Results and Recommendations from a Water Well Pilot Study: Rehoboth, MA

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Rehoboth Water Well Geo-Mapping Committee

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Summary

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Applications

Well completion reports include the following information: Drilling method, overburden and bedrock lithology, well depth, depth to bedrock, surface seal type, fracture enhancement (yes or no), casing details, location of water-bearing zones, and details of the permanent pump. Following the drilling of a well, a well test is performed. The information that is recorded on the well completion report regarding the well test is as follows: date, method, yield, time pumped, pumping level, time to recover, recovery depth, the static water level, and the flowing rate. Formerly, the pump rate was also included while yield was not. Information on the well completion reports can be compiled and used for many purposes. In order to focus our efforts, we chose the entirety of Tremont St. to use as a pilot study area. We compiled usable information from 115 wells along the street (Figure 1).

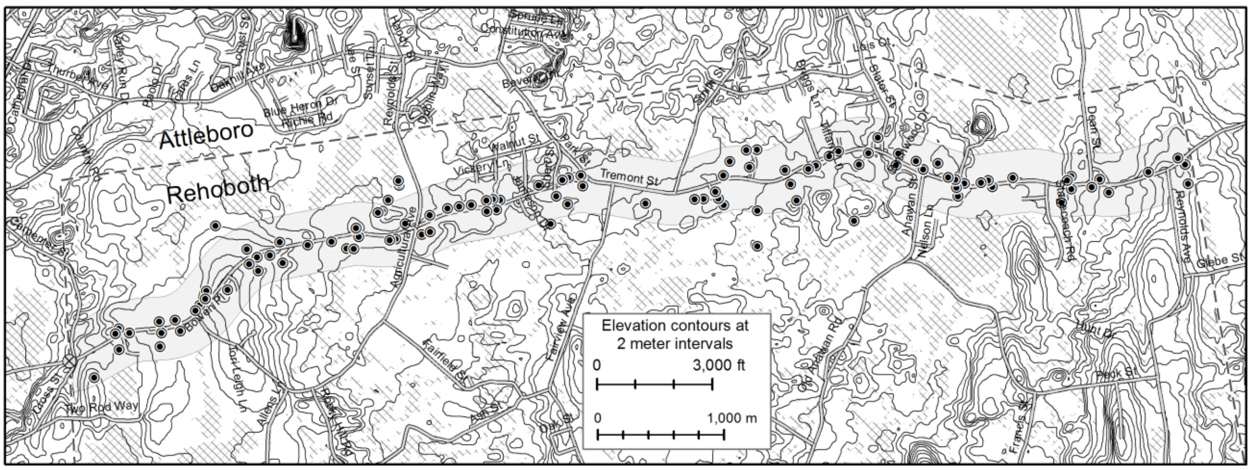

Figure 1. Location of water wells along Tremont Street for which well completion reports are available. Town boundaries are dashed. Hatched areas are wooded-and-open wetlands, significant recharge areas.

From this, we were able to construct a cross section of the terrain and water table along Tremont St. (Figure 2) and do a variety of analyses based on the well test data.

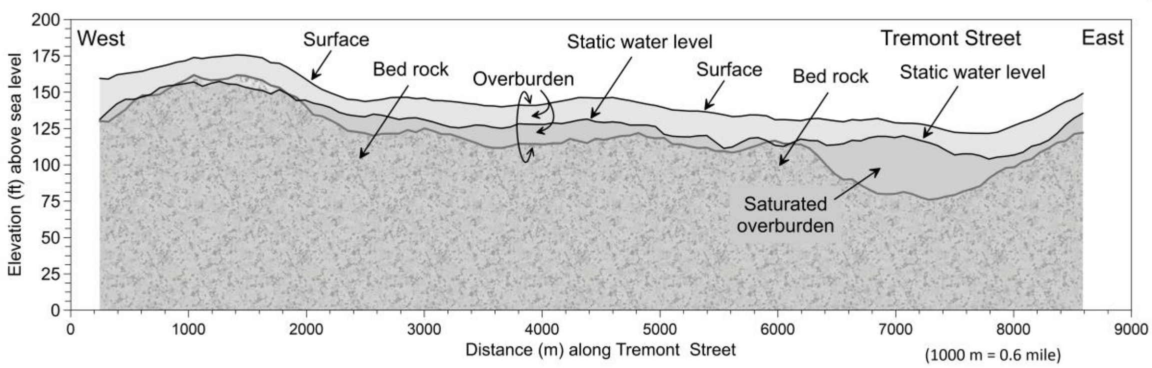

Figure 2. Working version of the elevation of the static water level and bedrock along the Tremont St. profile. Sea level is at the base of the figure at an elevation of 0 feet.

For town-wide analysis, the depth to bedrock and static water levels of each well can be used to generate a map showing the thickness of the saturated overburden across Rehoboth (Figure 3).

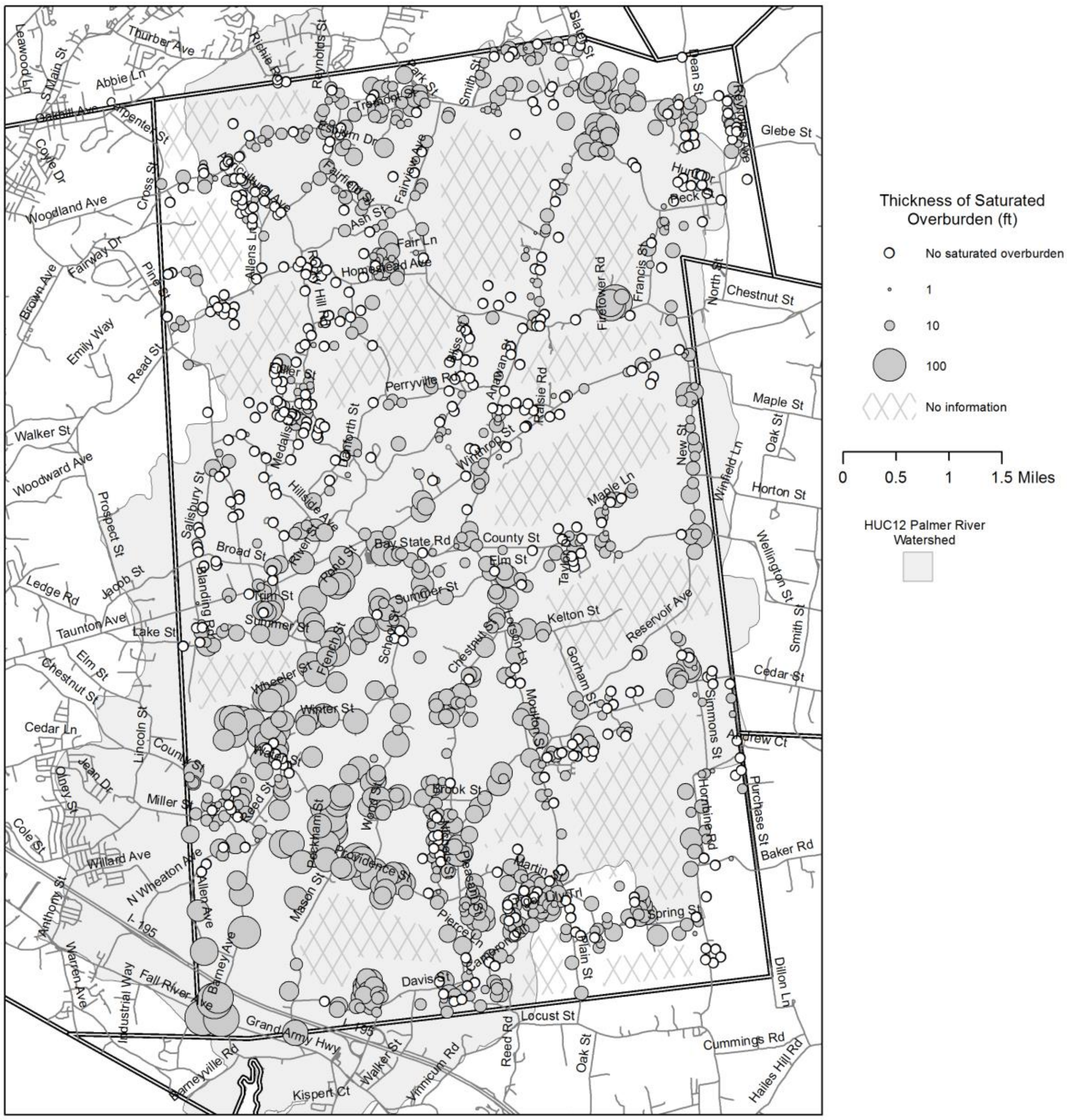

Figure 3. Thickness of saturated overburden (TSO).

In the process of compiling data, we also encountered many areas of weakness in the well completion reports that made analysis difficult or impossible.

Pitfalls

One of the common problems in well completion reports concerns the physical location of the well. Many well completion reports are lacking a street number or entire street address. Some of these are identified with a lot number or utility pole number, which, in conjunction with other resources, does make it possible to locate the physical address. Other well completion reports do have complete street addresses, but either the street name, house number, or street abbreviations are incorrect. The current electronic well completion report (2010-present) requires the driller to record the GPS coordinates of the wellhead, but this isn't as helpful as it could be. Many of the recorded coordinates are so incorrect that the wells are located on different continents. Another problem concerns the inability to validate reported well yields because of the manner in which the driller records the drawdown and recovery times during the well test. When taken at face value, many of the times suggest that the drawdown yield is a negative number and the recovery took 24 hours. These instances make calculating drawdown and recovery yields impossible, which, in turn, makes validating the reported yield impossible. In the past, there was an entry space for drillers to record the pump rate but no explicit request for the yield to be recorded. Currently, there is a field for yield but none for pump rate, which makes it impossible to calculate the drawdown yield with the information at hand.

Table. Recommended items to be included and verified in well driller's report.

Items currently expected in well completion reports:	***Required parameters for well test:***
1. GPS location 2. Owner w/ address 3. Driller's name or company & address 4. Date(s) of drilling 5. Depth to static water table 6. Depth to bedrock (thickness of overburden (soil)) 7. Total depth of well 8. Length of well casing 9. Casing length in bedrock 10. Details on the well test procedure (pump discharge, air lift, air blow . . .) 11. Well yield (gpm) 12. Fracture enhancement (yes or no)	1. Static water level 2. Pump rate 3. Pump time 4. Maximum drawdown depth 5. Recovery time 6. Depth to the recovered water level

Recommendations

Many of the problems could be avoided if the information on the well completion report was to be verified upon submission (see Table above). In many cases, this would require nothing more than making sure that none of the fields were left blank by the driller. Standardizing the methods of recording the information would further reduce confusion. For example, if drillers had guidelines to follow when it comes to measuring and recording drawdown and recovery times, there would be no question about how a driller calculated the yield that is posted on the well completion report. In some cases, simply enforcing state guidelines already in place would make for more reliable well tests. The state recommends a drawdown period of at least 4 hours, but a large percentage of drillers (~31%) fail to do that. It is also critical that the pump time be recorded. When it comes to measuring the recovery time, there is no value in a 24-hour recovery period other than making sure that the well meets the state requirement of recovering to 85% of the original water level in 24 hours. In order to gather usable recovery data, the driller needs to record recovery times and levels prior to reaching a full recovery. The current well completion reports indicate that measurements should be referenced from the ground surface for both drawdown and recovery depths, and times should be entered in the HH:MM format, both of which should be verified upon submission. Lastly, it is of vital importance that the GPS coordinates are correct. Both the GPS location and the street address should be crosschecked before the building permit is issued. Without taking these additional steps, the well data will continue to be of limited use.

Main Report

The following is the final report of the Rehoboth Water Well Geo-Mapping Committee, presented in four parts:

Part 1. Introduction

Part 2. Example applications of local well completion (WC) reports

Part 3. Assessing well yield from WC reports

Part 4. Assessing the general quality of well completion (WC) reports

Respectfully:

Katie E. Eyer, Co-Chairman

Jack (John F) Hermance; Co-Chairman

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Rehoboth Water Well Geo-Mapping Committee

Part 1. Introduction

Scope

Information on the quantity, quality, and distribution of water beneath the Earth's surface – groundwater – is of essential importance to the 13,000 residents of the Town of Rehoboth, 500,000 people in the Commonwealth of Massachusetts, and the more than 13 million households, throughout the nation, that rely on water wells for drinking water. This report addresses the type and status of information that is available for our community's water wells.

Common terms and concepts

Groundwater is water beneath the earth's surface. ***Bedrock*** refers to the ***consolidated*** geo-material underlying the surface of the earth everywhere. The vernacular of New England uses the terms "***bedrock***" and "***ledge***" interchangeably. An ***aquifer*** is an underground water-bearing zone of permeable material. A ***bedrock aquifer*** is one in which connected pores, joints and fractures in otherwise impermeable material provide space for the storage and migration of groundwater. An ***unconsolidated aquifer*** is one composed of sand, gravel and/or clay. The ***water table*** is the interface beneath which the subsurface geologic material is saturated, or filled to maximum capacity, with groundwater. The term ***water table*** is synonymous with ***groundwater*** table. The ***static water level*** is basically the depth beneath the surface of the local water table under undisturbed conditions.

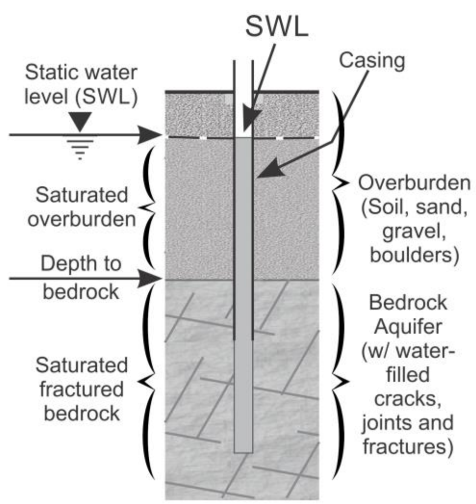


Figure 1.1. Hydrogeological features typically identified by a groundwater well, and recorded in a driller's well completion report.

In Rehoboth, each new producing water well is expected to draw water from a bedrock aquifer. Groundwater in the aquifer is recharged from precipitation – rain and snow – falling within its ***recharge zone***, also known as a ***catchment***, ***drainage basin*** or ***watershed***. These four terms tend to be used interchangeably in hydrology and are features that may be local or regional in scale. It is commonly accepted by hydrologists that ***surface waters*** from storm runoff, nearby streams and wetlands readily experience a two-way interchange with ***groundwater***.

Assessing the subsurface from well driller reports
While federal and state agencies attempt to keep current with the public demand on these water supplies, long term sustainability needs to be addressed at the local level, typically through local boards of health in collaboration with a host of local stakeholders ranging from planning boards and conservation commissions to individual homeowners and residents.
Critical information can be provided by well drillers through their ***well-completion*** (***WC***) reports that are expected to contain information on the design of the well and its physical characteristics, such as the total depth of the completed well, the depth of the static water level (or water table), and thickness of overburden or depth to bedrock (Figure 1.1). In addition, the figure shows a well casing that typically penetrates into the bedrock 10 – 20 feet, intended to seal deeper potable water from possible shallow contamination sources.

Finally, the WC report should contain information on the conduct and results of a well test usually performed by the driller to determine the well yield, or the rate at which a producing well can supply water to the user. Most homeowners consider the well yield along with water quality to be the two most important attributes of their well.

Thus, if reliable WC reports were routinely available for planning, as well as for mitigating particular threats to groundwater supplies, the local community would be in a much stronger position to understand the long-term management and sustainability of its groundwater resources.

Paradigms for the behavior of groundwater in the earth's subsurface
The amount of available water in an aquifer is determined by the porosity of the material and the balance between water inputs and outputs to the system, such as rainfall, stream flow, vertical and lateral flow of groundwater, and evaporation back to the atmosphere. In the absence of dynamic inputs or outputs, the distribution of groundwater is illustrated by the basic paradigm in Figure 1.2.

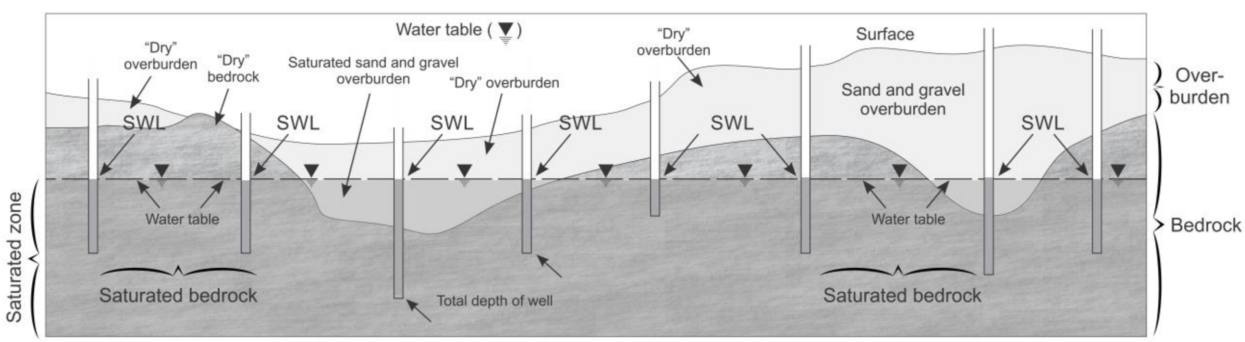


Figure 1.2. A vertical cross-section illustrating the type of hydrogeology considered in this report. Unconsolidated material (sand, clay and gravel, including boulders) is generally at the surface (light gray), underlain by bedrock (darker gray). A zone saturated with groundwater transects the area, with a water table having a uniform elevation. In this case the static water level in water wells is at a uniform elevation between wells, but may be at a different depth beneath the surface and the respective wellhead. Water table is symbolized by the vertical triangle.

Water permeates subsurface soils and fractured bedrock, forming a more-or-less horizontally uniform water table – a ***static water level*** (SWL). The figure emphasizes that the static water level of groundwater is the same in fractured bedrock as it is in the adjacent overburden of unconsolidated soil. Drillers' WC reports provide essential information characterizing the local water table, and the partitioning of available water between usually more permeable overburden and less permeable bedrock.

Typically, however, local inputs and outputs of water are responsible for a quasi-dynamic departure of the local water table from being strictly horizontal. The result is a persistent spatial modulation of the elevation of the water table as shown in Figure 1.3. In other words, the strictly horizontal water table at constant elevation in Figure 1.2 is the exception to the more common situation in Figure 1.3.

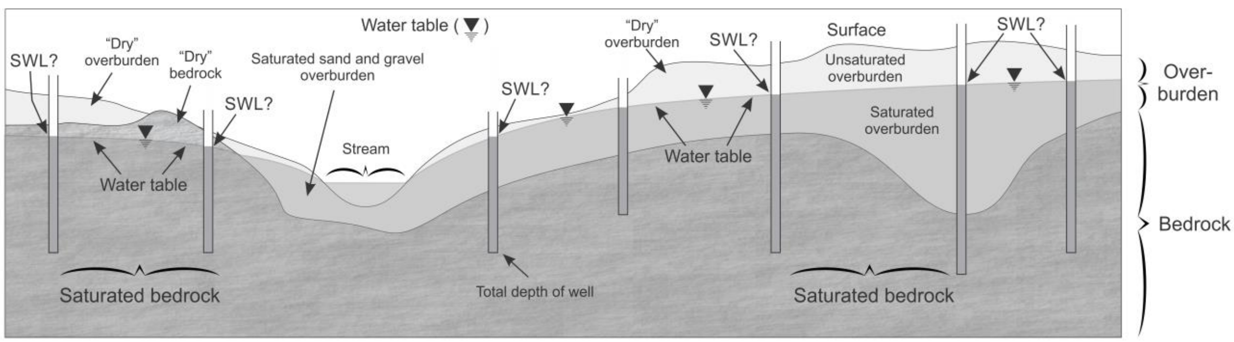


Figure 1.3. Example showing the vertical modulation of the elevation of the water table due to variable inputs and outputs of water to and from the system. The label for the static water level (SWL) in each well is shown with a question mark since the water level in even undisturbed wells is seldom truly "static". Assigning a value for SWL needs to be exercised with some caution.

Due to the increased horizontal travel time of infiltrated rainwater from areas some distance from an outflow feature, such as a stream, the static water level tends to "*mound*" under adjacent highlands. Even though the elevation of the water table in the figure changes from one well to another, providing the water inputs and outputs are quasi-static, the shape of the water table may be quasi-static, so the concept of a static water level might be appropriate for a non-discharging well. Real world fluctuations in seasonal and local precipitation patterns may undermine this assumption.

