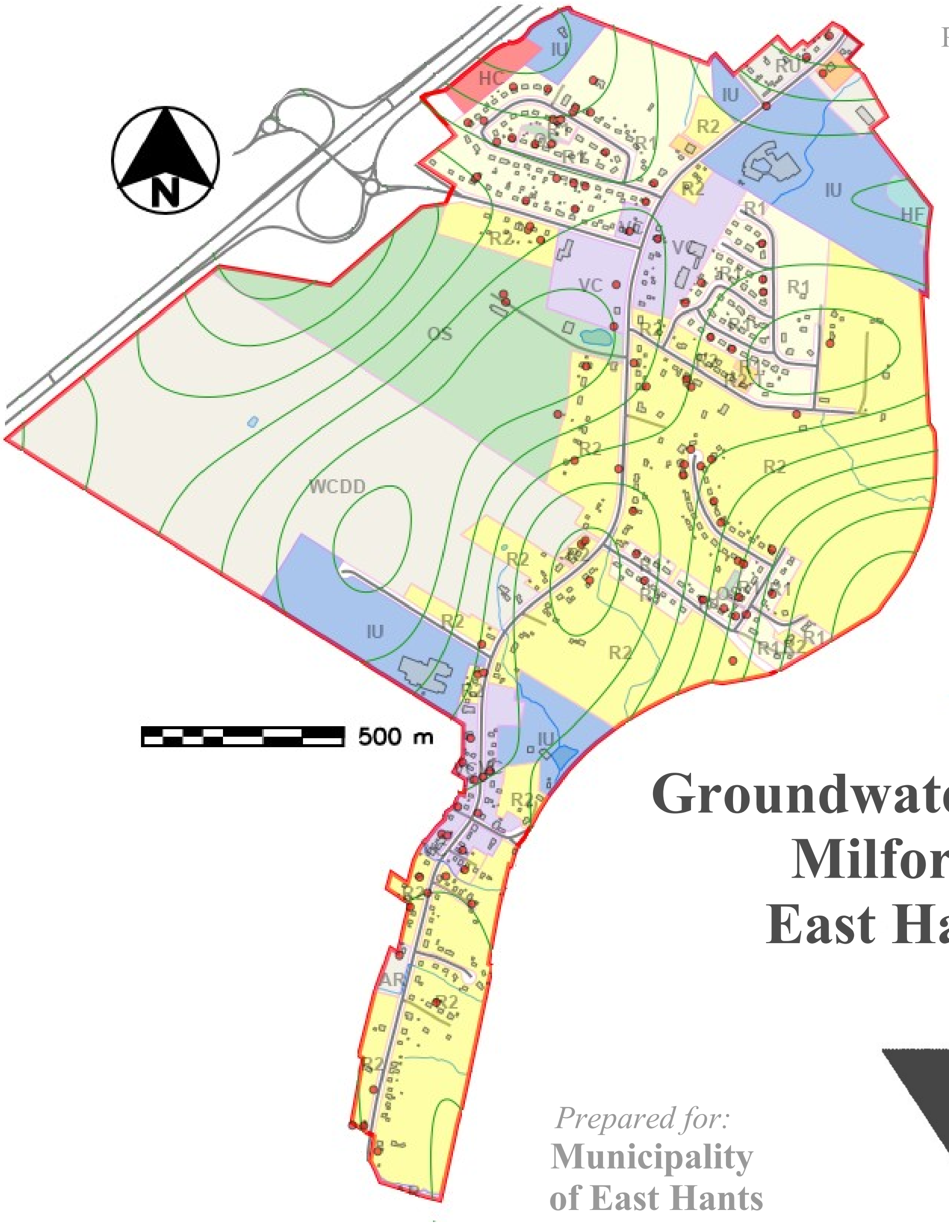
earth-water Concepts inc.

March 2021

Project 169UB02



Groundwater study
Milford GMA
East Hants, NS

Prepared for:
Municipality of East Hants

Working with Nature's Science to provide credible environmental and water resource solutions...

PO Box 51015, Halifax, Nova Scotia B3M 4R8
Phone 902 457-7010 fax 902 45703934

Milford groundwater study, report summary

The Milford GMA is one in which the Municipal Planning Strategy is to promote and encourage residential and commercial growth. Within the Milford GMA, however, there have been concerns from residents regarding access to sufficient quantity of drinking water and the impact that new development might have on the supply of drinking water.

