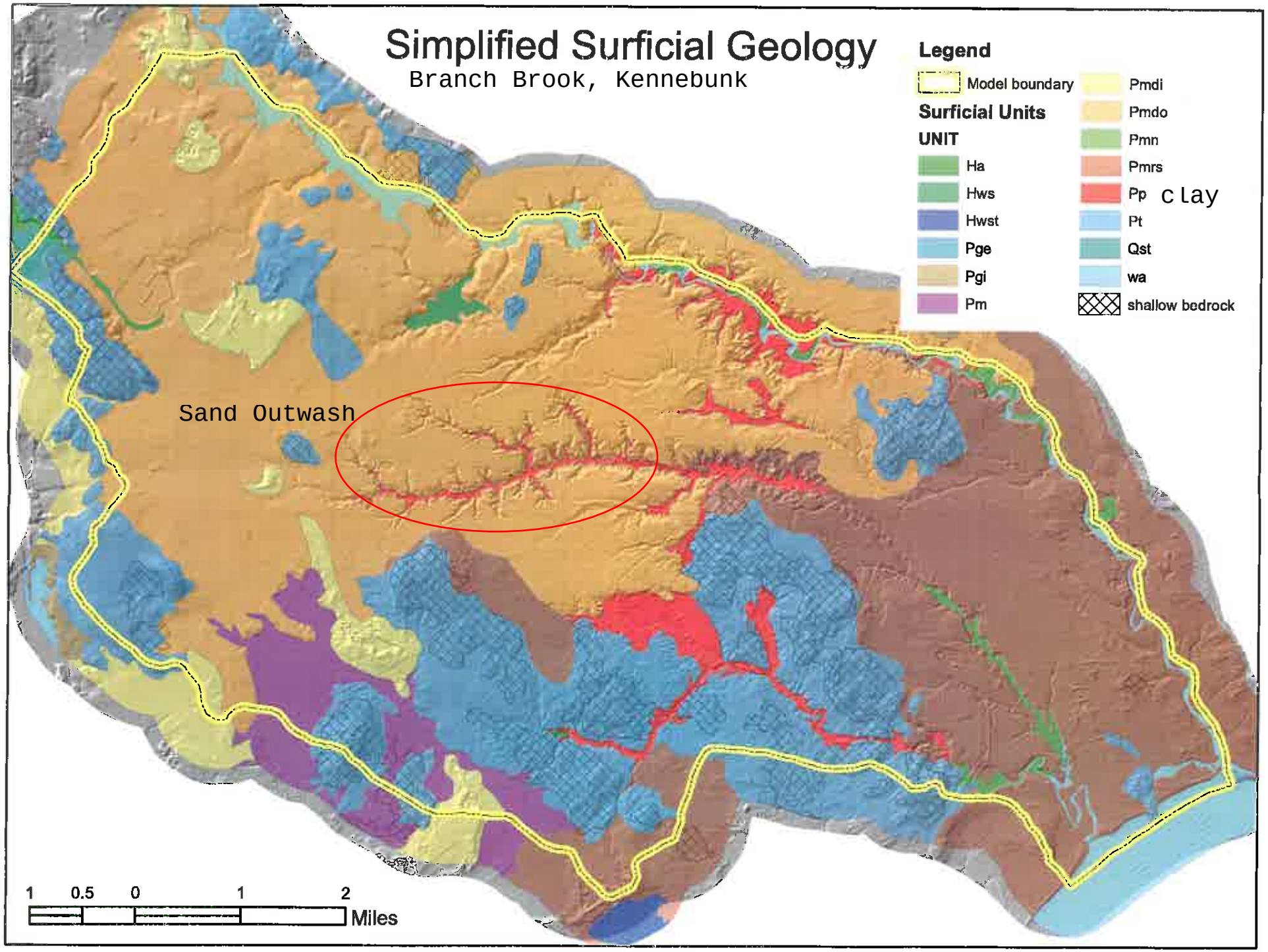
Attachment 3



Elevation Contours of Shallow Ground Water Table (NAVD88, ft.)
Town of Lamoine, MacQuinn Gravel Pit Expansion Review
Digital Elevation Model Developed from 2-m LiDAR
Grid is UTM, NAD83, 19N, meters
RGG 3-26-14 131.06066

RANSOM Consulting, Inc.

Attachment 4


Simplified Surficial Geology
Branch Brook, Kennebunk
Legend
Model boundary
Surficial Units
UNIT
Ha
Hws
Hwst
Pge
Pgi
Pm
Pmdi
Pmdo
Pmn
Pmrs
Pp
clay
Pt
Qst
wa
shallow bedrock
Sand Outwash
1
0.5
0
1
2
Miles