The elevation of the static water level is often a good approximation of the local hydraulic head, and since the flow of groundwater is in the direction of the negative gradient of hydraulic head – which is often in the direction of the downslope of the water table – Figure 1.3 shows a pattern of groundwater flow to the left on the right side of the figure, and of flow to the right on the left side of the figure. Thus, an effective way to "map" the elevation of the water table in cases like the figure is to reconstruct the shape of the static water level using available WC reports. This needs to be done prudently, however, and verified if possible. Moreover, contrary to a conventional adage, the local flow direction of groundwater does not invariably track the downward slope of the watertable. Anawan Pond, for example, receives significant recharge from springs along its bottom.

Objective of the current study and report
The proposed objectives and expected outcomes of this project are described by its mission statement as approved by the Rehoboth Board of Selectmen:

> ***Mission statement:*** Because groundwater wells provide drinking water for all residents of the Town of Rehoboth, it is imperative to understand the nature and distribution of this essential resource. In particular, the town boards and commissions, along with its residents, need to develop a deeper understanding of subsurface conditions related to water supply. For this purpose, the Board of Selectmen has approved the formation of the Rehoboth Water Well Geo-Mapping Committee to perform a pilot study to explore and summarize the information currently available. At present, the best source of information is well drillers' reports, which summarize key information on depth of the water table, thickness of overburden, total depth drilled and the expected productivity (or flow rate) of wells. The initial focus will be on merging well drillers' notes from three sources: 1) the MassDEP, 2) the Rehoboth Board of Health, among other town offices, and 3) the 2016-2017 collaborative study between the Town and Roger Williams University. The immediate objective is to properly locate water wells by street address and to construct selected profiles and 2-D maps of the water table, depth to bedrock and related features. Information will be compiled from all sources, with past drillers' reports being assessed for scope and reliability. The product will be a report that summarizes present knowledge drawn from these drillers' notes, assesses the time and difficulties related to generating and assimilating these data, and makes recommendations on future information needed from water wells that are essential for plans to sustain this valuable resource. (Dated: 8 April 2018.)

Sources of data used for this study
While groundwater studies in Rehoboth have relied on water well data for decades (c.f., Willey, Williams, and Tasker, 1983; Bohidar, Sullivan and Hermance, 2001), the current effort may be traced back to 2016, when MassDEP provided a summary spreadsheet of 2,039 water well driller's records to the Town of Rehoboth's Water Commission (MassDEP, 2016). This database is a set of off-line spreadsheets compiled by the MassDEP, ostensibly containing all of the information from the well completion reports that were on file with the state at that time. The MassDEP (2016) data provided the basis for the 2016-2017 project of the Rehoboth Water Commission and Board of Selectman with undergraduate students from the Roger Williams University (RWU) Community Partnerships Center (CPC), under the supervision of Professor Mark Brickley of RWU. Complementary well data were provided for the current study through Bill Napolitano of SRPEDD who sent us a copy of the now out-of-print Massachusetts Hydrologic-Data Report No. 25. (Also published by the USGS as Willey, Williams, and Tasker, 1983.) A final resource for crosschecking the BOH and MassDEP data was approximately 750 photocopies of selected well completion reports for Rehoboth, for the period June 30, 1972 to December 29, 1995. The copied reports were on file with the state[1] in 1995 and supplied to this

[1] See "Responsible state agency" in the ***Glossary***.

study through Brown University from earlier pilot studies.

Historically -- since pre-2018 versions of the MassDEP WC report spreadsheet database are currently in use -- one should note that the on-line SearchWell (2018) database (recently amended to the current EEA (2018) database), appears to have been populated with selections from the same data found in the MassDEP (2016) spreadsheet, although MassDEP (2016) contains additional parameters, of which the most important may be well yield. At some point in early 2018, the SearchWell database became the Energy and Environmental Affairs (EEA) Data Portal (EEA, 2018). Whereas, in April 2018, the SearchWell database was lacking in certain information available on the original WC reports, some of the missing items had been entered into the EEA (2018) database by July 2018. However, based on the website's description of the MassDEP EEA (2018) database, the information in the summary reports generated by its search engine is to be taken "as-is", implying the MassDEP's sense of *caveat utilitor*; i.e. "let the user beware," a caution that we enjoin all those accessing these data to adopt.

Part 2. Example applications of local WC reports

Scope

Data typically provided on driller WC reports, such as depth of the static water level, depth to bedrock, total well depth, and other metrics are a rich source of information for characterizing subsurface features related to groundwater. Part 2 of this report illustrates applications of data currently available from local WC reports for the Town of Rehoboth.

Example application*: *Delineating overburden aquifers

An important attribute of the hydrogeological landscape of the town is the presence and lateral distribution of water-saturated overburden[1] at the surface.

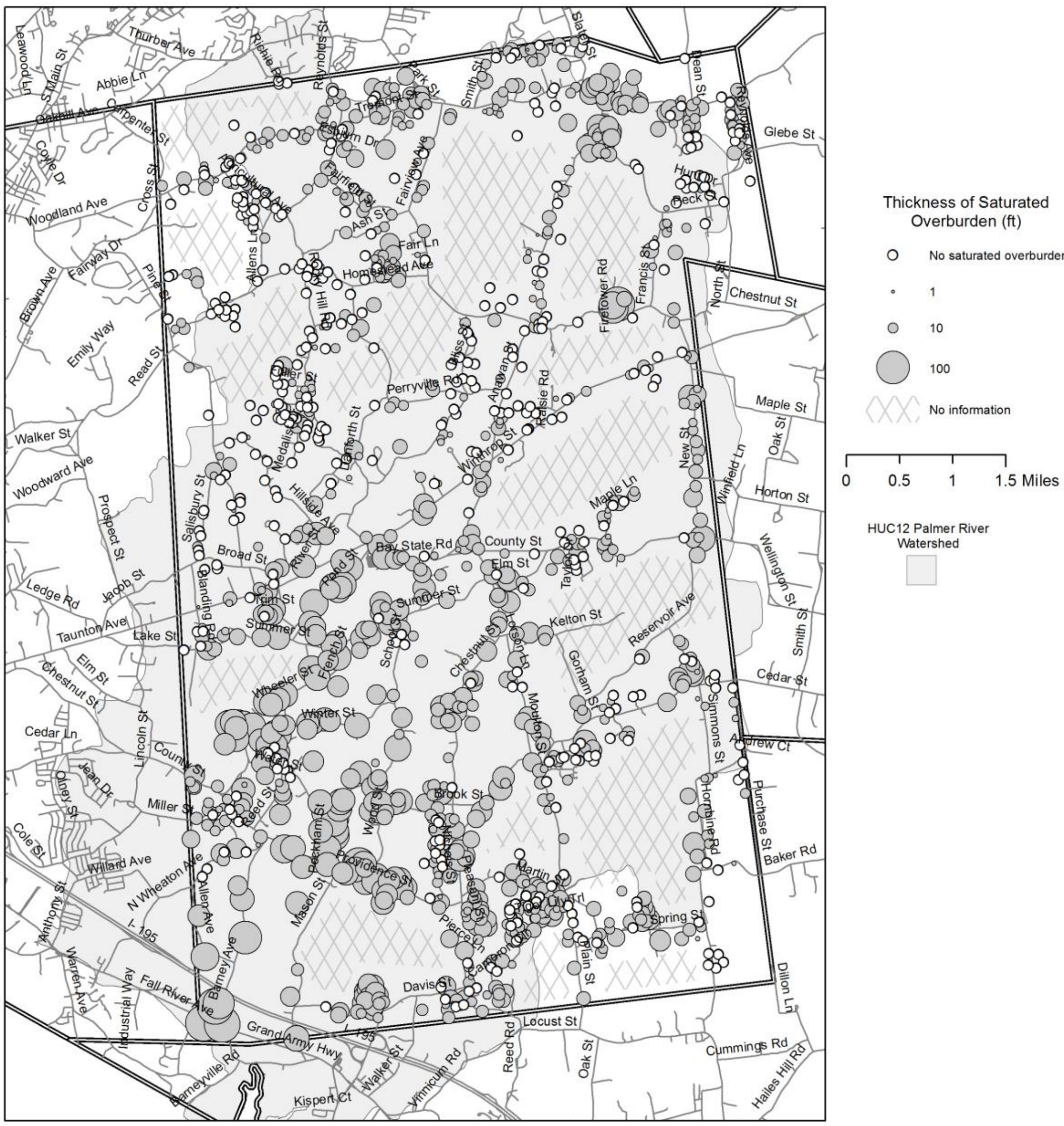


Figure 2.1. Thickness of saturated overburden (TSO).

[1] Note: See the *Glossary* for the definition of "*overburden*".

The hydraulic conductivity of unconsolidated sand and gravels is usually an order of magnitude or greater than typically fractured bedrock, thus providing a principal pathway for the subsurface flow of groundwater throughout the watershed. The ***thickness of saturated overburden*** (TSO) is one of the most robust parameters to be determined from drillers' WC reports, and Figure 2.1 is a map showing current information on the variability of TSO throughout the township. Only two routinely reported parameters, depth to bedrock (d_{BR}) and depth of the static water level (d_{SWL}), are required to determine TSO. Mathematically, $\mathrm{TSO} = \left(d_{BR} - d_{SWL}\right)$ as long as the static water level is shallower than the depth to bedrock ($d_{SWL} < d_{BR}$). However, if the SWL is equal to the depth of bedrock, or deeper *than* bedrock ($d_{SWL} \geq d_{BR}$), we set TSO = 0; that is to say, there is no water-saturated overburden. The diameter of grey symbols is scaled for each well to reflect the local TSO > 0 ft. Small white symbols denote sites where there is no water-saturated overburden – a case where the driller reports bedrock at the surface, or a SWL deeper than the depth to bedrock. Areas of the map are hatched to emphasize the absence of information, underscoring that data on subsurface conditions for more than 20% of the township simply do not exist. These gaps might be filled in the future by drilling, or by a variety of surface and subsurface geophysical methods, such as seismics, resistivity, ground penetrating radar and/or gravity, among others.

What is most striking in Figure 2.1 is the remarkable difference in TSO north of Route 44 (Winthrop St.) compared to south of Route 44, particularly the total absence of saturated overburden (TSO = 0) in many places. Substantial thicknesses of saturated overburden are quite common in the southwest sector of the town, whereas such deposits are lacking or of diminished thickness in most areas of the northern sector of the town. The major exception to this, north of Route 44, is in area in the northeast sector of the township in the vicinity of the intersection of Anawan Street and Tremont Street, where significant thicknesses of saturated overburden are present at one of the headwaters of the East Branch of the Palmer River.

The sprinkling of locations across the map showing "no saturated overburden" has important applications for the subsurface runoff of groundwater. Each of these symbols may be thought of as a bedrock outcrop – although they may not be actual outcrops at the surface, they are outcrops through the local water table, hence tend to block the lateral flow of groundwater in the more highly conductive overburden. Such blockages are strikingly absent in the southwest sector of the town, largely in the area between Barney Avenue and Mason Street, and east along Providence Street, as far as Oak Swamp Brook, extending north along the east side of the main Palmer River. With a little imagination, one can suppose a continuous channel of saturated overburden east of? the Rocky Hill highland, roughly in concordance with the West Branch of the Palmer River, all the way to Tremont Street and the northern edge of the Palmer River watershed. The north-south extent of a contiguous system of saturated overburden is not as clear for the East Branch of the Palmer River. Although data are limited, based on experience elsewhere in the township, and lacking evidence to the contrary, one might hypothesize a zone of saturated overburden in the eastern sector, having variable thickness, extending from north to south along the chain of major wetlands.

To do more than speculate with these kind of data, one would need a great deal of faith in current WC reports, with the acquisition of high quality drilling data in the future. In the following sections, we look more closely at what some of these data might tell us.

Tremont Street Profile. Figure 2.2 shows the location of private and public water wells in a swath along Tremont Street, which spans the west-to-east width of North Rehoboth.

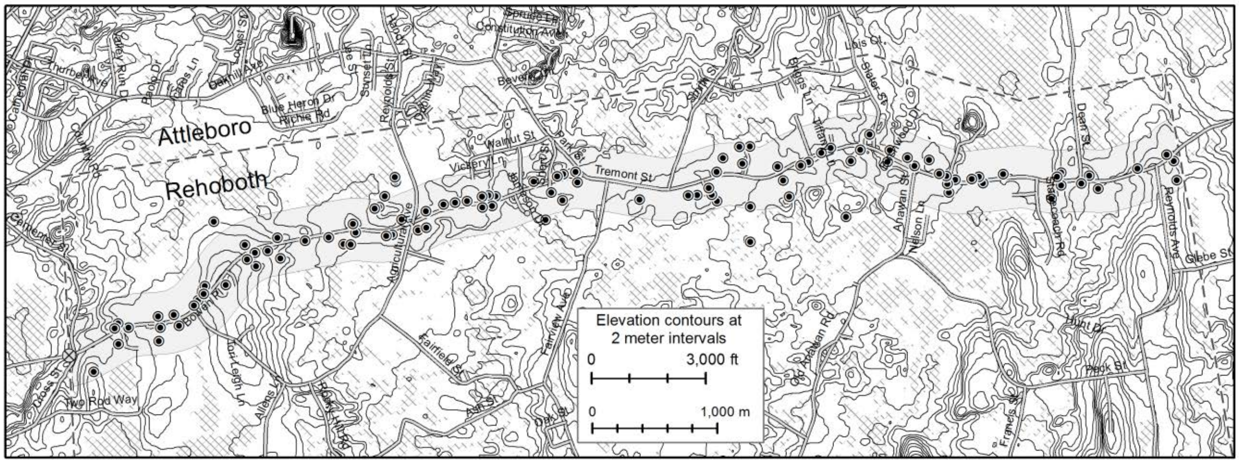


Figure 2.2. Location of water wells along Tremont Street for which WC reports are available. Town boundaries are dashed. Hatched areas are wooded-and-open wetlands, significant recharge areas.

Information from well completion reports from Tremont St. should provide a perspective of the principal hydrogeologic elements – static water level, depth of bedrock, and maximum depth of well – for the northern part of town.

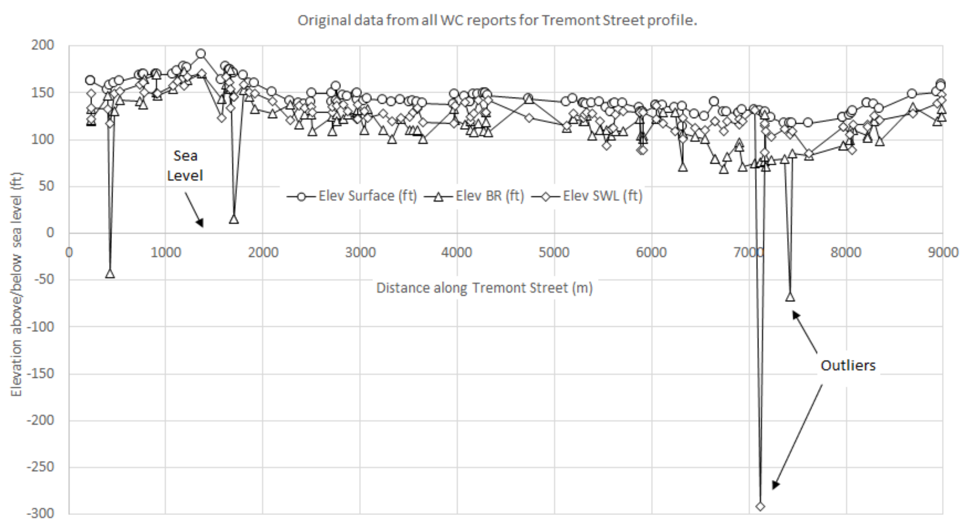


Figure 2.3. Unscreened profiles along Tremont Street of the surface elevation, depth to the static water level (SWL), and depth to bedrock (BR) from available WC reports. The significant dropouts in bedrock elevation and static water level are typical glitches[2] in WC report entries that need to be identified and corrected by hand.

Figure 2.3 shows unscreened profiles of raw WC data for the wells shown in Figure 2.2. The figure shows profiles of the elevation above sea level of the surface, the static water level (SWL), and bedrock (BR). For example, in spite of obvious glitches[2] in the data, the overburden-bedrock interface seems to be systematically deeper for wells at a distance between 6,500 m and 8,000 m along the eastern section of the profile. This and other features might be extracted from the raw

[2] The term "glitch" in this report denotes any number of types of faults in our database, such as data dropouts, errors in data entry or transcribing, missing values, etc.

data by one or more types of screening and/or filtering, often requiring the hands-on inspection of WC reports on a well-by-well basis. A preliminary result from such a screening is shown in Figure 2.4.

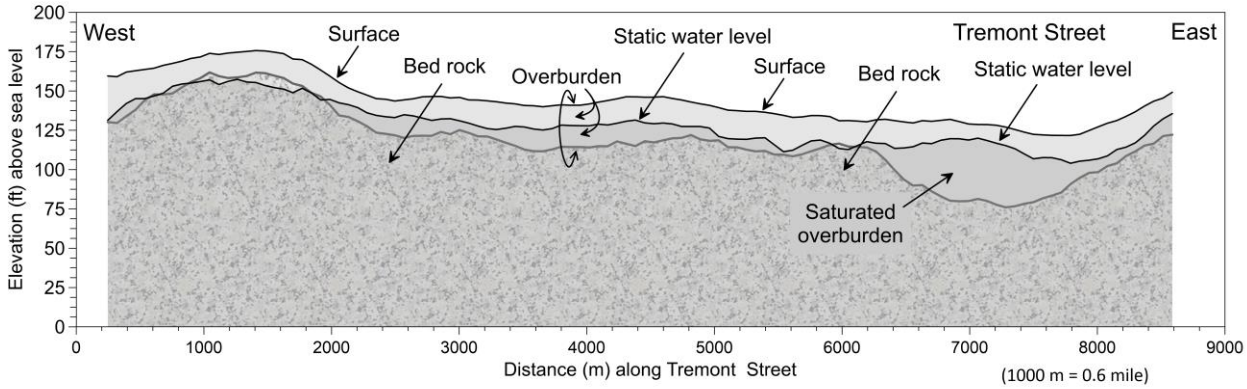


Figure 2.4(a). Example of a *work-in-progress.* Approximate elevation of the static water level and bedrock along the Tremont St. profile. Sea level is at the base of the figure at an elevation of 0 feet.

Figure 2.4(a) shows the result of interpolating the well data in Figure 2.3 to equally spaced values after rejecting outliers and applying a nine-point averaging window (a mean smoothing distance of 650 m). While the results are provisional, the deeper bedrock – hence, thicker zone of saturated overburden – in the east, beneath Hemlock Swamp and Little Cedar Swamp, accords with the map of TSO in Figure 2.1. In the west, the higher elevation of bedrock is associated with the northward extension of Rocky Hill. Figure 2.4(a), in conjunction with the original WC data in Figure 2.3, might provide a basis for planning further investigations. The 40-foot thick zone of saturated overburden close to the east end of the profile (from 6400 m to 7800 m) is a feature similar to those classified as ***high yield overburden aquifers*** elsewhere in town.

Figure 2.4(b) is an expanded vertical scale version of panel (a) showing the ***total depth*** of each well relative to sea level. (Mean sea level (MSL) is shown by the horizontal dashed line at 0 elevation in the figure.)

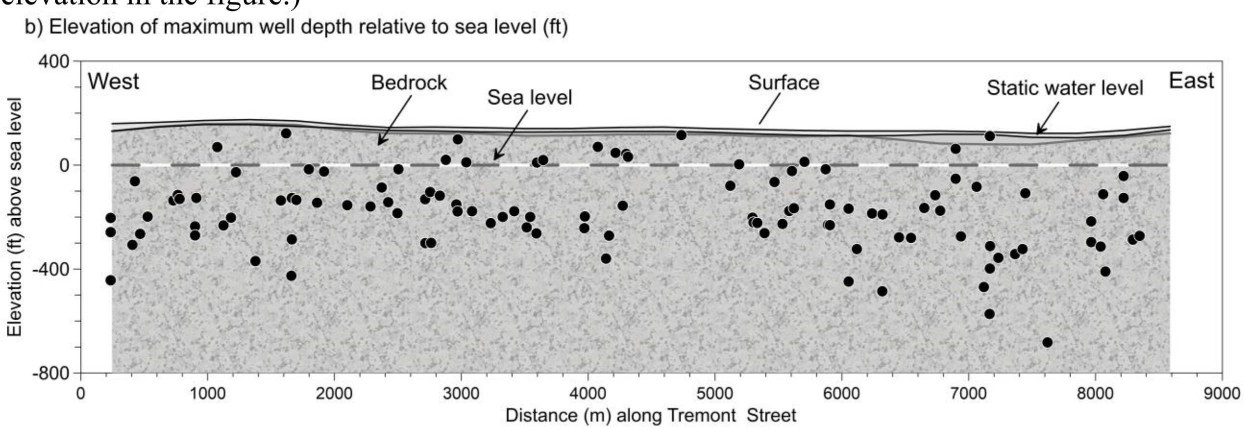


Figure 2.4(b) Elevation of the maximum depth of wells. Sea level is shown by the dashed horizontal line.