When submitting applications for rezoning, developers are asked to demonstrate that their development will not adversely affect groundwater for existing residents and that there is sufficient groundwater for the proposed development. But this can be costly and time consuming, and those studies are usually limited to the boundaries of the properties to be developed and may not fully address aquifer issues outside of them.

This study attempts to look at things in a more holistic manner – by addressing known groundwater quantity and quality issues and other facets of groundwater supply concern for the entire Milford GMA – to serve as a resource to assist Council in deciding where new growth can occur, how much growth can be supported with on-site water services, or whether to use a more cautionary approach to development in specific areas.

The study’s terms of reference were for a desktop review of currently available data, with mapping to be included as required to help support its findings. So while this study needed to look more broadly at the regional geology to properly define nearby aquifer characteristics, its area of focus was within the boundaries of the Milford GMA, to:

- Identify groundwater supply issues for the existing property owners within the community.
- Identify known water quality issues within the GMA and note whether these issues are costly for homeowners to treat.
- Characterize the general availability of water in the community, such as:
    - areas where water quantity/quality would provide challenges to existing and new residents of that area,
    - areas where water is plentiful and be be promoted for development, and
    - expected impacts to existing and potential future water supply as the community develops.
- Recommend any further investigation or study as warranted.

This report includes a primer on aquifers that covers different types of aquifers and how they and wells work – information necessary to understand the details presented later in the report. So readers who are unfamiliar with aquifers are encouraged to read it.

The Milford GMA is located at the southern edge of the Shubenacadie-Musquodoboit sedimentary Basin, a part of the much larger Maritimes Basin in which more than a 10 km thickness of sediment were deposited during a long (400 Ma[1]), complicated sequence of significant tectonic continent-building and rifting events.

Those geological events have directly influenced the earth materials that make up the aquifer units that the wells in the Milford GMA draw their water from, their yields, and the quality of the water they produce. So Section 4 of this report gives a brief (but sufficiently detailed) description of the area's geologic history and of the resulting geologic bedrock units that underlie the Milford GMA – which goal is to give readers the contextual background necessary to properly interpret the descriptions given later of the aquifer and water quantity and quality characteristics from wells drilled within the Milford GMA.

Footnotes are provided wherever deemed necessary to explain to readers some of the technical terms used in this study report.

The water-bearing bedrock units that are present and from which wells drilled within the Milford GMA may obtain water include the Carboniferous age (350 to 325 Ma) Green Oaks Formation, which directly underlies most of the Milford GMA, the younger Watering Brook Formation, which underlies only the southern tip of the community, and the MacDonald Road Formation, which may also serve as a water source, but with certain quality concerns, which underlies all of the community.

The sub-aerial extent of the Early Cretaceous age (144 to 125 Ma) Chaswood Formation, an essential component of the Shubenacadie-Milford Aquifer Complex (SMAC) that supplies decent quality water to many farms north of the community and which serves the village of Shubenacadie, was mapped as part of this study. The SMAC is unfortunately not present below the Milford GMA, which is situated on a bedrock topographic high right at the edge of the Chaswood Formation fluvial valley that was incised into the surface of the much older MacDonald Road and Green Oaks Formations. So it was not reviewed further during this study.

While the community is almost entirely underlain by Pleistocene tills, due to their too great depth, constructing productive dug wells in these surficial deposits appears viable only at a few locations within the community – at the very north and within the open space zones lands at the northwest edge of the Milford GMA. However, since dug wells are much more vulnerable to surface sources of contamination than drilled wells, their use is generally not advised in denser urbanized areas, such as at the Milford GMA.

There are 375 records in the Nova Scotia well log database for wells that are said to have been constructed within the Milford GMA. Of those, one is a dug well; the other 374 have been drilled into bedrock. And of those drilled wells, detailed UTM coordinate locations are available for only 100 wells. Those 100 wells are the basis upon which much of this study was carried out.

The wells in the community are relatively shallow, with an average depth of only 33.5 m (range 4.6 m to 61.6 m). But due to the relatively thick overburden present and the apparent fracturing and/or weathering of the bedrock immediately beneath it, well casing

---

[1] The abbreviation "Ma" stands for "million years".

depths average 20 m (6 to 12 m is typical in Nova Scotia), and range from 1.5 m (which does not meet today's well construction standards) to 56 m.