A typical total well depth is 305 ft below the local ground surface (BGS), such that most wells extend below sea level. Later in this section we address the possibility that the pattern of maximum well depths is different between the west section and the east section of the profile. We first, however, consider a similar west-to-east profile in the southern part of the town.

Providence Street Profile. Figure 2.5 shows the location of private and public water wells in a swath along Providence Street, spanning the west-to-east width of South Rehoboth.

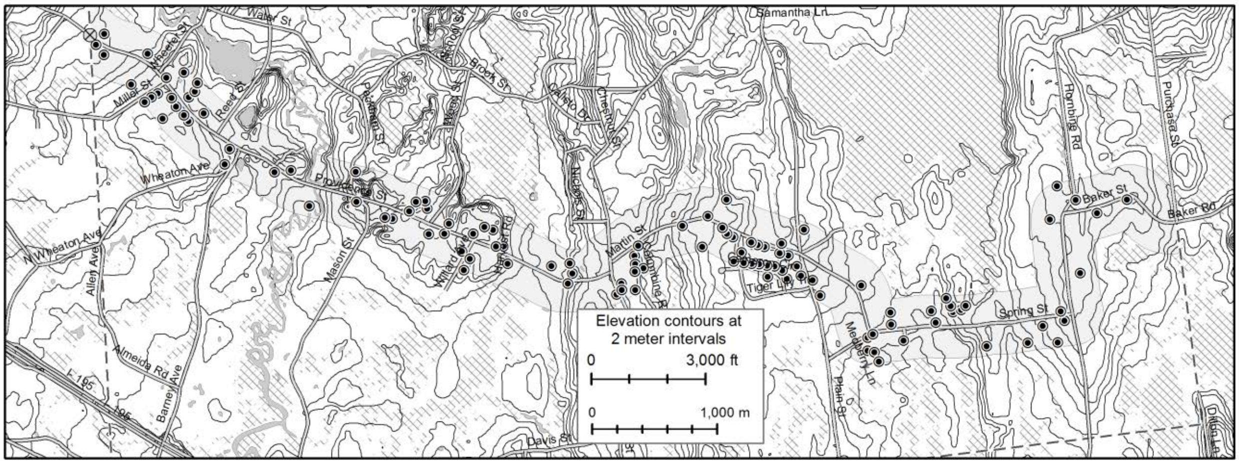


Figure 2.5. Location of water wells along Providence Street for which WC reports are available. Town boundaries are dashed. Hatched areas are wooded-and-open wetlands, significant recharge areas.

A qualitative view of surface features, along with the elevation of maximum well depth from WC reports, is shown in Figure 2.6.

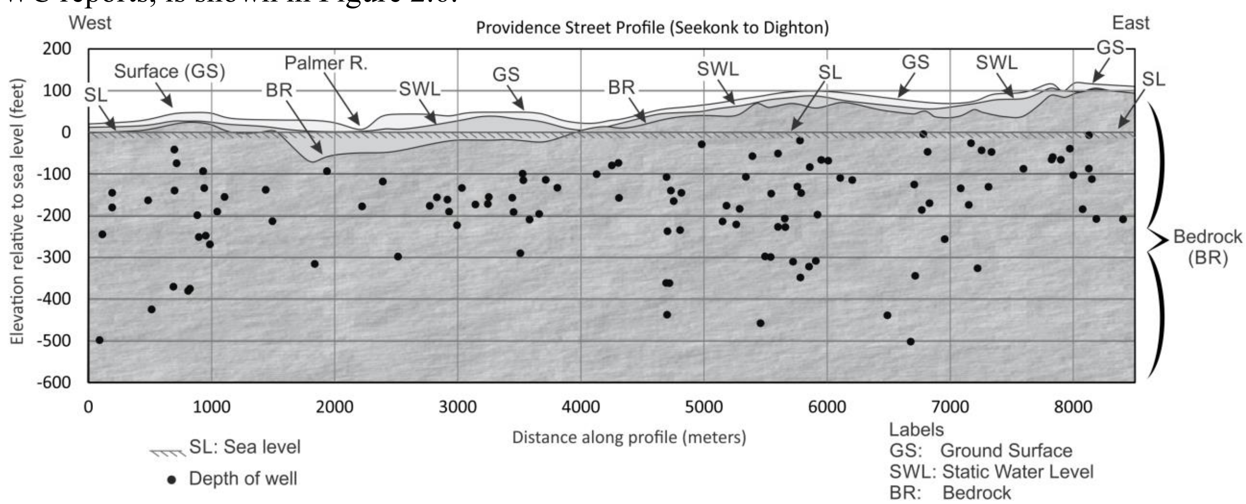


Figure 2.6. Composite cross-section of WC information along the Providence Street profile. All elevations are relative to sea level. It should be noticed that most of the wells shown here extend into, and are drawing water from, bedrock that is significantly below sea level.

A number of aspects of the profile along Providence St. profile between Barney Ave. and Oak Swamp Brook stand out from the rest of the profile and most of the rest of the town. The area along this profile in the immediate vicinity of the Palmer River was previously studied in some detail using well data in conjunction with geophysical methods by Bohidar, Sullivan and Hermance (2001) whose results are summarized in Figure 2.7.

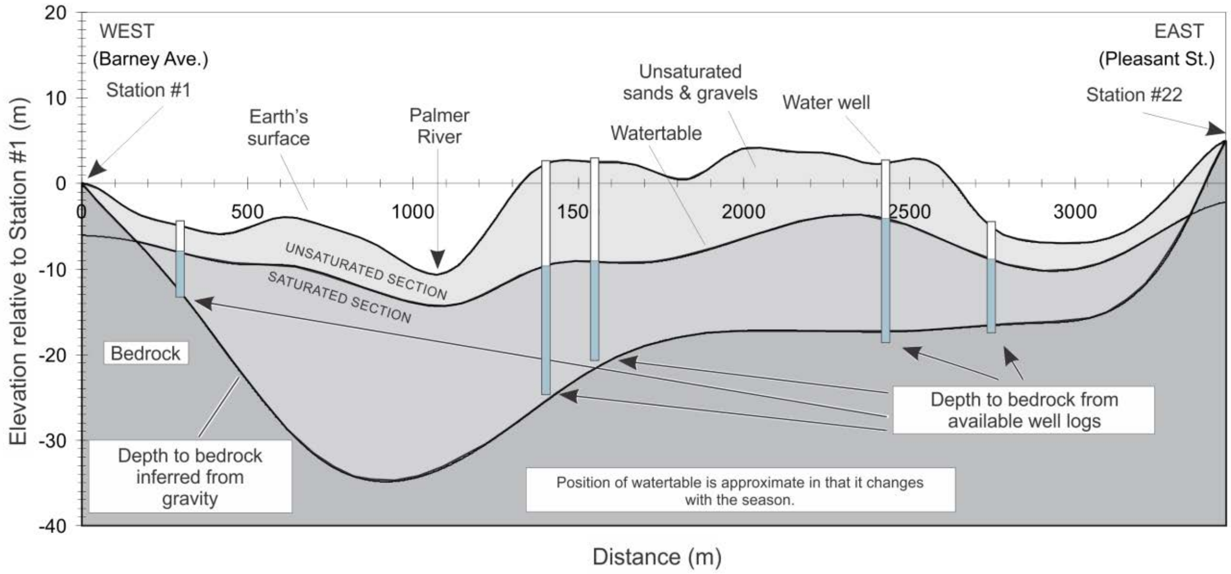


Figure 2.7. Synthesis of selected geophysical data in the immediate area of the Palmer River (after Bohidar, Sullivan and Hermance, 2001). Profile extends from Barney Ave. (Station #1) in the west to approximately Pleasant St. (Station #22) in the east. Both vertical and horizontal scales are in meters (m), where 1 m = 3.2 feet.

On average in Rehoboth, bedrock is 31 feet below ground surface. Excluding the previously mentioned segment, the average depth to bedrock is 28 feet along the Providence St. profile. However, between Barney Ave. and Oak Swamp Brook, the average depth to bedrock is 75 feet, with a range between 40 and 130 feet. In this area, the static water level (BGS) averages 22 feet (but apparently comes to the surface along the Palmer River and Shad Factory Pond). This means the thickness of saturated overburden is 50 feet or more (up to 75 feet in Figure 2.7, and more than 100 ft along Barney Ave. to the southwest). According to drillers' WC reports, the overburden in this area contains a mixture of sand and gravel in unspecified proportions, where the overburden in the adjacent areas is typically described as gravel. Unfortunately, details in the WC descriptions on layering of soil types in the unconsolidated overburden at each well site, or on the relative distribution (e.g. size and whether mixed or sorted) of grains or particles within each formation, are not sufficient to allow one to judge the relevance of the driller's logs to estimating the hydraulic conductivity of the saturated overburden. Consequently, one is unable to judge the maximum well yield that might be expected from the future development of such aquifers using empirical approaches (such as Willey, Williams and Tasker, 1983).

Example: Are there systematic differences in WC well depths?
Tremont St. versus Providence St. profiles. Comparing differences in WC well depths between the Tremont St. profile (Figure 2.4(b)) and the Providence St. profile (Figure 2.6), the Tremont Street profile has a mean well depth of 319 feet (sd = 142 ft; note[3]) and the Providence Street profile has a mean well depth of 249 feet (sd = 110 ft). A t-statistic of 4.15 implies that the mean depths can be assumed to be different, with an expected error of less than one in 100.

West Tremont St. versus East Tremont St. There may also be differences in the mean WC depths along each profile. With reference to Figure 2.4(b), there is a t-statistic of 2.20 for the difference between the mean depth of 291 ft (sd = 138 ft) for Tremont St. west of 4800 m and the

[3] Lower case "sd" denotes *standard deviation*.

mean depth of 349 ft (sd = 142 ft) for Tremont St. east of 4800 m. Such a t-value implies that the estimates may be from different groups, with an expected error of less than one in 20.

West Providence St. versus East Providence St. With reference to the Providence St. profile in Figure 2.6, a t-statistic of 1.72 for the difference between the mean WC depth (229 ft; sd = 98 ft) west of 4500 m, and the mean WC depth (264 ft; sd = 118 ft) east of 4500 m, implies the well depths are drawn from different populations, with an expected error of less than one in 10.

Exploring for the reason for this difference along Providence St. Unfortunately, the terms used by drillers in their WC descriptions of the bedrock in this same area do not illustrate any clear-cut lithological differences. Using the three wells on Green Ln. and the well on nearby 114 Providence St. as examples for the western section of the profile, the four different drillers describe the bedrock beneath the cluster of wells, respectively, as "*granite*", "*grey rock, medium",* "*granite*", and "*sandstone and shale*" (Table 2.1).

Table 2.1. WC reported bedrock types in adjacent wells (West).

Well ID	Address	Bedrock type
269248	2 Green Ln	Granite
269832	6 Green Ln	Grey medium rock
269322	10 Green Ln	Granite
144843	114 Providence St	Sandstone and shale

Since the four wells are very close together, it seems plausible that the four different drillers are seeing the same material and generically describing it in different terms. For the eastern section of the profile having deeper wells, we have Table 2.2.

Table 2.2. WC reported bedrock types in two adjacent wells (East).

Well ID	Address	From	To	Bedrock type
253843	2 Columbine Rd	50	120	Shale Grey
		120	135	Shale Black
		135	235	Shale Grey
		235	250	Shale Grey
		250	300	Shale Black/Grey
269214	151 Martin St	42	142	Rock
		142	218	Rock
		218	219	Grey Medium Rock
		219	319	Rock
		319	419	Rock
		419	485	Rock
		485	486	Grey Medium Rock
		486	505	Rock

Again, it's apparent that no clear-cut difference in lithology is being made, either among wells in a cluster, or between wells along different segments of the profile.

This type of equivocacy is commonly encountered when identifying bedrock types throughout the town. Without further information, therefore, it isn't possible to correlate the recorded maximum well depths with the local lithology (i.e. composition) of the bedrock.

Is elevation a factor in local differences in maximum well depth?

Another factor affecting maximum well depth may be differences in elevation: wells drilled on high terrain may have to go deeper to get to adequate groundwater. We have assessed this possibility for the Providence Street profile, using a linear least squares regression of y, the elevation (relative to sea level) of the base of each well, to x, the elevation of the ground surface at the well head. Mathematically, we have

$$y = 0.572\,x - 221$$
$$R^2 = 0.023$$
$$R = 0.152$$

In this case, R^2 is the coefficient of determination, and R is the Pearson correlation coefficient.

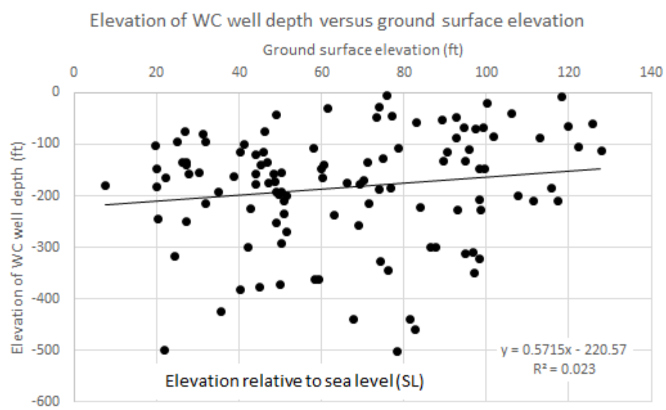


Figure 2.8. Regression of the elevation of the base of each well (determined from subtracting the WC depth from local elevation) versus the elevation of the ground surface at the well head.

The results shown in Figure 2.8 show a relatively low correlation, with a poorly determined slope (0.572 ft/ft), implying that whatever weak dependence there is between well depth versus elevation is largely masked by the wide range of uncorrelated well depths.

Example application: Elevation of the static water level versus elevation of the ground surface

Figure 2.9 shows a linear least squares regression of the local static water level (SWL) as determined relative to sea level (not relative to BGS has usually reported on WC forms) versus the local elevation of the respective wellhead.

Mathematically, the results are summarized by

$$y = 1.052x - 20$$
$$R^2 = 0.909$$
$$R = 0.953$$

where x is the elevation of the wellhead, and y is the elevation of the static water level, both relative to sea level. Not only is the correlation high, but the slope close to unity shows a close conforming of groundwater surface to topographic relief – which we interpret as a consequence of groundwater mounding. The above linear relation implies an intercept of the y-axis of -20 ft, which is a consequence of the mean depth of groundwater below the surface.

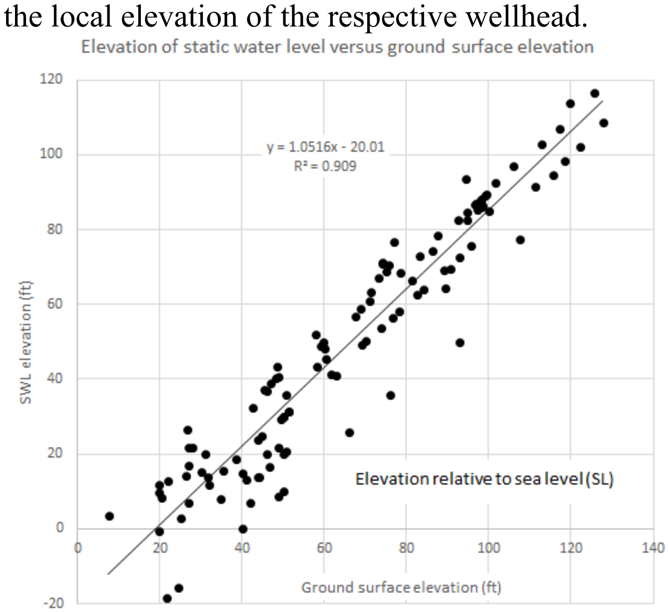


Figure 2.9. A regression of static water level (SWL) above sea level versus the local elevation of the earth's surface at the wellhead.

Part 3. Assessing well yield from WC reports

From the point of view of a homeowner or developer, the ***yield*** of a well − its expected sustainable production in gallons per minute (gpm) − is often its most significant attribute. In general, best practice dictates determining yield using a formal ***well test***, with the resulting metrics being recorded in the driller's ***well completion (WC) report***.

Procedures for a well test

Following MassDEP recommended procedures, a formal well test can provide two estimates of yield: ***drawdown yield*** and a complementary ***recovery yield***. To do so, the profession expects drillers to record at least the following six basic parameters in their WC reports.

Principal well test parameters

1. Static water level
2. Pump rate
3. Pump time
4. Maximum drawdown depth
5. Recovery time
6. Depth to the recovered water level

With these data, both *drawdown yield* and *recovery yield* can be computed, although the MassDEP currently requires that only a single yield value − or its proxy − be posted on a WC form. Most professionals agree, however, that the advantage of having two semi-independent estimates of yield is that they can be validated against each other, as well as against other methods for estimating yield.

Computing yields from a well test

Ideally, a well test begins and continues at a fixed pumping rate (or discharge rate) over a specific pumping time. During the drawdown of the water level in the well, water is pumped from two sources: from the original water stored in the well and water extracted from the aquifer. A typical domestic water well is usually six inches in diameter, so that water stored in each foot of depth in the well is 1.47 gallons per foot. Drawdown yield ($Yield_{DD}$) is given by

$$Yield_{DD} = P_{rate} - \frac{1.47\left(DD_{\max} - d_{\mathrm{SWL}}\right)}{T_{DD}} \qquad (3.1)$$

where P_{rate} is pump rate (gallons per minute; gpm) , $DD_{\max}$ is maximum drawdown (ft), d_{SWL} is depth to the static water level (ft), and T_{DD} is the pump time (minutes).

Drillers often use a simpler, though more restrictive, version of (3.1) having the form

$$Yield = P_{rate} \qquad (3.2)$$

In other words, when using (3.1) they assume the yield is equal to pumping rate, neglecting the contribution from stored water in the well bore. This may not be a valid measurement of the sustainable well yield because, for short drawdown tests, it might be that the volume of discharged water from the well is mostly the water originally stored in the well, not that from the aquifer. For example, consider a typical drawdown of 200 feet at a pump rate of 5 gpm. It would take 60 minutes to just pump all of the stored water from the well, and according to (3.1), it would take at least 300 minutes for the computed yield on the left to be within 20% of the pump rate on the right. Thus, if one is to assume that

$Yield_{DD} \approx P_{rate}$, they need to be confident that drawdown time, T_{DD}, is long enough that significantly more water has been pumped from the aquifer than originally stored in the static water column of the well bore, ***preferably by a factor of five*** or more.

Recovery yield is the rate at which the water level in the well recovers following the termination of discharge. Assuming recovery has occurred over a time period T_{recovery}, the ***recovery yield*** is

$$Yield_{\text{recovery}} = \frac{1.47\left(DD_{\max} - D_{\text{recovery}}\right)}{T_{\text{recovery}}} \tag{3.3}$$

where D_{recovery} is the instantaneous depth to the recovering level at time T_{recovery} following the termination of discharge.

The need to standardize the documentation of a well test

Whereas the fundamental principles of a well test are quite clear, recording the key parameters often varies from driller to driller and are not infrequently mis-transcribed by the responsible monitoring agency, causing the archived results to be difficult for end users to decipher.

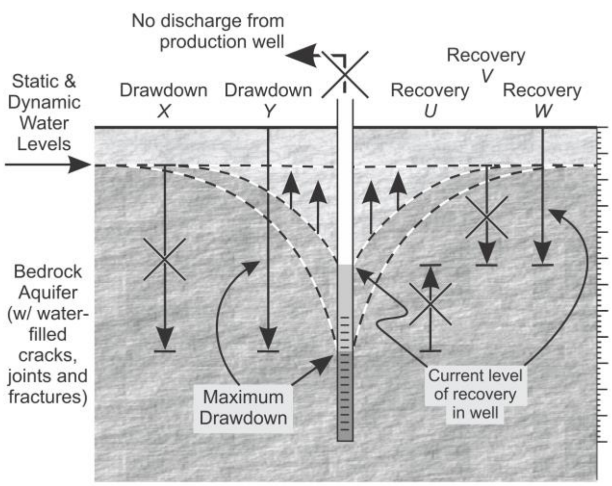


Figure 2.1. Modes for recording drawdown and recovery.

Figure 2.1 illustrates various combinations of drawdown and recovery that drillers have used for their WC reports. MassDEP expects that drawdown will be recorded using mode *Y*, and recovery will be recorded using mode *W*.

Each of the vertical arrows in the figure represents an assessment of the respective water level in the well. Drawdown measurements are shown on the left of the figure, and recovery measurements are shown on the right. Modes *X, U,* and *V* do not follow the currently MassDEP approved convention so are crossed out here for emphasis. However, many drillers have used, and still use, them.

Counting the variations in procedures for measuring drawdown (there are 2 on the left of Figure 2.1) and those for measuring recovery (there are 3 on the right), there are 6 random combinations of the two metrics that may be entered into the well completion (WC) report. Anyone using data from these reports needs to be aware of this. If this random array of entries is taken literally, and the end-user assumes that relations (3.1) and (3.3) apply, then only one combination (drawdown mode *Y* and recovery mode *W*) will be correct, and five combinations will be wrong. In other words, 83% of reported yields could be in error, and only 17% of the random combinations will be correct. While actual data entries are not quite so random, for a representative set of WC reports we have investigated, approximately 30% of the records seem to have documented "*Recovery*" using mode *U* (SWL), rather than the expected mode *W* (BGS) that is appropriate for D_{recovery} in relation (3.3).

Thus, the need for promulgating clear definitions of the fundamental well test parameters, along with careful adherence by well drillers, with monitoring for quality assurance (QA) by the MassDEP and local monitoring agencies, is essential for the public.

Part 4. Assessing the general quality of well completion (WC) reports

Overview of the databases derived from well completion (WC) reports

Major issues

Driller well completion (WC) reports are the cornerstone of this analysis. As a matter of state and local policy, it is expected that all driller WC reports for the town should be filed with the Board of Health (BOH, 2018), as well as independently with the MassDEP. The following discussion summarizes the findings of our investigation assessing the type and quality of this information, particularly data available in electronic formats that can be used for the type of "Big-Data" type number crunching required for GIS mapping and its associated spatial and statistical analysis. Our objective in Part 4 is to document the following, most common types of problems with well completion (WC) reports:

1) Mis-location, or no location given for, respective wells. Apparently, in some cases, the driller was unfamiliar with using GPS. In other cases, the location is simply not posted[1] by the driller, and the oversight not attended to by the BOH and MassDEP.

2) Incomplete entry of data. (Spaces for data entry on the WC reports are simply left blank by drillers, with no quality control from monitoring by local or state authorities.)

3) Mis-interpretation or misunderstanding by the driller of how drawdown and recovery should be measured and entered. Properly selecting the duration of drawdown times and recovery times for an adequate well test are not commonly appreciated by drillers, the BOH or the MassDEP.

4) Incomplete or erroneous transcriptions of data by MassDEP from driller's WC reports to MassDEP databases[2], usually as an attempt to transmute or convert data recorded in previously prescribed formats into accord with current prescribed formats (particularly troublesome when converting the metrics of well tests).

5) Posted values of well yield typically lack validating evidence from an associated well test.

Database

Here, we review again the scope of the database we accessed, for purposes of describing some of the general issues with the data for which we present specific case examples throughout the rest of Part 4. A major dataset we initially planned to use is a spreadsheet provided to the Rehoboth Water Commission in 2016 by the MassDEP (2016) purportedly containing all of the information from well completion (WC) reports that were on file with the state at that time. Relevant metrics are organized in a spreadsheet format with wells identified by a Well ID number assigned by MassDEP. We began updating this information in early 2018 with more recent information downloaded from the MassDEP searchable SearchWell (2018) database that, now (Midyear, 2018) has transitioned into the current EEA (2018) electronic database maintained by the MassDEP. The on-line EEA (2018) database allows the user to

[1] The term, "*posted*" refers to data values explicitly declared by MassDEP or entered by drillers in their respective WC (well completion) reports.

[2] "*MassDEP databases*" refer to MassDEP (2016), SearchWell (2018) and EEA (2018) spreadsheets or on-line transcribed MassDEP WC summary reports.

download information in spreadsheet form that is intended to consist of Well ID, Town, Street Number, Street Name, Latitude, Longitude, Date Completed, Well Type, Work Performed, Total Well Depth, Depth to Bedrock, and Static Water Level. Unfortunately, one of the most important attributes of groundwater wells – *yield* – is not available from publicly accessible (i.e., on-line) MassDEP spreadsheet databases (neither SearchWell, 2018; nor EEA, 2018). Alternatively, a metric that the MassDEP refers to as "*yield*" is available on-line through a well-by-well, searchable database of individual MassDEP edited and amended WC reports (see EEA, 2018).

However, the MassDEP version of "yield" should be thought of as – at best – a proxy for the *true* yield, since the posted metric approximates the true yield only over a narrowly defined range of well test conditions… conditions that MassDEP (2018) WC reports hardly ever describe in sufficient detail for the public to be able to validate the values. By this we mean that to corroborate the yield value, many professionals (e.g. Pierce, 1998) recommend that – in addition to the parameters listed in the last paragraph – at least six fundamental parameters are needed to verify a complete two-way well test: static water level, pump rate, pump time, maximum drawdown, recovery time, and level of recovery. Regrettably, however, in many cases some of this critical information is missing, or simply not requested on state-mandated driller's WC forms. According to one subset of the town's WC reports, 62% of the driller's WC forms (those prior to 2001) did not provide a space to explicitly post the driller's determined yield. Although after 2001, while an entry for *yield* appeared on a new version of the driller's form, no pump rate is explicitly posted. Not only has the MassDEP-required format of WC reports been modified a number of times over the years, but not all drillers have kept up with these changes, particularly when terms are not clear and when conventions for recording the principal well test parameters are revised. For example, there is a generation of WC reports that expect recovery to be measured from maximum drawdown, whereas the latest WC version defines recovery to be recorded relative to the ground surface – the exact opposite. Ambiguities such as these might be the cause that often the MassDEP has not transcribed driller's information properly, particularly when attempting to transform the results from previous well test conventions to current well test conventions. Compounding the issue, we found that many data fields were blank on the MassDEP-supplied WC reports and spreadsheets, largely because the drillers, themselves, did not properly complete their drilling reports – omissions that were unfortunately not caught by responsible quality control monitors. Consequently, the manner in which the posted value of yield for a specific well is determined is generally a mystery to users of the data.

In order for us to fill in these blanks and correct the most glaring errors for a selected sample of wells, certain well locations were determined from records at the town Assessor's Office. Missing information on an actual well, or data that was not transcribed properly by MassDEP, was provided from well completion records at the BOH (2018), and supplemented by the 750 or so photocopied well completion reports from 1995 and earlier supplied by Brown University. Our final count provided useful data from, at most, 1,310 WC driller reports, out of an estimated 4,000 wells in town. Many of these 1,310 reports, however, had their own specific problems as described in the following.

Problems with the posted locations of wells

For any kind of spatial analysis of well metrics, it is necessary to have both the street location of the well, as well as its geographic ordinance. The following discussion will touch upon a number of problems with the manner in which MassDEP has allowed well drillers to describe the location of respective wells.

Geo-coordinates of wells

Figure 4.1 represents information from the current (Sept. 2018) EEA (2018) WC report spreadsheet for those Rehoboth wells having posted GPS coordinates. While only Rehoboth wells should appear on the downloaded database, clearly this is not the case.

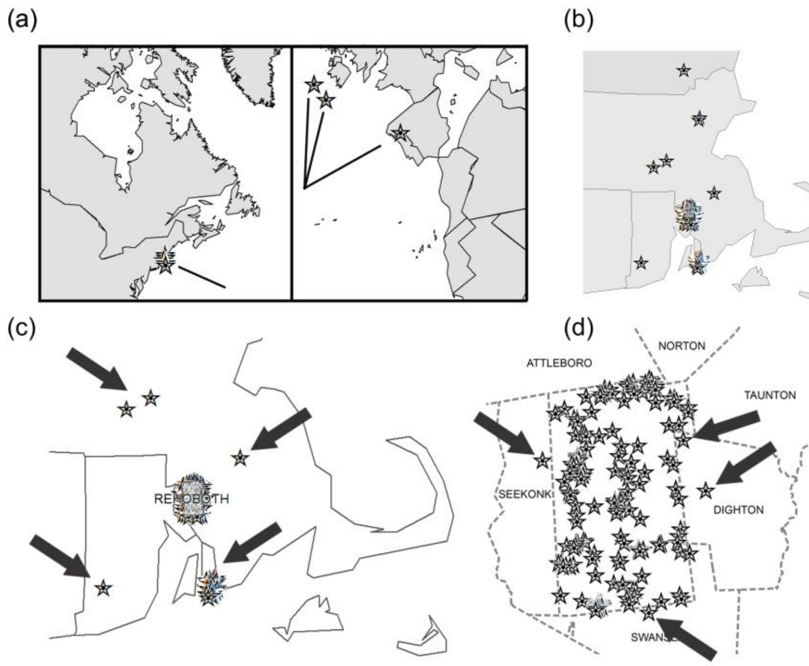


Figure 4.1. Available GPS locations for selected Rehoboth water wells from transcriptions of WC driller reports posted to the EEA (2018) publically-available spreadsheet database.

The EEA (2018) on-line database, in Sept. 2018, listed 2,103 WC records for Rehoboth, of which 250 had posted geographic latitude and longitude. For some reason, ten (10) of these well locations were assigned identical values of 42.00 N, 71.00 W, which of course is not their actual location. Panel a) shows all the GPS-posted wells in the current database. Some are scattered around the North Atlantic. The left panel of the figure shows, as should be expected, the principal cluster of wells in New England. Panel b) is an enlarged view of the left panel a), showing wells located in Eastern New England. Panel c) shows wells in Southeastern New England, and Panel d) shows wells in and in the immediate vicinity of Rehoboth. The majority of these well completion reports do include complete street addresses, which would make it possible to establish the correct location of the well. For example, ID 152721 is correctly listed as 19 Tori Leigh Ln., in spite of the fact that the listed GPS coordinates locate the well somewhere near Upton, MA. Another example is that of ID 652499, which is 224 Tremont St. instead of a point in the North Atlantic to the west of Ireland. Because of the effort required to cross-reference each of these erroneous GPS locations, they were dropped from the analysis. It is clear that well drillers either need to use more reliable instruments to determine the GPS coordinates of each well or need to become more familiar with the operation of the devices that they are using. Including GPS coordinates has been a MassDEP requirement since 2007, but there appears to be little (if any) follow up as to the accuracy of these locations.

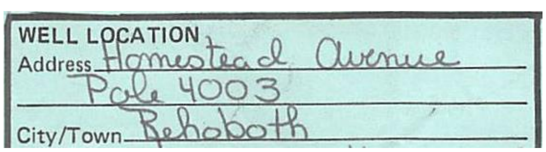
We emphasize that these problems in geolocation are still present in the current EEA (2018) MassDEP online database, and while largely corrected in the derived databases available through the Water Commission, some caution is recommended when using the latter.

Misspelling of street names and wrong street types

When machine (i.e. computer) searching and plotting well locations, the simplest abnormality in the formats of street names becomes a problem. For example, spelling: 6 Puchase St is actually 6 Purchase St, 20 Purchace St is actually 20 Purchase St, 14 S Old Anawan Rd is actually 14 South Old Anawan Rd, 34 Smoth St is actually 34 Smith St, 20 Talbot Ln is actually 20 Talbot Dr. In the latter case, the confusion between street types – St or Ave, Rd, Dr, Ln, Cir, and so forth – is endemic to the WC databases.

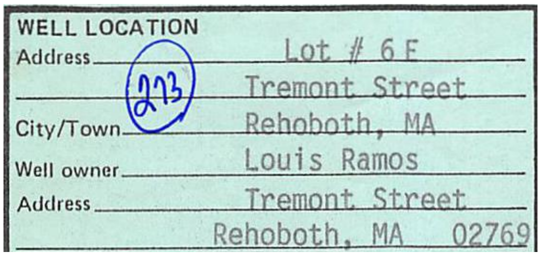
Missing or inadequate reporting of street numbers for wells

In times of extensive housing development, or in the case of a new subdivision, drillers often drill wells without knowing the final address of the lot where they have drilled the wells. Looking back through the decades, these cases are treated in a number of different ways by the drillers. Some drillers simply write the name of the street on the well completion report, which is sometimes impossible to reference after time passes. (For example, Tremont St., ID[3] 270565 and ID 270570; but no street number.) Other drillers will use the nearest electric pole number. While tracking down an address on this basis is time-consuming, it is an effective means for identifying a well's location. (For example, 150 Homestead Ave., formerly Pole 4003, ID 270158.)


WELL LOCATION
Address Homestead Avenue
Pole 4003
City/Town Rehoboth

If a development has been surveyed and lot numbers assigned, the drillers are likely to know the lot number of the well. If the lot number has been assigned and is recorded on the well completion report, it is possible to track down the ultimate street address through the assessor's database or maps on file with the assessor's department. When a well driller submits the well completion report to the Board of Health, most often accompanied by the water quality test results, this information is filed according to street address. In cases where there is no street address written on the well completion report by the driller, it is sometimes written on the report by the person who files the information. See the following example of 273 Tremont St., ID 269948, formerly Lot #6E, which is also an example of the drillers using lot number and street name.

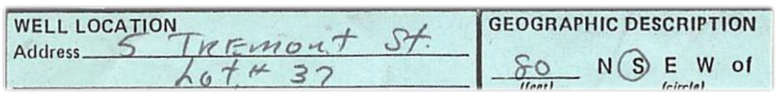
[3] Well ID number assigned by MassDEP; generally not available in the Town's Board of Health files.



WELL LOCATION
Address Lot # 6 F
273
Tremont Street
City/Town Rehoboth, MA
Well owner Louis Ramos
Address Tremont Street
Rehoboth, MA 02769

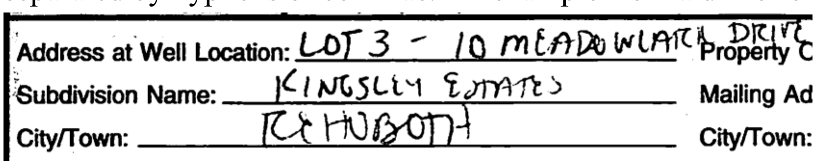
There are certain cases where the driller knows both the lot number of a well and the street address. Drillers deal with this possibility in different ways, and sometimes the result is clearer than others. The best-case scenario is that both the lot number and the street address are recorded separately on the well completion report.

Example: 5 Tremont St.



WELL LOCATION
Address 5 Tremont St.
Lot # 37
GEOGRAPHIC DESCRIPTION
80 (feet) N S E W of (circle)

Another option – but less clear – involves recording the lot number and street number together, separated by hyphens or commas. An example from a driller's WC report follows.



Address at Well Location: LOT 3 - 10 MEADOWLARK DRIVE Property C
Subdivision Name: KINGSLEY ESTATES Mailing Ad
City/Town: REHOBOTH City/Town:

In this case, upon our referring to the assessor's map, or to the assessor's property report card, the lot number has been entered first, followed by the street number. However, at other times the driller may enter the street number first. In some cases, these unconventional methods of recording the address (often undefined or unexplained) were more clearly annotated by the driller on the well completion report, but only the specific posted entries have subsequently been copied verbatim into the MassDEP spreadsheet databases. Driller notes were therefore lost. The following table shows the currently available address locations as copied from the MassDEP (2016) and most recent EEA (2018) spreadsheets.

Example of preliminary locations assigned new wells.		
WELL_ COMPLETION_ ID	WELL_ STREET_ NUMBER	WELL_ STREET_ NAME
152760	Lot 11-21	Sassafras Road
154950	Lot 5-18	Meadowlark Drive

Consequently, it is difficult for a member of the public to locate a well at a particular address, or to decipher the street address on the EEA(2018) spreadsheet database using a software search function (e.g. Excel or ArcGIS). Confounding the problem is that the more common procedure by the MassDEP is to leave the street number field blank unless the well completion report has an actual street number on it. Of the town-wide 744 paper records that we compared to the SearchWell (2018) database, 204 of them (27%) were not recorded in the database because they were identified either by lot number or pole number. Without these unique identifiers, the information in the database is essentially useless, as the records are not tied to physical locations.

Overall, it's estimated that there are approximately 4,000 water wells in the town, of which there are currently (16 Nov. 2018) 2,107 wells listed in the EEA (2018) spreadsheet database. Of these, 561 have no street number or lot number. An additional 107 have mixed lot numbers. In other words, approximately 32% of reported wells in Rehoboth have no searchable street address. Considering these, along with the roughly 2,000 wells with absolutely no records at all, we estimate that 64% of the total wells in town have no searchable street address. In other words, only 36% of Rehoboth's wells have information that can be related to a particular household at a particular location.

Problems with non-standard time formats

Problems persist in the transcription of drawdown times and/or recovery times from written driller reports to the MassDEP (2016) spreadsheet database. There are mixed formats in the MassDEP (2016) that basically require the analyst to go through thousands of entries line-by-line. As an example, time entries vary in format from 00:00:00 to 00. We find "2 hr.", "2hr.", "120 min" used interchangeably. A list of representative time formats used in the MassDEP (2016) database is given in Table 4.1. Scanning the possibilities, there are a number of opportunities for confusion.

Table 4.1. Examples* of various formats for drawdown and recovery time.

Index†	Time	Index	Time	Index	Time	Index	Time
1	0:01:00	9	0:30:00	17	000:07	25	0:00:14
2	1:00:00	10	0:30	18	001:15	26	0:00:00
3	1:00	11	:03	19	2 hr.	27	0
4	:10	12	:30	20	2 hrs.	28	0:05
5	24	13	000:30	21	2hr.	29	0:05:00
6	18:00	14	30	22	7.45	30	1:45
7	1:55	15	30 mins.	23	0:15	31	1:45:00
8	24:00:00	16	30mins.	24	4:00;00		

*Examples from MassDEP (2016) supplied database.
†Index refers to format style, e.g. Index:1 is Format 1 in the text.

For example, Format 9 (0:30:00) is likely to be 30 minutes, but what might Format 10 (0:30), Format 11 (:03), Format 12 (:30) and Format 13 (000:30) represent? And while one might expect Format 14 (30) to represent 30 minutes, how does this accord with Format 5 (24), which we suspect to be 24 hours.

While such issues with time formatting may often be resolved with reference to the original WC report, it requires line-by-line hand-editing, when resolving drawdown and recovery times in the MassDEP (2016) spreadsheet database. Whereas the latter is fraught with these and other problems, it is still one of the main data sources currently being used by the town and its collaborators (e.g. RWU (2017)), in various applications of computer analysis and GIS databases. As pointed out previously, one of the most important attributes of a completed water well is its yield, for which proper reporting of drawdown time and recovery time are essential.

Yield: **The foundational attribute of water wells**

Ideal case: Two types of yield; drawdown yield and recovery yield

In many people's view, the *yield* of a producing water well is one of the ultimate measures of a successful project and is second in importance only to the water quality of the well. In this section we will be assessing, in some detail, the accuracy with which this parameter has been determined for the wells in Rehoboth. It is commonly agreed, among groundwater professionals, that the best way to determine yield is from a formal well test as described in Part 3. Such a well test should consist of two phases: the drawdown phase while the well is being discharged, then, upon terminating discharge, the recovery phase of the water level in the well as it returns to its pre-pumping static level. Each phase allows one to determine a quasi-independent value of yield: a *drawdown* yield and a *recovery* yield. If done correctly, the two estimates should agree. If not, one might hesitate in placing too much reliability to a driller's or the MassDEP posted[4] yield. Here, for wells having sufficient test data, we propose to compare the WC posted yield with values for the yield that we compute directly from the driller's well test data. This will be an attempt to assess whether the driller's posted yield is consistent with the raw well test data that may, or may not, have been used to compute it. Databases upon which we draw for this study are MassDEP (2016), the summary WC report forms available through the SearchWell/EEA (2018) web site, and selected WC reports on file with the local Board of Health (2018) and our previous studies.