Interpolation of the well log data from wells with known locations into 3-D surface maps reveals that well casing depths and well total depths generally match the trends of the bedrock surface topography, which becomes deeper towards the east within the Milford GMA. Thus, except for a few areas along the eastern edge of the community, the costs to drill wells in at Milford Station be expected to be roughly at par with the average cost to drill wells elsewhere in Nova Scotia.

Driller blow test yield rates reported for wells in the Milford GMA are generally quite high, averaging 92 L/min for the 100 wells with known locations, and averaging 66 L/min with a range of 2.3 L/min to 455 L/min for all 374 drilled wells on record in the community. To put this into perspective, a blow test yield rate of 2.25 L/min is generally considered to be enough to meet most residential needs, providing there is sufficient cold-water storage[2] (available drawdown) in the well to meet peak water demands.

There are pumping tests (more elaborate tests than driller blow tests, which are typically of 6, 12, 24 or more often, 72 hours duration) on record for wells drilled in the Green Oaks Formation in the Milford GMA; those test results are commensurate with the driller blow test yield rates reported (but with 0.5 to 0.75 adjustment factor applied).

The static water levels in wells, which in general follow the ground surface and bedrock surface but in a subdued fashion, are relatively deep within the community, ranging from zero (flowing well conditions) to 39.6 m (averaging 17.9 m in all wells). And since most wells are generally shallow, this makes for relatively short water columns, or small amounts of available drawdown (small cold-water storage volumes) in many of the Milford GMA wells.

A review of available drawdown versus driller blow test yield rates suggests that the areas with the least available drawdown are predominantly where driller blow test yield rates are also highest – namely, in the area from the Rennie Lane and Bayberry Dr. subdivision and southwest to include all of Riverside Dr. and the area in the northwest half of the community south of Riverside Dr.

It would appear that high yields encountered while drilling wells may have encouraged drillers to advance wells to shallower depths in those areas. While this may perhaps not have been an issue when the wells were first drilled, aquifer stresses caused by continued pumping at existing wells over time may have lowered the water table generally, and higher yields may not compensate that general lowering of the water table. This may explain complaints about water quantity. And for the more vulnerable wells, this is a matter that may be exacerbated by well interference resulting from pumping at additional wells drilled for new development.

---

[2] Cold water storage is that water present within the water column between the static (non-pumping) water level in a well, and the bottom of the well (or top of the pump). Low yielding wells will draw from this storage during periods of higher water demand (early mornings, supper time), which is replenished by the well yield during periods of low water use (at night).

Estimates were made of the groundwater recharge (replenishment of aquifers) and aquifer water storage within the immediate Milford GMA region. Those analysis suggest that there should be sufficient source water replenishment from recharge to support around 560 homes (or equivalent) as an ultra-conservative (almost unreasonable) estimate, to upwards of 1,900 homes (or equivalent) using a still conservative but more realistic recharge area of about 500 m around the Milford GMA, assuming a daily consumption rate of 1,350 L/day per home over 365 days. Calculations further suggest that there is sufficient water stored in the local surficial and bedrock aquifer units to support those 1,900 homes through several decades of droughts.

However, as was noted above, where water quantity issues may arise and complaints increase may be based on the very shallow wells that exist within the community, and the potential for aquifer stresses dropping groundwater levels over time or as a result of well interference from new development. Our well interference analysis using three (albeit very hypothetical and very conservative) scenarios suggests that due largely to the very shallow depths of the wells in the Milford GMA, up to 15.5% of all existing wells under two scenarios, and up to 39% for the other scenario, may not meet the Nova Scotia Environment criteria for well interference.

The Green Oaks Formation, which serves as the main aquifer unit beneath nearly all the Milford GMA, is comprised mostly of carbonate deposits and only minor gypsum and halite. So based on this and a limited amount of available water quality data within the Milford GMA (only 11 water samples) and other data from outside the community, this aquifer unit should be expected to produce moderately to very hard water calcium-bicarbonate type water with moderate TDS and iron and manganese concentrations that are near or slightly above their aesthetic guideline values.