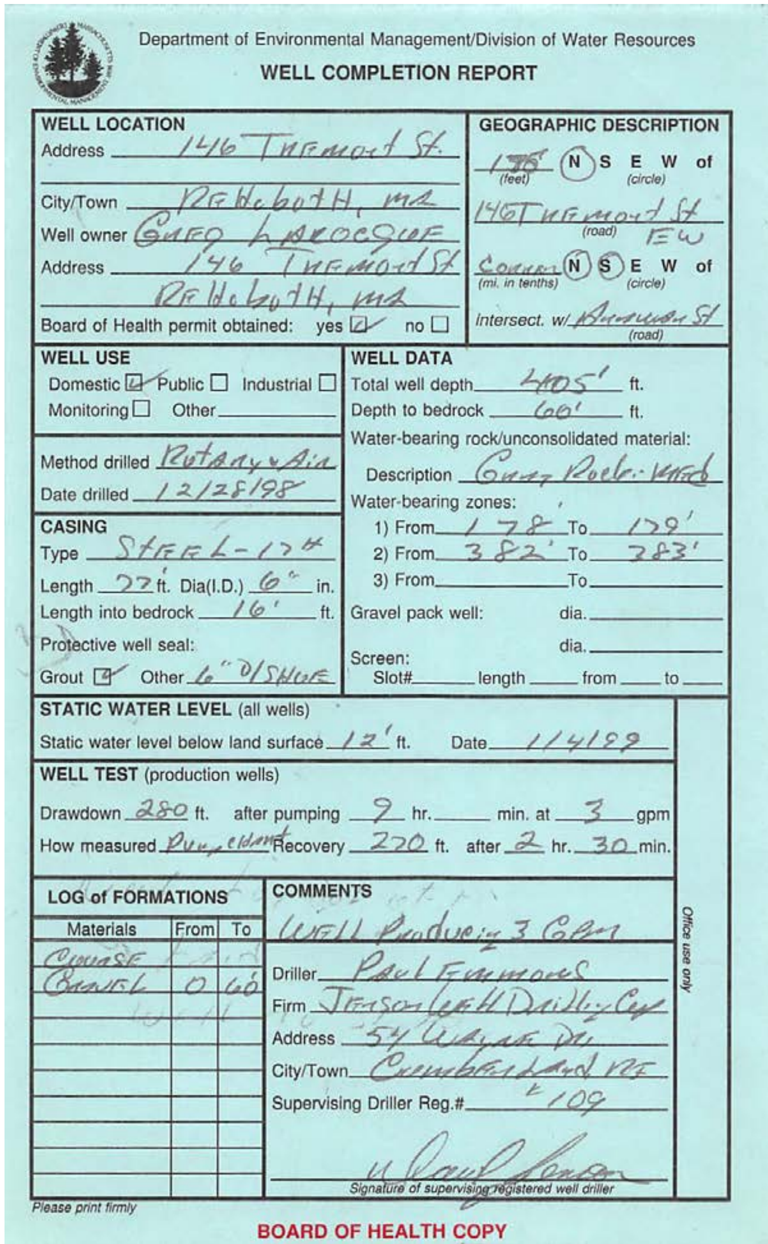
Our ultimate objective is to assess the quality of MassDEP posted values of yield. It appears that some of these values have been determined by drillers; however, a substantial number do not appear on the original driller well completion (WC) reports. The latter values appear to have been produced and logged into the MassDEP (2016) database by parties unknown, using methods (i.e. formulas or equations) that are not described. For purposes here, we assume these auxiliary yield estimates have been produced and authenticated by the offices of the MassDEP. We illustrate this with the following example.

Example of driller's reported yield compared to MassDEP's reported yield

This section illustrates the summary analysis of a driller's WC report in conjunction with its transcription and recasting of metrics by MassDEP (the latter from the summary MassDEP WC report at EEA, 2018). We use example data from the well at 146 Tremont St., Rehoboth, MA; MassDEP ID 269176 (Figure 4.2 (a)).

[4] The term, "*posted*" refers to yield values explicitly declared by MassDEP or entered by drillers in their WC reports.

Figure 4.2 (a). Example Driller's WC report (Blue sheet on file with BOH). Address: 146 Tremont St., Rehoboth, MA; MassDEP ID 269176



Department of Environmental Management/Division of Water Resources

WELL COMPLETION REPORT

WELL LOCATION

Address 146 Tremont St.

City/Town Rehoboth, MA

Well owner Greg Larocque

Address 146 Tremont St

Rehoboth, MA

Board of Health permit obtained: yes ☑ no ☐

GEOGRAPHIC DESCRIPTION

150 (feet) (N) S E W of (circle)

146 Tremont St (road) EW

Corner (mi. in tenths) (N) (S) E W of (circle)

Intersect. w/ Anawan St (road)

WELL USE

Domestic ☑ Public ☐ Industrial ☐

Monitoring ☐ Other

Method drilled Rotary & Air

Date drilled 12/28/98

CASING

Type Steel - 17#

Length 22 ft. Dia(I.D.) 6" in.

Length into bedrock 16' ft.

Protective well seal:

Grout ☑ Other 6" D/Shoe

WELL DATA

Total well depth 405' ft.

Depth to bedrock 60' ft.

Water-bearing rock/unconsolidated material:

Description Gray Rock - Hard

Water-bearing zones:

1) From 178 To 179'

2) From 382' To 383'

3) From To

Gravel pack well: dia.

dia.

Screen:

Slot# length from to

STATIC WATER LEVEL (all wells)

Static water level below land surface 12' ft. Date 1/4/99

WELL TEST (production wells)

Drawdown 280 ft. after pumping 9 hr. min. at 3 gpm

How measured Pump, clean Recovery 270 ft. after 2 hr. 30 min.

LOG of FORMATIONS

Materials	From	To
Coarse Gravel	0	60

COMMENTS

Well Producing 3 GPM

Driller Paul Emmons

Firm Jenson Well Drilling Co.

Address 54 Wagner Dr.

City/Town Cumberland RI

Supervising Driller Reg.# 109

Signature of supervising registered well driller

Office use only

Please print firmly

BOARD OF HEALTH COPY

***Discussion*:** This is an example of a relatively correct and completely filled out well completion report, adhering to the standards of 1998, whereby drillers were expected to record drawdown using Mode *Y* and recovery using Mode *U* (see Part 3, Figure 3.1), this is *not* the convention currently recommended by the MassDEP, and the following MassDEP transcription of the driller's report has attempted to bring the old format into accord with the present (2018) format.

Figure 4.2 (b). Example: Transcribed MassDEP WC summary report Address: 146 Tremont St., Rehoboth, MA; MassDEP ID 269176 .

MassDEP

Well Completion Report

WELL LOCATION

GPS North:
GPS West:
Assessors Map:
Address: 146 Tremont Street
Assessors Lot:
Sub Division:
Permit Number:
City/Town: REHOBOTH
Date Issued:
Board Of Health Permit Obtained: Y

Work Performed	Well Type	Drilling Method Overburden	Drilling Method Bedrock
New Well	Domestic	Air Rotary	Air Rotary

ADDITIONAL WELL INFORMATION

Developed:
Disinfected:
Total Well Depth: 405.00
Fracture Enhancement:
Well Seal Type: Cement/Bentonite
Depth to Bedrock: 60.00

PERMANENT PUMP (IF AVAILABLE)

Pump Description:
Type:
Nominal Pump Capacity:
Intake Depth:
Horsepower:
Comments: Well is located 185' North of Tremont Street, at the corner of Anawan Street. Protective well seal=6" drive shoe. Casing length into bedrock 16'. Well producing 3GPM.

CASING

From(ft)	To(ft)	Type	Thickness	Diameter
0.00	77.00	Steel	17#	6

SCREEN

From(ft)	To(ft)	Type	slotsize	Diameter

WELL SEAL / FILTER PACK / ABANDONMENT MATERIAL

From(ft)	To(ft)	Material Description	Purpose

STATIC WATER LEVEL(ALL WELLS)

Date Measured	Depth Below Ground Surface
01/04/1999	12.00

WELL TEST DATA (ALL SECTIONS MANDATORY FOR PRODUCTION WELLS)

Date	Method	Yield(GPM)	Time Pumped (hrs & min)	Pumping Level (Ft. BGS)	Time To Recoover (Hrs & min)	Recovery
01/04/1999	Constant Rate Pump	3.00	9:00	280	2:30	12

OVER BURDEN

From(ft)	To(ft)	Lithology	Color	Comment	Water Zone	Loss / Add of Fluid	Drill Stem Drop	Drill Rate
0.00	20.00	Gravel		Coarse	No			
20.00	40.00	Gravel		Coarse	No			
40.00	60.00	Gravel		Coarse	No			

BEDROCK

From(ft)	To(ft)	Lithology	Comment	Water Zone	Drill Stem Drop	Extra Large	Drill Rate	Rust Stain	Loss / Add Of Fluid	# of Fract Per Ft
60	160		Rock	No						
160	178		Rock	No						
178	179		Grey Medium Rock	Yes						
179	279		Rock	No						
279	379		Rock	No						
379	382		Rock	No						
382	383		Grey Medium Rock	Yes						
383	405		Rock	No						

Compare data for a single well transcribed from the MassDEP's* (*2016*) *spreadsheet with original driller's WC report.
(***Address 146 Tremont St., ID 269176***)

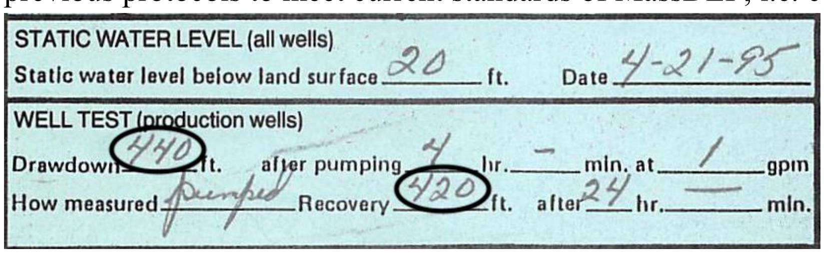
Table 4.2. Compare metrics from MassDEP (2016) spreadsheet database (rows 1 &2) with original driller's WC report (row 3; shaded).

WELL_ COMPLETION_ ID	PROPERTY _ TYPE	WT_ METHOD	Pump rate (gpm)	WT_ DRAW-DOWN	WT_ TIME-PUMPED	WT_ RECOVERY	WT_ TIME	YIELD	FLOWING	SW_ DEPTH	DATES (WT)
269176	WATER_ LEVEL									12	04-Jan-99
269176	TEST_ WELL	CR	NA	280	9:00	12	2:30	3			04-Jan-99
269176	Domestic	*	3	280	9	270	2 hr 30 min	NA		12	04-Jan-99

Note on Table 4.2:
Lines 1 and 2 are from MassDEP (2016) transcribed database (spreadsheet).
Line 3 (grey shade) data are from original driller's WC report (Blue sheet)
NA indicates that the respective form or spreadsheet does not record this category, although the driller notes, in his comments at the bottom of his form, that the yield is 5 gpm.
* Driller notes described this as "Pump & Wait"
Water levels are in feet (ft)
Flow rates and yields in gpm.
WT_METHOD, "CR" denotes "*Constant Rate Pump*"

Inconsistencies in MassDEP transcriptions: compare two examples

Example 1. Figure 4.3. 124 Tremont St. (ID 269420), an example of the recovery being adjusted from previous protocols to meet current standards of MassDEP; i.e. currently, recovery is relative to BGS.


STATIC WATER LEVEL (all wells)
Static water level below land surface 20 ft. Date 4-21-95
WELL TEST (production wells)
Drawdown 440 ft. after pumping 4 hr. – min. at 1 gpm
How measured pumped Recovery 420 ft. after 24 hr. — min.

WELL SEAL / FILTER PACK / ABANDONMENT MATERIAL

From(ft)	To(ft)	Material Description	Purpose

STATIC WATER LEVEL(ALL WELLS)

Date Measured	Depth Below Ground Surface
04/21/1995	20.00

WELL TEST DATA (ALL SECTIONS MANDATORY FOR PRODUCTION WELLS)

Date	Method	Yield(GPM)	Time Pumped (hrs & min)	Pumping Level (Ft. BGS)	Time To Recoover (Hrs & min)	Recovery
04/21/1995	Constant Rate Pump	1.00	4:00	440	24:00	20

Note regarding Figure 4.3: In the original driller's report (top panel), the drawdown, 440 ft, is measured from the surface (i.e. BGS), whereas the recovery (420 ft) – according to the old standards – is the column height of the recovered water level which has returned to the original SWL, and transcribed and converted by the MassDEP (bottom panel) as a recovery of (440 – 420) = 20 ft (BGS)

(***A counter-example follows.***)

Example 2. Figure 4.4. 339 Tremont (ID 111540), an example where the originally driller-reported drawdown and recovery values (top panel) are retained by the MassDEP WC summary report (bottom panel) in the original database format.

12. WELL TEST DATA (PRODUCTION WELLS)							13. STATIC WATER LEVEL (ALL WELLS)	
Date	Method	Yield (GPM)	Time Pumped (hrs & min)	Drawdown to (Ft. BGS)	Time (hrs & min)	Recovery to (Ft. BGS)	Date Measured	Depth Below Ground Surface (FT)
4/2/02	Airlift	1	4hrs.	500	24hrs.	480	4/2/02	20'

WELL SEAL / FILTER PACK / ABANDONMENT MATERIAL

From(ft)	To(ft)	Material Description	Purpose

STATIC WATER LEVEL(ALL WELLS)

Date Measured	Depth Below Ground Surface
04/02/2002	20.00

WELL TEST DATA (ALL SECTIONS MANDATORY FOR PRODUCTION WELLS)

Date	Method	Yield(GPM)	Time Pumped (hrs & min)	Pumping Level (Ft. BGS)	Time To Recoover (Hrs & min)	Recovery
04/02/2002	Air Lift	1.00	4:00:00	500	24:00;00	480

Note that this April, 2002 version of the WC form has a space for yield, but none for pump rate. Also note that the recovery time is 24 hr, which if taken literally implies a recovery yield of 0.5 gpm, half of the driller's and MassDEP's declared value of 1.0 gpm.

Coping with the inconsistency in defining recovery level

These inconsistencies pose dilemmas when using a town-wide spreadsheet (MassDEP, 2016) to check the MassDEP WC yields against computed recovery yields from the actual well test data. Early-on in our analysis, from inspecting the spreadsheet, it became apparent that a significant number of drillers were interpreting the recovery level as the height of the column of recovered water above maximum drawdown (*Recovery Mode U* in Figure 3.1), as an alternative to the present day convention of the recovery being the recovered water level relative to BGS – the earth's surface (*Recovery Mode W*). Not knowing which might be the case for a given well test when analyzing the MassDEP (2016) database, in order to determine an optimum metric for the recovery yield, we elected to calculate the recovery yield in two ways: Method 1 assumes the driller used the depth of the recovered level relative to the surface (*Recovery Mode W* in Figure 3.1); Method 2 assumes the driller used the height of the recovered water column above maximum drawdown (*Recovery Mode U* in Figure 3.1). An alternative possibility, namely the driller using the depth of the recovered level relative to the local static water level, is not considered here, but conditions in the town should lead to yields similar to Method 1. Of the two estimates – Method 1 and Method 2 – a computer application selected the value of recovery yield closest to the MassDEP WC posted value of yield. (It is usually unclear in the MassDEP (2016) transcriptions as to the source of its posted yields.) Out of a sample of 1,200 MassDEP (2016) well test entries, approximately 14% produced better estimates of yield when the computation was based on Method 2 (i.e. cases where the MassDEP had failed to convert recovery levels to the current protocol).

Computing yields from a complete well test

It's best, of course, if data from a complete well test – drawdown *and* recovery – are available. We illustrate the results of this procedure in Table 4.3 by returning to our earlier example from 146 Tremont St. in Figure 4.2. We do this by comparing the computed drawdown yield from the original driller's WC report with the recovery yield computed using Method 1 (*Recovery Mode W*) and Method 2 (*Recovery Mode U*), and then comparing the results to the MassDEP posted yield, shown in Table 4.3. In this case, the recovery yield (2.6 gpm) from Method 2 wins out. We consider that it agrees quite well with the computed drawdown yield (2.3 gpm), where we use the pump rate posted on the original drillers WC form, and also agrees with the posted MassDEP yield.

Table 4.3. Output Yield (gpm); Compare posted and computed results.
Address: 146 Tremont St., Rehoboth. MassDEP ID# 269176. For WC reports see Figure 4.2.

Driller Posted WC Yield (gpm)	Drawdown yield (gpm)	Recovery yield; Method 1 (gpm)	Recovery yield; Method 2 (gpm)	MassDEP posted yield (gpm)
5	2.3	-0.02	2.6	3

Discussion. It is not clear in Table 4.3 (or our previous Table 4.2), whether the MassDEP has actually calculated the *yield* from the well test data and rounded the value up to 3 gpm, or simply transcribed (which is more likely) the driller's pump rate (3 gpm) into the respective "*yield*" data cell on the MassDEP WC summary report. (The latter seems to be the more standard procedure by the MassDEP.) The driller has posted a value of 5 gpm in the original WC report, which implies an upward rounding of almost 50%, or that the driller has used an alternative method for determining yield that he has not described. Summarizing the posted values and validation estimates in Table 4.3, we have driller posted WC yield = 5 gpm, computed drawdown yield = 2.3 gpm, computed recovery yield = 2.6 gpm, whereas the MassDEP posted yield = 3 gpm. The MassDEP, however, has discounted the driller's value, in this case, in favor of what we assume is the pump rate. For this particular well test, the pumping time of 9 hr is sufficiently long that, if the water level in the well has reached a steady level (i.e. equilibrium), MassDEP personnel, when transcribing the driller's WC results, might have assumed that the rate of discharge from the well (the pump rate) is approximately equal to the true yield. This leaves in question how the driller originally arrived at a yield of 5 gpm, when the declared pump rate was 3 gpm.

A town-wide reconnaissance of the consistency of well yield estimates

Our purpose here is to assess the town-wide quality of driller or MassDEP provided WC yields by determining the consistency between the latter values and values computed, where possible, from recovery parameters reported in the original MassDEP WC spreadsheet. (It is unfortunate that the MassDEP WC downloadable and searchable databases do not provide all parameters for a drawdown test. By restricting ourselves to the MassDEP electronic database, we are limited to using only the recovery phase, hence we can only compute the recovery yield.)

Procedure

Beginning with the MassDEP database of 2,039 wells, 81 of these do not have posted yields, so our analysis proceeds using 1,958 wells having reported yield.

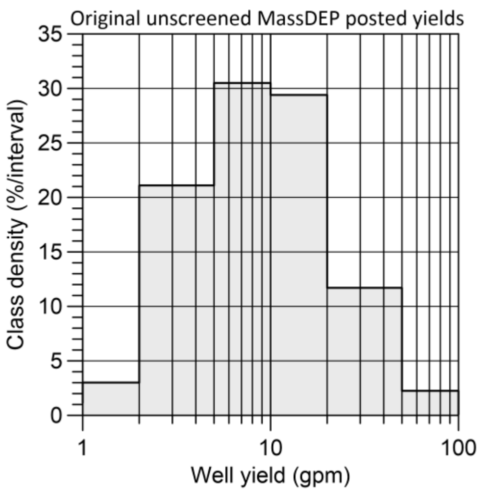


Figure 4.5. The percent concentration of posted MassDEP WC yield values within respective intervals.

Not all of these reported yields can be validated, but a distribution of their values may provide useful background for assessing groundwater potential in the town. A synoptic view of the MassDEP-supplied town-wide distribution of well yields that have not been screened for validity is shown in Figure 4.5. Clearly, approximately 60% of the WC yields appear to fall within the range of 5 to 20 gpm, with approximately 80% in the range from 2 to 20 gpm. These are the *posted* yields declared on the WC form by the driller, or eventually – perhaps amended – by the MassDEP.

Here, we want to validate the yields from these 1,958 posted values by comparing them to predicted values from associated well tests. Of the original inventory of wells (1,958), 1,735 have a posted recovery time, but this number reduces to 1,670 wells that have MassDEP reported values of both recovery time and recovery level, both of which are essential for computing the recovery yield. In other words, 17% of the WC reports reporting a value for yield provide no well test data by which these values might be confirmed.

Of the 1,735 wells, 1,161 could be located and merged among various databases but had variable quality information, reducing our inventory to 997 examples that had complete sets of all parameters. However, in lieu of a formal well test, it appears some municipalities in Massachusetts (such as Rehoboth) are willing to accept a well if, following drawdown, the water level of the well returns to 85% of its static level within 24 hours (1,440 min). This time period is much longer than the recovery time appropriate for determining most recovery yields in the town, so that our database was then culled of all recovery times longer than 1,200 min (397 WC reports), leaving 770 well reports where a MassDEP posted yield might be validated against the associated well's computed "*best*" recovery yield. In other words, only 770 out of the original 2,039 WC records for the town – 38% of the wells-of-record – have sufficient information to validate the yields posted by the driller and/or the MassDEP.

Figure 4.6 is a map of the spatial distribution of the original 770 culled, but unvalidated, MassDEP (2016) WC reported yields. The ubiquitous distribution of most wells – those having yields of 25 gpm or less – is quite evident. Generally speaking, the distribution of the higher yield bedrock wells seems more or less random and uniformly distributed over the town.

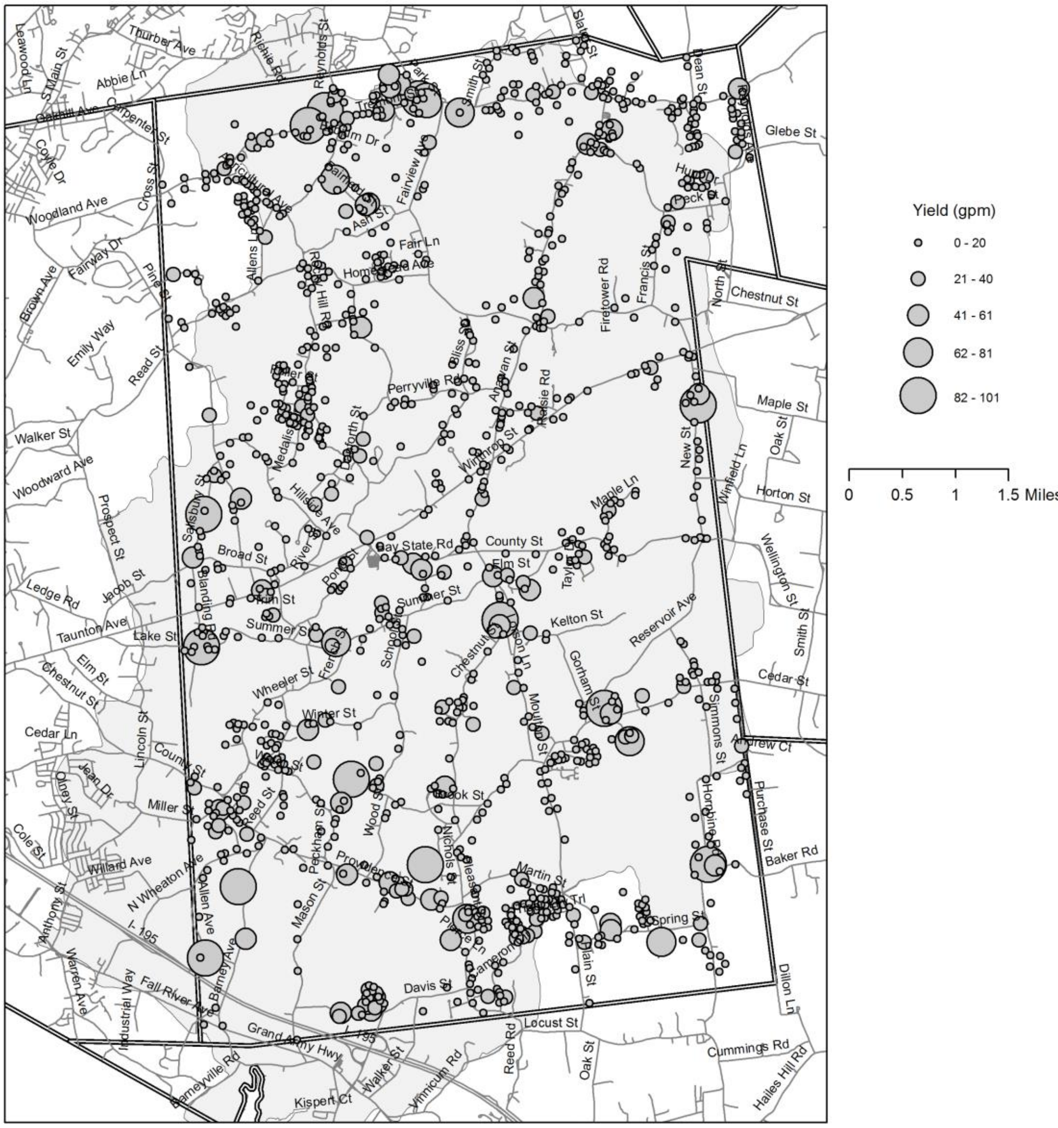


Figure 4.6. Map of MassDEP (2016) WC reported yields that can be assessed. Background grey area is the Palmer River watershed.

Compare computed recovery yields to WC posted yields

Regression of data pairs. Figure 4.7 is a scatter plot of the regression of 770 values of the "best" computed recovery yields versus the posted MassDEP WC yields. Ideally, the slope of the line should be unity (1.0), and the coefficient of determination – a typical metric for estimating the concordance of two variables – should be unity (1.0) or 100%.

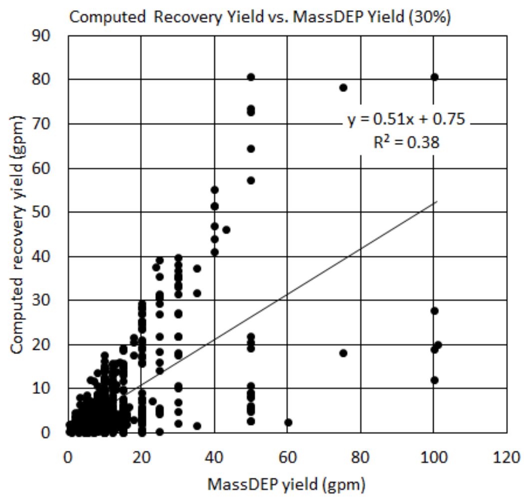


Figure 4.7. Regression of the computed recovery yield versus the WC/MassDEP posted yield.

The coefficient of determination ($R^2 \cong 0.38$) implies that the correlation between the two metrics is significant, however the slope of the regression line (0.51) implies a distributed bias such that, overall, the computed recovery yield values tend to be approximately 50% of the MassDEP posted yield, whereby ideally the slope of the line should be 1.0. Figure 4.7 provides another, stronger bias at larger posted yields. Whereas, at a posted yield of 50 gpm the mean predicted yield is 25 gpm, at a posted yield of 100 gpm, the mean predicted yield is 32 gpm. Thus, for the higher values of yield, such as needed by major users, WC reports tend to assert that yield is more than a factor of two to three greater than the corroborating recovery yield directly based on the driller's well test data. It is not clear whether this systematic inflation of WC yields is by design, by coincidence, or is an artifact of the well test procedure and analysis. However, it underscores the importance of having sufficient well test data available to validate the WC yield actually posted.

Ratio of predicted to MassDEP posted yield. The statistical deviation of the computed yield for each well from the WC posted yield can be represented as the ratio of the *computed* or *predicted* value to the MassDEP *posted* values. These 770 ratios (which ideally should have a value of unity, or 100%) have been ranked from smallest to largest, to present the cumulative distribution of error in Figure 4.8 and Table 4.4.

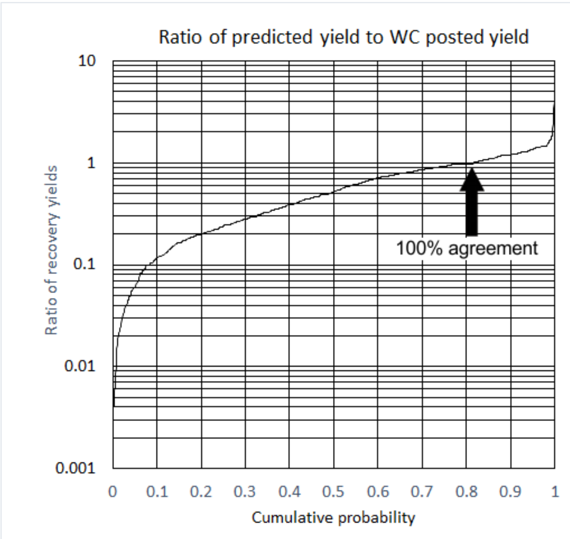


Figure 4.8. Cumulative plot of the ratio of the computed recovery yield to the posted yield values.

Table 4.4. Cumulative ratio of the computed to the posted yield values.

Quantile (%)	Ratio
5	0.06
10	0.12
25	0.24
50	0.52
75	0.92
90	1.19
95	1.36

Note that the median of cumulative percent is the ratio of 0.52 (52%), which is to say that, overall, considering all estimates – good and bad – the computed recovery yield is approximately half of the posted WC yield, consistent with the regression analysis of the previous section. The first quartile of the cumulative distribution is 0.24 (24%) and the 3rd quartile is 0.92 (92%), implying a bias, or clumping, of the center of mass of the distribution well significantly less than the ideal value of 1.0 (100% agreement) – approximately 80% of the values have ratios less than unity (computed yield smaller than posted yield), and only 20% of the values have ratios greater than unity (computed yield greater than unity). In other words, the error distribution is highly skewed, as pointed out previously with reference to the regression analysis in Figure 4.7.

Purging data pairs having large deviations. Clearly, we have to trim estimates where the deviation between the MassDEP posted yield and the computed recovery yield is beyond some bound. The smaller the deviation, the better, however the number of data pairs available for our analysis decreases proportionately. We have a total number of 770 data pairs, which by trimming samples having relative deviations greater than 50% (corresponding to a ratio of predicted to posted of between 0.5 to 1.5), leaves 378 data pairs. Trimming to a maximum of ±30% deviation (a ratio between 0.7 to 1.3) leaves 269 pairs, and trimming to ±20% maximum deviation (a ratio between 0.8 to 1.2) leaves 177 data pairs. As a middle ground between minimizing the expected deviation and having a meaningful number of data points, we elected to analyze the statistical distribution of the ±30% deviation population, which is to say that the respective computed recovery yields and the MassDEP posted yields are similar within a range of ±30% of each other.

Summary statistics for our three sample populations are given in Table 4.5, showing 6 gpm as the median of the computed "best" recovery yields compared to 10 gpm as the median of the raw MassDEP WC posted values – a bias of approximately 40% – generally reconfirming the results summarized in Figure 4.8.

Table 4.5. Summary statistics for the three sample populations.

Cumulative Quantile	MassDEP raw posted Yield	MassDEP Verifiable Yield	Predicted Best Yield (30% deviation)
5%	2.5	3	3
10%	3.5	4	3
25%	5	5	4
50%	10	10	6
75%	15	15	13
90%	30	25	27
95%	40	40	35
No. of samples:	1958	1278	268

Table Key

Cumulative Quantile: represents the percentage of the total number yields which are less than the value of the yield specified, respectively, and columns two, three and four.

MassDEP posted Yield: The value of the unscreened yield posted in the MassDEP online electronic database.

Verifiable Yield: The value of yield posted in the MassDEP electronic database that is associated with a recovery time less than 1,200 min. Not all have sufficient auxiliary well test data for direct comparison with predicted recovery yield.

Predicted Best Yield (30% deviation): The computed or predicted recovery yield that has a deviation equal to, or less than 30% of the MassDEP posted yield.

No. of samples: The number of samples for which the statistics have been calculated in the respective category.

This shift to lower values by the computed recovery yield is emphasized in Figure 4.9

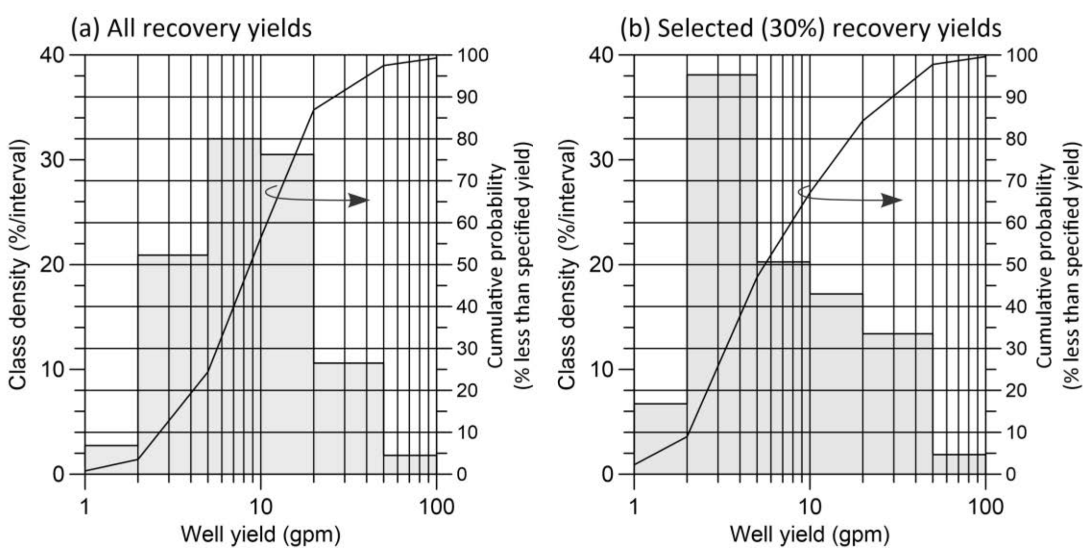


Figure 4.9. Panel (a) is the statistical distribution of 1,278 MassDEP yield values posted on the current MassDEP WC online summary reports and the MassDEP (2016) database sent to the town. Panel (b) is the distribution of the 268 computed recovery yields (±30%) based on well test data. The shift to lower yield values by the latter is noteworthy.

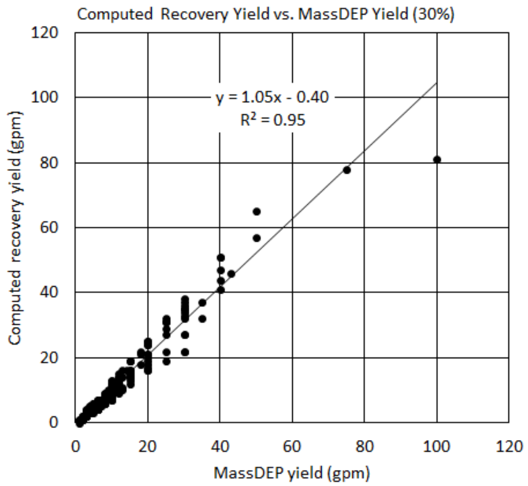


Figure 4.10. Scattergram of those computed recovery yields deviating less than or equal to 30% of the MassDEP posted yields.

Figure 4.10 is a regression analysis of the 268 data pairs whereby the computed recovery yield deviates ±30% or less from the MassDEP posted yield. Note that the coefficient of determination (R^2) is close to unity, and the slope is close to one, consistent with minimum bias.

We conclude that the analysis of these 268 data pairs serves two purposes. First, we have shown that computing a recovery yield from a driller's well test data can be an effective way to validate the posted yield on the WC report. Second, we have demonstrated that only 268 of the original 2,039 well reports (13% of the total number of available WC reports) have been adequately validated by well test recovery data.

Figure 4.11 is a map showing the computed recovery yield within a range of ±30% of the MassDEP yields. The map of these 268 wells might be compared with the previous map of the *unscreened* MassDEP yield in Figure 4.6. One's first impression is that fewer high yield wells appear in the screened dataset in Figure 4.11. A disturbing element of this analysis is the lack of wells for which high yields are validated within our ±30% deviation.

A sufficient number of examples (namely 268 validated cases) have a sufficiently small deviation that a fundamental error in how the recovery yield is computed – that is to say the basic mathematical relation – is unlikely. Rather the principal error appears to stem from 1) the data themselves, 2) problems with formatting and transcribing the data, 3) questionable procedures by the driller and/or the MassDEP in determining yield. The basic takeaways from this phase of our analysis are 1) only 13% of the MassDEP(2016) WC entries have been validated by well tests, and 2) still fewer of the posted *high yield* wells have actually been validated. The consequence poses a significant issue for planning future water supplies in the town.

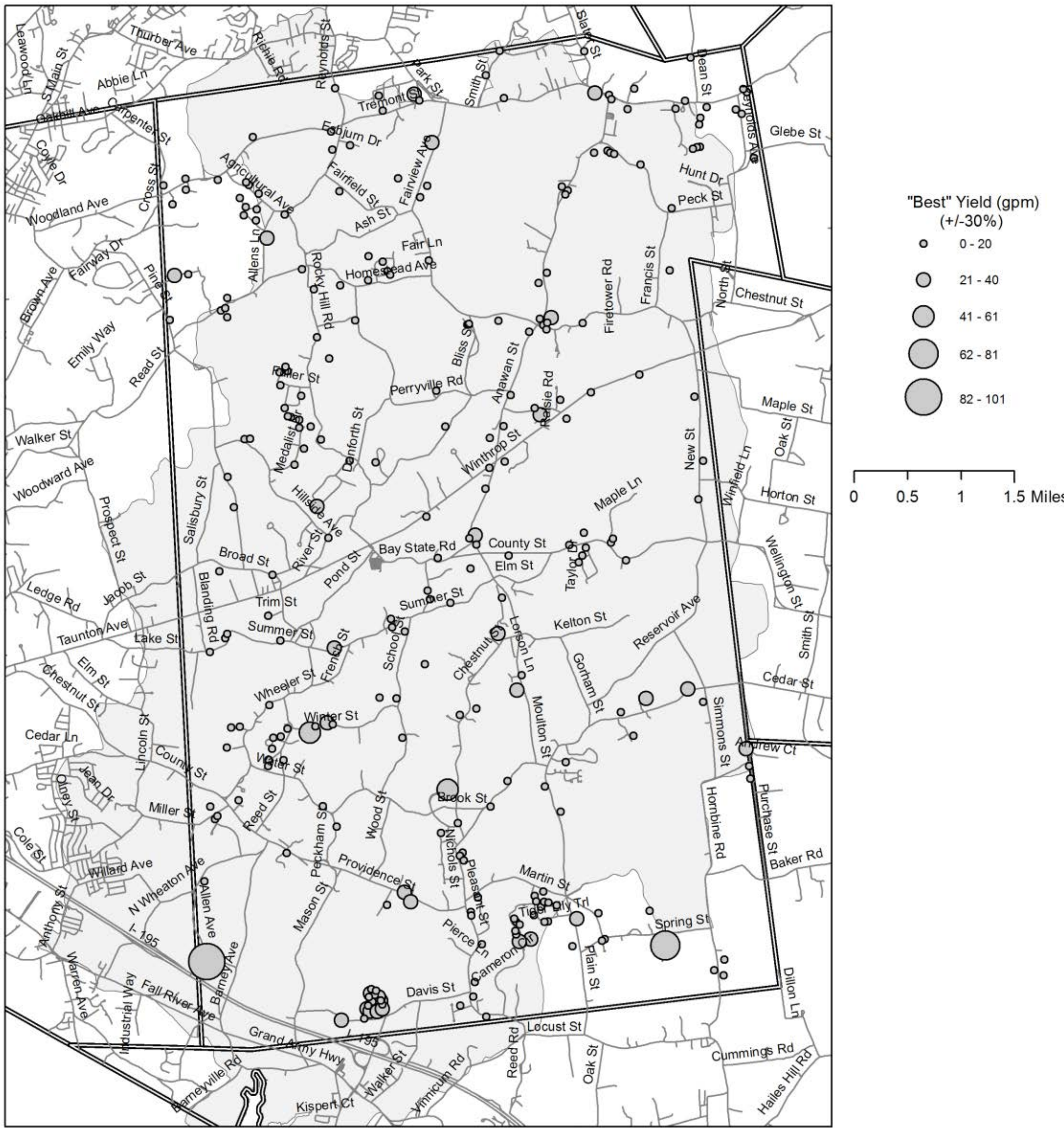


Figure 4.11. Map of Validated MassDEP (2016) WC reported yields. Background grey area is the Palmer River watershed.

We decided at this point that the MassDEP downloadable spreadsheet database has limited value for town-wide assessments of well yield. The data are incomplete, and in some cases, wrong. We felt that one needs to look more closely at the quality of each yield estimate, in particular, to identify and validate systematic patterns. This can only be done through inspecting the original in-house WC reports on file in the BOH office. While this is a monumental task for the entire town, we felt that a limited pilot study might provide insight into some of the basic problems. For one thing, we felt that there may be some advantage to including the drawdown yield to augment the recovery yield in validating the MassDEP posted yield values. For this, we need to reference the in-house WC reports at our local Board of Health. The MassDEP databases – either in spreadsheet form, or in the MassDEP WC summary report – are not suitable.

Pilot study

Purpose

In this section, we take a more detailed view of the types of problems associated with driller and MassDEP WC reports, particularly in determining well yields. Using a limited, while representative database, we compare the actual driller and MassDEP versions of selected WC reports and use this opportunity to compare all three values of yield: drawdown and recovery yield from well tests, and the yield posted on WC forms. We identify possible biases in the results and conflicts between what the driller has posted and what appears in the MassDEP reports. What and where is the source of some of these conflicts?

Compare driller to MassDEP WC reports; Examples from Tremont St.

Since we have neither the time, nor the resources to do a detailed well-by-well town record vs. MassDEP comparison for all the wells in town, we will tend to use Tremont St. as our microcosm of the entire town. However, as occasions arise, we will draw on WC reports from town-wide well reports.

Tremont St. as a microcosm of the entire town. We selected Tremont St. initially for our pilot study because it provides a continuous east-to-west profile of wells across the northern section of the town, demarking what we expected to be significant hydrogeologic elements for future planning. Well completion reports should provide such key features as static water level, depth of bedrock, and maximum depth of well. In addition, however, once we began to inspect the profile data in detail, it became clear that Tremont St. offered a cross section of the town on many different levels. In a sense, the analysis of well data from a profile along the street provides a microcosm of the development of the entire town over the last six decades.

Buildout history. Wells drilled along Tremont St. represent six recorded decades of drilling and the associated well completion reports, providing a rich cross-section of drilling methods and reporting quality over the years. Small areas of Tremont St. were developed at the same time, representing the larger subdivisions that have been built in different areas of Rehoboth. Table 4.6 shows that the percentage of houses built along Tremont St. by decade (1960s-2010s) closely mirrors the rate of development across the entire town.

Table 4.6. Compare rate of housing development in all of Rehoboth with that along Tremont St.

Town of Rehoboth, by decade:		Tremont St., by decade:	
1960s: 54	(2.7%)	1960s: 3 (2 unknown addresses)	(4.3%)
1970s: 46	(2.3%)	1970s: 0	(0%)
1980s: 279	(13.8%)	1980s: 13	(11.1%)
1990s: 807	(39.9%)	1990s: 48	(41.0%)
2000s: 752	(37.2%)	2000s: 32 (1 unknown address)	(27.8%)
2010s: 83	(4.1%)	2010s: 19	(16.2%)
Total = 2023 records (Provisionally)		Total = 115 total usable addresses	

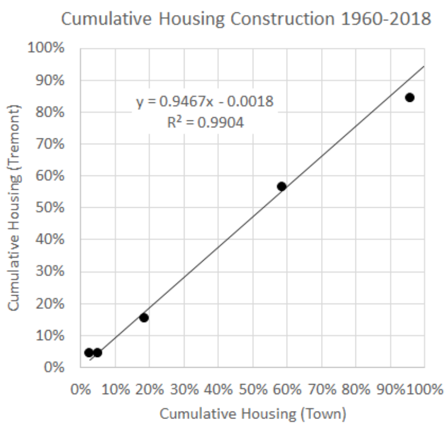


Figure 4.12.

The regression in Figure 4.12 underscores the similarity between the cumulative buildout of housing along Tremont St. and cumulative buildout for the entire town.

Missing driller WC reports. It's noteworthy that there is some element of mystery surrounding the absence of Rehoboth well completion reports for the 1960s-1980s. Using Tremont St. as an example, in the 1980s, only 15% of well completion reports that exist in the MassDEP (2016) files are also filed with the Board of Health. In the 1990s, this number increases to 88%. From there, the 2000s and 2010s are 90% and 84%, respectively. There is no obvious explanation for this lack of documentation, or why it should also extend to the state records during the 1970s. The following is a summary of the available Tremont St. WC reports (with reference to specific WC reports on file at the Rehoboth BOH).

1960s: These records exist only in the MassDEP databases [MassDEP (2016), SearchWell (2018), and EEA (2018)]. None are on file with the Rehoboth Board of Health.

1970s: Neither the MassDEP nor the Board of Health have any Tremont St. records for the 1970s. However, data from wells elsewhere are available, and the WC report for 20 Smith St. (ID 270473)[5] is a representative example of the 1970s.

1980s: There are 13 records for Tremont St., but only 2 are on file with the Board of Health. 221 Tremont St. (ID 270332) is a representative example of 1980s well completion reports, and is also an example of a very *incomplete* report.

1990s: Well drillers are required to submit copies of the well completion reports to both the MassDEP and the local boards of health. Looking at the records for Tremont St. in the 1990s, it is clear that this does not always take place. There are 48 records for Tremont St., 45 of which are Brown-supplied photocopies, 26 are found in both the MassDEP files and the BOH files, 3 are from the MassDEP files only, and 16 are in the Board of Health files only. A representative example of 1990s well completion reports is from 70 Tremont St. (ID 269679) and is also a good example of a properly completed report.

[5] Photocopy from Brown University.

2000s: 28 of 32 records are on file with the Board of Health. Three of the sheets found in Board of Health files are not on file with the MassDEP. By the year 2001, the blue well completion reports, which had been in use since the 1960s, had been replaced by a new form. However, drillers were still using blue sheets (see Glossary) until 2002 on Tremont St. In 2007, the format was revised and made recording the GPS coordinates required instead of optional. A representative example of the first-generation new well completion form is available from 550 Tremont St. (ID 134842). A representative example of the updated well completion form with required GPS coordinates is available from 336 Tremont (ID 152302).

2010s: 16 of 19 records are on file with the Board of Health. Five of the well completion reports are only in the Board of Health files, not with the MassDEP. In 2010, drillers began using electronic forms for the well completion reports. At this time, the MassDEP WC form transitioned from exclusively entering the pump rate to exclusively entering the yield, which in most cases seems to be simply the pump rate. One driller used the most recent hand-written sheet as late as 2017 on Tremont St. For a representative example of the electronic well completion report, which is the most current version of the form, see: 224 Tremont St. (ID 652499). Regarding the electronic forms: of the 12 used on Tremont St., 11 contained all of the necessary information. The single form that is missing information lacked the overburden lithology. One form was hand-written on the first page.

Summarizing the quality of WC reports for Tremont St.

For a valid well test, one would expect that the computed drawdown yield, the computed recovery yield and the MassDEP posted yield should be in relative agreement. However, this is often not the case. Of 115 addresses on Tremont St., there are only the seven (7) instances in Table 4.7 where the three values of yield lie within a range of ±30% of each other, which is only 6% of the well tests.

Table 4.7. Compare selected examples of yields from well tests with MassDEP posted values on WC summary forms. Values agree within a range of ±30%.

WELL ID	Pump rate	MassDEP WC yield	Recovery yield	Drawdown yield
269515	3	3	3.0	2.2
269176	3	3	2.6	2.3
269488	3	3	3.1	2.3
600243	5	3.5	3.5	3.6
269798	5	5	4.2	4.2
269971	6	6	4.6	5.3
269295	6	6	4.6	5.6

Relative to the MassDEP *posted* yield, of these 7 values, sometimes the *drawdown* yield agrees better and sometimes the *recovery* yield. The following section(s) describe possible reasons for such a poor validation rate.

Reasons for inadequate well test data

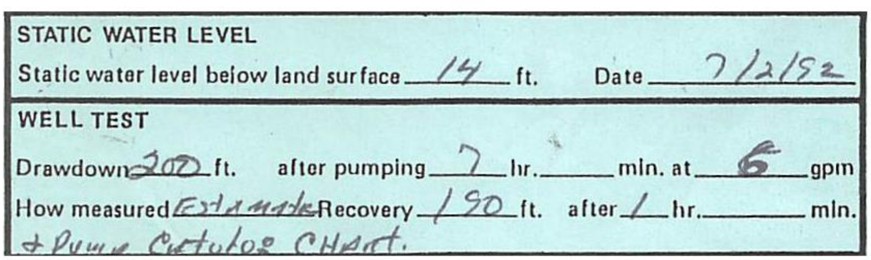
In this section, we discuss some of the reasons for such low success in using well test parameters to validate MassDEP posted yields. We begin with problems with the MassDEP transcribing the data in driller WC reports to the MassDEP database.

Inconsistencies with MassDEP transcribing data from driller WC reports

In reviewing driller WC reports from Tremont St., we have found occasions when the information appearing in the MassDEP (2016) database[6] has not been transcribed *completely* from the original driller WC reports, nor in some cases, *correctly*. The most striking example of this can be found in the columns labeled WT_DRAWDOWN and WT_RECOVERY. These are the columns that contain the depth of drawdown and level of recovery during the well test. The current convention is to make both measurements as depth BGS (below the ground surface), but upon viewing hundreds of well completion reports for the town from past decades, this has not always been the case. As far as the MassDEP (2016) spreadsheet is concerned, much of these data have been converted (presumably in the MassDEP offices) to reflect the current standard. However, there are glaring exceptions to this statement.

During the time period that the drillers were using the blue sheets (1960s until 2001), the convention appears to have been to measure *drawdown* from the ground surface (BGS) and *recovery* as the height of the water column (See Figure 3.1 in Part 3: Drawdown Mode *Y*, and Recovery Mode *U*). Some of these values (although not all) were subsequently converted to reflect measurements relative to BGS (Recovery Mode *W*) by the MassDEP. The MassDEP WC summary report (EEA(2018)) for the well at 5 Tremont St. (ID 269971) is another example of the well test parameters from a driller's WC report *having been converted* by the MassDEP (Figure 4.13).

Figure 4.13. 5 Tremont St. (ID 269971). Conversion of original driller's WC report by the MassDEP.


STATIC WATER LEVEL

Static water level below land surface 14 ft. Date 7/2/92

WELL TEST

Drawdown 200 ft. after pumping 7 hr. ___ min. at 6 gpm

How measured Estimate Recovery 190 ft. after 1 hr. ___ min.

+ Pump Catalog CHART.

WELL SEAL / FILTER PACK / ABANDONMENT MATERIAL

From(ft)	To(ft)	Material Description	Purpose

STATIC WATER LEVEL(ALL WELLS)

Date Measured	Depth Below Ground Surface
07/02/1992	14.00

WELL TEST DATA (ALL SECTIONS MANDATORY FOR PRODUCTION WELLS)

Date	Method	Yield(GPM)	Time Pumped (hrs & min)	Pumping Level (Ft. BGS)	Time To Recoover (Hrs & min)	Recovery
07/02/1992	Constant Rate Pump	6.00	7:00	200	1:00	14

Note that for this and many examples, there are often judgments involved by the MassDEP regarding what is meant by the drawdown and recovery levels. One might ask, on what basis does the MassDEP assume that the drawdown is relative to BGS for the WC report in the above Figure 4.13? Such an

[6] MassDEP (2016), refers to information contained in the spreadsheet provided to the town Water Commission by the MassDEP in 2016.

assumption is usually the case, by convention, but if this were the case for Figure 4.13, and the recovery represents the height of the recovered water column, then the water level in the well would have recovered to a final level of 10 feet, which is four feet above the original static water level (SWL) of 14 feet, which is physically unlikely. We will return to this example later, but, based on our inspection of hundreds of WC reports from Tremont St. and elsewhere in town, we feel the MassDEP tends to assume that the driller has recorded the original drawdown, 200 feet, as relative to grade (BGS). If so, we conclude that we are expected to discount the four-foot discrepancy as rounding off.

In the case of the records that *were* converted by the MassDEP, approximately 10 percent of these values were not converted faithfully to reflect the information on the well completion report. (See the following Figure 4.14.)

Figure 4.14. 406 Tremont St. (ID 269515). Example of driller records that *were not converted faithfully* to reflect the information on the well completion report.

STATIC WATER LEVEL (all wells)
Static water level below land surface 14' ft. Date 8/4/94

WELL TEST (production wells)
Drawdown 260 ft. after pumping 8 hr. ___ min. at 3 gpm
How measured Pump Chart Recovery 250 ft. after 2 hr. ___ min.

WELL SEAL / FILTER PACK / ABANDONMENT MATERIAL

From(ft)	To(ft)	Material Description	Purpose

STATIC WATER LEVEL(ALL WELLS)

Date Measured	Depth Below Ground Surface
08/04/1994	14.00

WELL TEST DATA (ALL SECTIONS MANDATORY FOR PRODUCTION WELLS)

Date	Method	Yield(GPM)	Time Pumped (hrs & min)	Pumping Level (Ft. BGS)	Time To Recoover (Hrs & min)	Recovery
08/04/1994	Constant Rate Pump	3.00	8:00	260	2:00	14

Contradictions in conversions by the MassDEP. In cases where the drawdown and recovery are the same on the well completion reports, it seems the MassDEP was sometimes conflicted on whether to adjust/convert these values to reflect a measurement from the static water level (as in Figure 4.15), or at times not doing such an adjustment (as in Figure 4.16).

Figure 4.15. 196 Tremont St.; MassDEP ID 269488. Example of converting values to reflect a measurement from the static water level.

STATIC WATER LEVEL (all wells)
Static water level below land surface 12' ft. Date 10/12/94

WELL TEST (production wells)
Drawdown 280 ft. after pumping 12 hr. ___ min. at 3 gpm
How measured Pump Chart Recovery 280 ft. after 2 hr. 15 min.

WELL SEAL / FILTER PACK / ABANDONMENT MATERIAL

From(ft)	To(ft)	Material Description	Purpose

STATIC WATER LEVEL(ALL WELLS)

Date Measured	Depth Below Ground Surface
10/12/1994	12.00

WELL TEST DATA (ALL SECTIONS MANDATORY FOR PRODUCTION WELLS)

Date	Method	Yield(GPM)	Time Pumped (hrs & min)	Pumping Level (Ft. BGS)	Time To Recoover (Hrs & min)	Recovery
10/12/1994	Constant Rate Pump	3.00	10:00	292	2:15	12

(***A counterexample follows.***)

Figure 4.16. 417 Tremont St. (ID 269648). An example where the driller's values were *not* adjusted to current (2018) standards.

STATIC WATER LEVEL (all wells)
Static water level below land surface 10 ft. Date 1/14/94

WELL TEST (production wells)
Drawdown 10 ft. after pumping 4 hr. ____ min. at 15 gpm
How measured Pump Recovery 10 ft. after ____ hr. 5 min.

WELL SEAL / FILTER PACK / ABANDONMENT MATERIAL

From(ft)	To(ft)	Material Description	Purpose

STATIC WATER LEVEL(ALL WELLS)

Date Measured	Depth Below Ground Surface
01/14/1994	10.00

WELL TEST DATA (ALL SECTIONS MANDATORY FOR PRODUCTION WELLS)

Date	Method	Yield(GPM)	Time Pumped (hrs & min)	Pumping Level (Ft. BGS)	Time To Recoover (Hrs & min)	Recovery
01/14/1994	Constant Rate Pump	15.00	4:00	10	00:05	10

(Other information: 30' BR Depth; 130' WC Depth; 10' SWL; 40; Casing; 10' into BR.)

To be consistent with current protocols, *drawdown* should be relative to BGS or local grade, not, apparently, relative to SWL, as implied here. Recovery should also be reported relative to BGS, which it seems to be, in this case. Thus, various conventions are used here that are not concordant with current MassDEP recommendations. Recasting driller results in such a manner is a direct contravention to our previous example – Figure 4.15 – where MassDEP converted WC values for both drawdown and recovery to the currently recommended BGS reference.

A possible work-around to address the contradicting conventions for reporting "recovery". It appears that some drillers faced with the dilemma of which definition of "recovery" is appropriate on a WC form take a more pragmatic approach, as in the following example.

Figure 4.17. 8 Tremont St. (ID 270462). The posted recovery is one half of the posted drawdown, and MassDEP did not convert the respective drawdown and recovery data.

STATIC WATER LEVEL
Feet below land surface 12
Date measured 7/31/81

GRAVEL PACK WELL
Yes ☐ No ☒

WATER QUALITY TESTS MADE
Chemical ☒ Biological ☒

Water-bearing Materials
Sand: fine ☐ medium ☐ coarse ☐
Gravel: fine ☐ medium ☐ coarse ☐
Screen:
Slot # ____ length ____ from ____ to ____
Split Screen *(or 2nd screen)*
Slot # ____ length ____ from ____ to ____
Depth To Bedrock ____

PUMP TEST
Drawdown 360 feet after pumping 0 days 25 hours at 4 GPM.
How measured A/K Recovery 180 feet after 1 hours.

WELL SEAL / FILTER PACK / ABANDONMENT MATERIAL

From(ft)	To(ft)	Material Description	Purpose

STATIC WATER LEVEL(ALL WELLS)

Date Measured	Depth Below Ground Surface
07/31/1981	12.00

WELL TEST DATA (ALL SECTIONS MANDATORY FOR PRODUCTION WELLS)

Date	Method	Yield(GPM)	Time Pumped (hrs & min)	Pumping Level (Ft. BGS)	Time To Recoover (Hrs & min)	Recovery
07/31/1981	Air Lift	4.00	00:15	360	1:00	180

Comments: It seems significant that the level of recovery (180 feet) is one half the maximum drawdown (360 feet). In this case, the computation of the recovery yield in Table 4.8 does not depend on which definition of recovery – Mode 1 or Mode 2 – is assumed to apply. We feel this approach appears to be a clever workaround by the driller, since either definition of recovery level applies. Hence, computing the recovery yield by Method 1 produces the same value as computing the recovery yield by Method 2.

Table 4.8. Well address: 8 Tremont St. MassDEP ID # 270462.

a) Input Well Test Data (User supplied)						
Static water level (ft, BGS)	Discharge pump rate (gpm)	Pump time (min)	WT Drawdown (ft, BGS)	WT Recovery level (ft, BGS)	WT Time for recovery (min)	WC Yield (gpm)
12	4	15	360	180	60	4

b) Output Yield (gpm); Computed results			
WC Yield (gpm)	Drawdown yield (gpm)	Recovery yield; Method 1 (gpm)	Recovery yield; Method 2 (gpm)
4	-30.10	4.41	4.41

(***Note***: The rather surrealistic value of drawdown yield for this case (–30 gpm) is discussed in the following section.)

Reasons for inconsistencies in reporting <u>drawdown yield</u>

Continuing with the example in Figure 4.17 for Well ID# 270462 at 8 Tremont St., the results in Table 4.8 do not work out so well for the *drawdown yield* (computed here as *minus* 30.10 gpm). It appears that the MassDEP office transcribed the driller's value of *pump rate* of 4 gpm for the *yield*, which is usually ill-advised, and, in this case – for a reported pumping time of 15 min – computes to a negative

(–30.10 gpm) drawdown yield, which is physically impossible. The reason for such a non-physical result is a consequence of the fact that the recorded pump time (15 min) is not sufficient to evacuate the original water column stored in the well and significantly tap into the production of water from the aquifer.

Drawdown is 360 feet after pumping 0.25 hours (15 minutes) at 4 gpm. These numbers pose an immediate inconsistency, since pumping for 0.25 hours at 4 gpm will expel 60 gallons (15 minutes x 4 gallons/minute = 60 gallons). Clearly, it will take much longer to empty a 360-foot-high column of water. Remembering that one foot of pipe is 1.47 gallons, the 360-foot drawdown height would have a volume of 529 gallons. 529 gallons/4 gpm = 132 minutes. It would take more than 2 hours to empty even the initial column of water in the well bore at 4 gpm. In this particular instance, the well test method is described as "*Air*," which could mean either "*air lift*" or "*air blow*". Although not documented in the WC report, either of these methods might use air pressure to clear the water column, and the flow rate or yield could be measured once the well has reached equilibrium. Consequently, the 15 minutes measured in this example could be 15 minutes at equilibrium. However, there is no evidence of this indicated on the well completion report, and it should not be assumed unless explicitly described in the driller's notes.

To summarize this example, at a pump rate of 4 gpm for 15 min, a total volume of 60 gal of water will be discharged from the well – the equivalent of 41 ft of stored water in the well, which is not even close to the 360 ft of drawdown that was recorded. The reader will recall the following rule-of-thumb from Part 3 of this report: To assume – even approximately – that yield is approximately equal to pump rate, the drawdown pump time needs to ensure that significantly more water has been pumped from the aquifer than originally stored in the static water column of the well bore, ***preferably by a factor of five or more***.

The well report MassDEP ID # 270462 for 8 Tremont St., Rehoboth, is only one of a number of original driller WC reports containing inconsistent well test metrics that are then promulgated into inconsistent postings by the MassDEP.

Reasons for inconsistencies in reporting recovery yield

An estimate of yield can be calculated from well test data on the MassDEP (2016) spreadsheet using the height of the recovered water column and its associated time to recover. Both of the latter are reported in the WC report, and as we have described in Part 3, can be used to determine *recovery yield*. However, we found that most of such estimates of *recovery yield* are much lower than the posted yields on the WC reports. One explanation for this involves the procedure used by the respective driller to determine the length of recovery time that is recorded on the well completion report. If a driller, as a matter of habit, checks the recovery after 4 hours and sees that it is a full recovery, this is often the time entered on the well completion report – it is seldom the precise length of time for recovery to some assigned water level. For example, if the recovery time recorded on the sheet is 4 hours, but the actual time to full recovery is 2 hours, the recovery rate, hence the recovery yield, will appear to be half of what it actually is. A much better practice would be to record the actual water level in the well at specific times throughout the recovery sequence.

Not using a true recovery time could lead to the type of systematic bias we reported above. This is illustrated in a simple way. Based on the reported yield and the drawdown depth (measured as column height), it is possible to calculate a ***predicted recovery time***. Knowing that the diameter of the well bore is 6", the volume of the length of one foot of pipe is 1.47 gallons. Therefore, multiplying the drawdown in feet by 1.47 gallons/foot gives the volume of the water column in gallons that needs to be replaced by the recovery. The yield is the rate at which this recovery takes place, so multiplying the volume of the recovered column by the yield (in gpm) gives the time in which recovery should have taken place, using the form

$$\textit{Predicted recovery time} = (\textit{Height of recovered column} \times 1.47)/(\textit{Posted yield}) \qquad (4.1)$$

Along Tremont St., there are 75 well completion reports with sufficient information to make this calculation. However, 10 of those reports include a 24-hour recovery period, and one uses a 21-hour recovery; these 11 records were dropped from the analysis, leaving a subtotal of 64 wells having sufficient well test data to validate the posted value of yield. Based on these 64 records, 28% (18 out of 64) reported a posted recovery time that was within ±20% of the predicted recovery time based on relation (4.1). This is consistent with the computed recovery yield being in accord with the WC posted yield for these 18 cases. An example of when the *predicted* recovery time from (4.1) is almost identical to *posted* recovery time is 509 Tremont St. (ID 600243), summarized below in Table 4.9.

Table 4.9. Well test parameters for Well ID: 600243; 509 Tremont St.

WC date: 30 Sept. 2010	Pump rate: 3.5 gpm	WC recovery time: 95 min
Well test method: CR*	Pump time: 240 min (4 hr)	MassDEP Yield: 3.5 gpm
SWL: 25 ft	Drawdown: 250 ft	Computed DD Yield: 2.1 gpm
Bedrock depth: Unknown	Recovery depth: 25 ft	Computed recovery yield: 3.48 gpm
Total depth: 305 ft	Height of drawdown column: 225 ft	

*Constant rate pump

From this table, we can compute that the predicted recovery time is 94.5 min [(225 ft × 1.47 gal/ft)/3.5 gpm]. The posted recovery time (recorded by the driller) was 95 minutes, thus a 99.5% agreement between the two recovery times. ***In short, the recovery yield is a valid parameter, provided the procedure is executed properly.***

However, approximately half of the WC reports along Tremont St. have posted recovery times that differ by more than ±50% of the predicted recovery time. Of the WC reports that were useful for Tremont St., almost 80% report recovery times that are *longer* than the predicted recovery time using (4.1). An example of such a conflict between predicted recovery time and posted recovery time is the WC report from 460 Tremont St. (ID 270315) summarized in the following Table 4.10.

Table 4.10. Well test parameters for Well ID: 270315; Address: 460 Tremont St

WC date: 19 March 1987	Pump rate: 100 gpm	Recovery time: 15 min
Well test method: Air lift	Pump time: 15 min	MassDEP Yield: 100 gpm
SWL: 20 ft	Drawdown: 165 ft	DD Yield: 86 gpm
Bedrock depth: 40 ft	Recovery depth: 20 ft	Recovery yield: 14 gpm
Total depth: 165 ft	Height of drawdown column: 145 ft	

Using the well test information recorded by the driller (a 145 foot recovery in 15 minutes), the recovery yield would appear to be 14 gpm as opposed to the posted value of 100 gpm. This underscores a significant inconsistency between the posted yield of 100 gpm and the recovery yield computed from actual data recorded during the well test. This inconsistency is explained by noting that the *predicted* recovery time from relation (4.1) is 2 minutes [(145 ft × 1.47 gal/ft)/100 gpm], whereas the *posted* recovery time (as recorded by the driller) was 15 minutes. This implies that the predicted recovery time is only on the order of 14% of the posted recovery time.

What is the actual case?

Is it a yield of 14 gpm or a yield of 100 gpm?

An unsettling alternative is that the driller may have inflated the actual measured yield. This is unlikely, since referring to the original well test data, one can compute a *drawdown* yield of 86 gpm. It thus appears that any inflation of the posted yield may be slight, although documentation of the procedure for using air lift to measure a pump rate of 100 gpm is not given. The lesson is that one should be – needs to be – very clear on the provenance of WC reported metrics, reinforcing the assertion that well drillers need to employ proper protocols to accurately report well test data.

Example of a case where drawdown yield and recovery yield agree

For an alternative well test example, the following reference to 5 Tremont St. (Well ID 269971, Figure 4.18) is a good example. The well completion report reads: Drawdown 200 feet after pumping 7 hours at 6 gpm. The elevation of the drawdown water column in the well is 186 ft, which the driller appears to have rounded up to 190 ft. This corresponds to a water volume of 190 ft x 1.47 gal/ft = 279 gallons. With a pump rate of 6 gpm, it would take 47 minutes to clear the column of all 279 gallons (279 gallons / 6 gallons/minute = 46.6 minutes). This is a much more realistic and trustworthy well test because 7 hr (420 min) is long enough for the initial water column to be emptied and for discharge from the aquifer to the well to approach equilibrium.

Figure 4.18. 5 Tremont St. (ID 269971). Example well test parameters.

STATIC WATER LEVEL

Static water level below land surface 14 ft. Date 7/2/92

WELL TEST

Drawdown 200 ft. after pumping 7 hr. ____ min. at 6 gpm

How measured Estimate Recovery 190 ft. after 1 hr. ____ min.

+ Pump Catalog Chart.

WELL SEAL / FILTER PACK / ABANDONMENT MATERIAL

From(ft)	To(ft)	Material Description	Purpose

STATIC WATER LEVEL(ALL WELLS)

Date Measured	Depth Below Ground Surface
07/02/1992	14.00

WELL TEST DATA (ALL SECTIONS MANDATORY FOR PRODUCTION WELLS)

Date	Method	Yield(GPM)	Time Pumped (hrs & min)	Pumping Level (Ft. BGS)	Time To Recoover (Hrs & min)	Recovery
07/02/1992	Constant Rate Pump	6.00	7:00	200	1:00	14

Computational details are given below in Table 4.11.

Table 4.11. Computational details on well test at 5 Tremont St.; Well # 136899

Input Well Test Data (User supplied)						
Static water level (ft, BGS)	Discharge pumping rate (gpm)	Pumping time (min)	WT Drawdown (ft, BGS)	WT Recovery level (ft, BGS)	WT Time for recovery (min)	MassDEP WC Yield (gpm)
14	6	420	200	14 (round to 10)	60	6

Output Yield (gpm); Computed results (gpm)			
MassDEP WC Yield	Drawdown yield	Recovery yield; Method 1	Recovery yield; Method 2
6	5.4	4.7	0.34

The predicted recovery time using the MassDEP posted yield of 6 gpm and recovery column of 190 ft is 46.6 min, somewhat less than the 60 min recorded by the driller that led to the computed drawdown yield of 4.7 gpm. Thus, it seems that if the true production yield is the 6 gpm posted by the driller, then the drawdown time was too short, and the time at which recovery was recorded by the driller was too long.

MassDEP recommends a minimum of four hours for the drawdown portion of a pump test. However, for wells along Tremont St., 29% of the drillers (33 out of 115) have done the test for less than the specified four hours. In recent years (following the introduction of electronic well completion reports) 33% (4 out of 12) did not employ the mandated minimum time.

As mentioned in reference to Figure 4.13, the above Figure 4.18 for 5 Tremont St. is also an example of the type of transcription that MassDEP sometimes applies to data recorded under a different format. In this case, the driller's WC report shows a recovery of 190 ft, and the MassDEP WC summary report shows a recovery of 14 ft. There is an implied inconsistency between the driller's declared SWL depth of 14 ft, compared to the 10 ft difference between a total drawdown of 200 ft and a recovery of 190 ft. The disparity of four feet is unaccounted for, except to shrug it off as rounding off by one or the other parties.

Overview of the quality of drawdown yield tests for Tremont St. Out of a total of 115 wells on Tremont St., 56 have sufficient well test data to allow a comparison of computed drawdown yield with MassDEP posted yield.

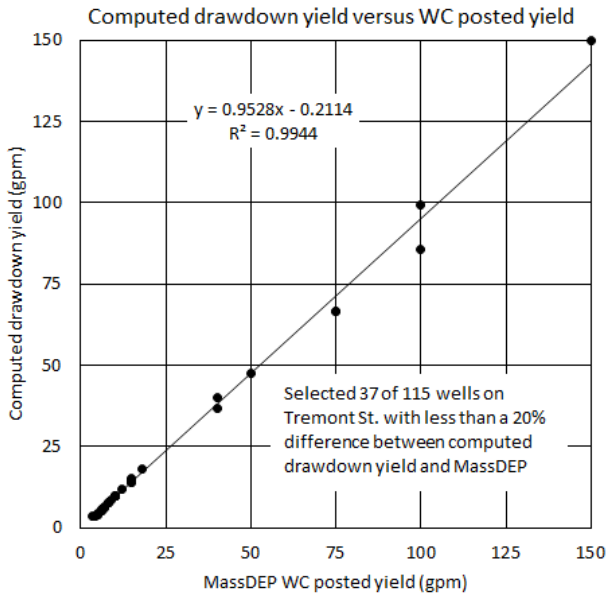


Figure 4.19. Showing the agreement between computed drawdown yield and MassDEP posted yield for a similarity of ±20%.

In other words, only 49% of the wells along Tremont St. have sufficiently complete WC reports that permit validation of the posted yield with drawdown well test results.

Figure 4.19 shows 37 selected examples of 115 wells (32% of the total) on Tremont St. with less than a ±20% difference between computed drawdown yield and MassDEP posted yield. The purpose of this figure is to emphasize that the drawdown yield is, indeed, a reliable indicator of the operational production of a well, *providing proper procedures are followed*.

Figure 4.20 compares all available computed drawdown yields and MassDEP posted yields for Tremont St. Of 56 WC records having a MassDEP posted yield able to be checked with computed drawdown well test data, seven (7) computed drawdown yields were less than zero (i.e. negative yields).

Ninety-two percent (92%) have negative deviations implying either a bias of computed drawdown yields to lower values, or the MassDEP posted yields to higher than valid values. Approximately 30% have deviations of more than 20% between the computed drawdown yield and the MassDEP posted yield.

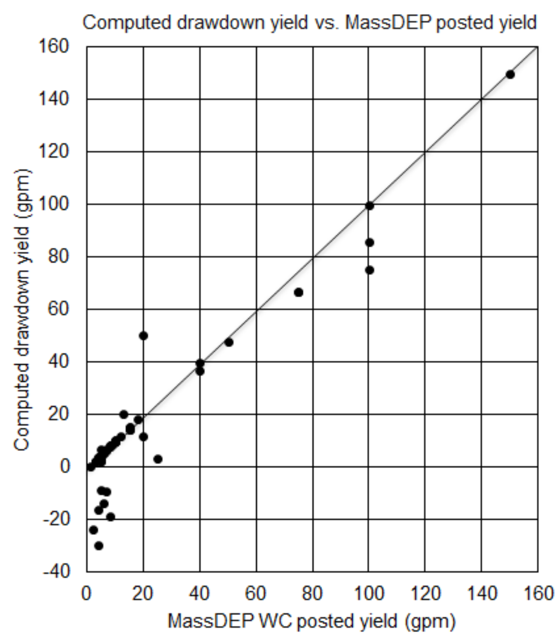


Figure 4.20. Compare *all* available computed drawdown yields and MassDEP posted yields for Tremont St.

Out of 56 pairs of posted yields and DD yields, three (3) MassDEP posted values differed from the pump rate. Of those three examples, the posted yield was closer to the computed drawdown yield than to the pump rate.

Who is doing the drilling and how self-consistent are the reports?

On Tremont St. (as a representative microcosm of the town), 10 drilling firms drilled 85% of all recorded wells drilled between 1963 and 2017. Eight other firms drilled 11 wells, and 5 wells do not have driller information. Of the 11 wells drilled by other firms, 2 records are incomplete and 3 have a similarity of $\pm 20\%$ between projected and actual recovery time. Table 4.12 summarizes the main body of work by the 10 principal well drillers on Tremont St.

Table 4.12. Summarizing WC results by 10 principal drillers on Tremont St.
A&W Artesian Well Company 10 (5 incomplete, 2 @ $\pm 20\%$)
Ace Wells and Pumps or Ace Drilling 10 (5 incomplete, 2 @ $\pm 20\%$)
All About H2O 8 (2 incomplete, all 24 hour recovery)
Cumberland Well Co. 3 (1 incomplete)
Hadrose Well Drilling 7 (4 incomplete)
Jenson Well Drilling 33 (3 incomplete, 7 @ $\pm 20\%$)
Numa Drilling 12 (5 incomplete, 4 additional with 24 hr recovery, 1 @ $\pm 20\%$)
Roy Jaswell and Son 8 (3 incomplete, 2 @ $\pm 20\%$)
Thom's Well and Pump 5 (5 incomplete, all 24 hour recovery)
Water Well Systems 3 (1 @ $\pm 20\%$)
Total: 99 wells (out of 115)

On a town-wide basis, Jenson Well Drilling Corp. drilled 595 of 2023 or 29.4% of all wells in Rehoboth and 28.7% of Tremont St. wells.

Precision of well test validation. Of the Jenson-drilled wells on Tremont St., 23.3% (7 out of 30) have a predicted recovery yield [according to (4.1)] that is within $\pm 20\%$ of the recorded yield. All of the other drillers combined (excluding Jenson) are responsible for a total of 45 wells with calculable recovery yields, of which 24.4% (11 of 45) have a predicted drawdown yield that is within $\pm 20\%$ of the posted yield on the well completion report. It is noteworthy that the five instances where all three values of yield – the WC reported yield, the computed drawdown yield, and the computed recovery yield – are consistent with one another (within our prescribed $\pm 20\%$ similarity) are wells having yields producing less than 4 gpm. If this tendency is validated, the reason(s) that lower yields are better estimated needs further study.

Complete versus incomplete records. Only 75 of the 115 records on Tremont St. have enough well test information to compute yield. That means that 34.8% of the records are either incomplete or the driller used a 24 hour recovery period. Jenson, on the other hand, had 30 of 33 (90.9%) complete records. Only one driller, Water Well Systems, has a better record of completion, but they only drilled three wells along Tremont St., so the sample size is statistically inadequate for evaluation. Only one of the three wells met the $\pm 20\%$ similarity cutoff.

General Overview

Inconsistent quality of WC reports

General well data. Standard procedures are unclear, poorly defined, mis-reported or ill-enforced. Certain data may simply not be entered on the original forms or not carried over through the transcription process to the MassDEP archives. From a sample of 744 driller WC reports that we compared to the SearchWell (2016) database, there were 54 instances where a value in the Total Depth, Depth to Bedrock, or Static Water Level fields was either missing or incorrect. In addition, of the three dates typically shown on previous WC reports and by MassDEP (2016) – completion of drilling, date of well test, and date of filing – the only date that appears on the more recent digital WC form is the date of the well test, which is rarely the same as the date that the well was drilled or when water quality was tested. Also missing are the name of the property owner and the driller/drilling company. This contradicts the recommendation of MassDEP (Pierce, 1998) that if a property owner were to have questions about their well or needed information concerning their well, they should contact the well driller directly. Since the well driller is not identified on the new format of the digital WC report, this possibility is precluded.

Documenting the well test. If the MassDEP expected that the past standard was to measure drawdown relative to BGS and recovery from the base of the column (i.e., maximum drawdown depth) to the top (i.e., level of recovery), it seems that the in-house MassDEP conversions should be more uniform and consistent. Also, there is no notation of this having, or not having, taken place for respective well reports, so anyone currently using the database is expected to trust the yield information to be accurate (or at least faithful to the well completion report), when frequently this is not the case.

Rounding off

After inspecting the combined data from the wells along Tremont St., certain patterns emerge, one being the tendency of drillers and the MassDEP to round off posted yields in WC reports. Yield values appear to be rounded to the nearest whole number if the yield is 15 gpm or less. If the yield is more than 15 gpm, the number seems to be generally rounded to a multiple of 10, with the exception of 25 and 75 gpm. Thus, even if proper procedures were followed, and a complete inventory of well test metrics were recorded, values of reported yields may not be as precise as needed, or expected, by the well's user. One matter contributing to the inflation of posted yield values over actual operational yield values is the MassDEP election to employ *pump rate* as a proxy for the *actual* well yield, which is automatically self-inflating. The true yield is invariably ***less*** than the pump rate, and for the cases where it is reported as being ***greater than*** the pump rate there needs to be further clarification of the test procedure. It is physically impossible to measure a yield that is of higher value than the maximum discharge.

Confusing well yield with pump rate

A specific point of confusion between the driller's WC "blue sheets" (circa 1960 to early 2000s; see Glossary) and the MassDEP version of transcribed WC information concerns yield and pump rate. On the previously used blue sheets – that account for approximately 60% of the town's historic inventory of well records – there were spaces to record pump rate, duration of pumping and maximum drawdown. These three metrics are sufficient to *compute* the yield. However, such a calculation seems to have been at the driller's discretion, because there was no field that was explicitly called "yield" on the blue sheets. On the other hand, the MassDEP transcribed well reports appearing in MassDEP (2016), SearchWell (2018) or EEA (2018) databases list a category for "yield" but no pump rate. In fact, it appears that the MassDEP transcriptions simply substitute "pump rate" for "yield".

As reported in Part 3, pumping on a well at a fixed rate is typically drawing water from two sources: water initially stored in the well bore and water that is drawn from the aquifer surrounding the well. The latter is what is properly referred to as "*well yield*". In the WC reports we have inspected, it is the exception, rather than the rule, that a well test is described in the MassDEP databases in such a way to separate pumping rate into discharge of the water initially stored in the well itself and the discharge of "new" water drawn from the aquifer.

This is confusing and misleading. For example, using *x, y,* and *z* to represent numerical values, respectively, for drawdown (in feet), drawdown time (discharge or pumping time in minutes), and pumping rate (in gallons per minute) of the respective quantities, the sheet should provide information in the sense that: "drawdown is *x* ft. after pumping for *y* length of time at *z* gpm." When read in this manner, the *z* value is the rate at which both stored water and water from the aquifer is pumped from the well. However, in the on-line MassDEP databases, this value appears in a column labeled YIELD. Without additional information on the procedure specifically used for this particular well test, the conclusion cannot be drawn that pump rate equals yield (see Part 3).

Conclusions

Completeness and accuracy are two separate, yet equally important, factors when it comes to the well completion reports. In order to be able to verify the information on the reports, it is essential to have all of the drawdown and recovery information, including the pump rate. With a complete set of well test values, it is possible to calculate both the drawdown and the recovery yields. However, it appears that very little pre-test attention is paid to selecting the optimal drawdown time or the optimal recovery time, or to real-time monitoring of either, information that is critical for calculating the drawdown yield and recovery yield to use as a validation of the WC posted drawdown yield.

Glossary

***BGS* (*Below Ground Surface*):** An abbreviation used to denote that the measured distance is to a point beneath the surface at the well head.

***Blue sheets*:** Refers to the format, color and time period of the particular WC form employed by drillers and the MassDEP from the 1960s until 2001. This distinction is made since the information recorded by drillers depended on specific forms required to be in use.

***Overburden*:** Unconsolidated earth materials (soil, sand, clay, gravel and boulders) unbonded in various proportions.

***Responsible state agency*:** Over the six decades of well completion data spanned by this report, the title of the state agency responsible for collecting these records has included the Dept. of Environmental Management/Division of Water Resources; MA Water Resources Commission/Division of Water Resources; Massachusetts Department of Conservation and Recreation/Office of Water Resources, and currently the Massachusetts Department of Environmental Protection (MassDEP). For the convenience of this report, all these titles are subsumed under the rubric of the current name "*MassDEP*".

TSO: Thickness of Saturated Overburden. Defined as $\mathrm{TSO} = \left(d_{\mathrm{BR}} - d_{\mathrm{SWL}}\right)$, as long as the static water level (d_{SWL}) is shallower than the depth to bedrock (d_{BR}), otherwise if the SWL is *equal to*, or *deeper than* bedrock ($d_{\mathrm{SWL}} \geq d_{\mathrm{BR}}$), $\mathrm{TSO} = 0$.

***Yield* (or *well yield*):** The rate (gallons per minute) at which a producing well is able to extract water from a local aquifer under expected operating conditions.

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