But since the Green Oaks Formation is only about 140 m thick below the Milford GMA, when seeking larger well yields or available drawdown (i.e. for commercial use), caution should be exercised to avoid drilling through it and into the MacDonald Road Formation below, which is reported to possibly contain more gypsum and/or halite. However, commercial water treatment methods may be able to deal with those issues.

Water softeners should be able to adequately treat most domestic well water quality issues for wells drilled into the Green Oaks Formation (and which may be required at most wells within the community). However, some wells drilled into the Green Oaks Formation may encounter gypsum and/or halite, which if not shut out with well casing, could produce water with elevated concentrations of sulphate and/or sodium. Water treatment by reverse osmosis (RO) may be better suited to those wells.

The Watering Brook Formation, which directly underlies only the southern-most part of the Milford GMA, is reported to contain much more gypsum and/or halite than the Green Oaks Formation. As such, wells drilled into that bedrock unit may be expected to produce harder, calcium-sulphate type water, likely with higher total dissolved solids, and possibly with concentrations for iron and manganese that may be 3 to 4 times their guideline values.

While water softeners may be able to treat water from some wells drilled into the Watering Brook Formation, the use of RO treatment systems may be much better suited to wells drilled within the southern-most parts of the Milford GMA.

Alternatively, it may be possible and cost beneficial in some cases (particularly in the eastern-most part of the formation) to drill through the Watering Brook Formation into the Green Oaks Formation beneath it and to advance well casings to seal off any gypsum and halite zones that may be present in the shallower parts of the well.

As with any community with on-site domestic wells, care must be exercised to mitigate against possible urban sources of groundwater contamination. These may include road salt, petroleum product spills, fertilizers and pesticides, and leaking central sewage collection systems. If one is not already in place, consideration should maybe be given to developing some form of source water protection plan for the Milford GMA.

Table of contents

Table of contents (cond’t)

    6.4.1 Groundwater flow, potential water capture areas 53
    6.4.2 Precipitation 54

List of tables

List of figures

Report disclaimer

This report was prepared for the sole benefit of the Municipality of East Hants for the purpose of describing the nature of the source water for individual, on-site water supply wells within the boundaries of the Milford Growth Management area (GMA), East Hants, NS. This report cannot be used for any other purpose for by any other person or entity without the express written consent of earth-water Concepts inc., and the Municipality of East Hants.

The work and interpretations in this report are based solely on desktop evaluations and and other data available at the time work was carried out. The data and interpretations presented in this report are based solely on the conditions present and data available when the work was performed. There are levels of uncertainty adherent to any desktop assessment of this sort which are subject to change as different information becomes available. Data obtained for this study represent conditions about a limited area surrounding the subject area and as such, the information obtained can be expected to be variable with respect to location and time. This work is specific to the Milford GMA, conditions and land use considerations described herein, and cannot be used or applied under any circumstances to a location and situation that has not been specifically outlined.

The information presented in this report is based upon work undertaken according to sound geoscience practices by trained professional and technical staff under a set scope of work and budget. Should future investigations provide information which supplements or differs from the information presented in this report, we request to be notified and permitted to reassess the results and interpretations provided herein.

Original Signed

0004

Richard P. Gagné, P.Geo. FGC
Sr. Hydrogeologist/Hydrologist
earth-water Concepts inc.

1. Introduction

The Municipality of East Hants (MEH) has commissioned earth-water Concepts inc. to complete a groundwater study for the Growth Management Area (GMA) of Milford, NS.

1.1 Background and purpose

The Milford GMA is one, among others, in which the Municipal Planning Strategy is to promote and encourage residential and commercial growth. Within the Milford GMA, however, there have been concerns from residents regarding access to sufficient quantity of drinking water and the impact that new development might have on the supply of drinking water.

When submitting applications for rezoning, developers are asked to demonstrate that their development will not adversely affect groundwater for existing residents and that there is sufficient groundwater for the proposed development. But this can be costly and time consuming for developers, and those groundwater studies, which usually are limited to the boundaries of the properties to be developed, may not fully address aquifer issues outside of those boundaries.

This study attempts to look at things in a more holistic manner – by addressing known groundwater quantity and quality issues and other facets of groundwater supply concern for the entire Milford GMA – to serve as a resource to assist Council in deciding where new growth can occur, how much growth can be supported with on-site water services, or whether to use a more cautionary approach to development in specific areas.

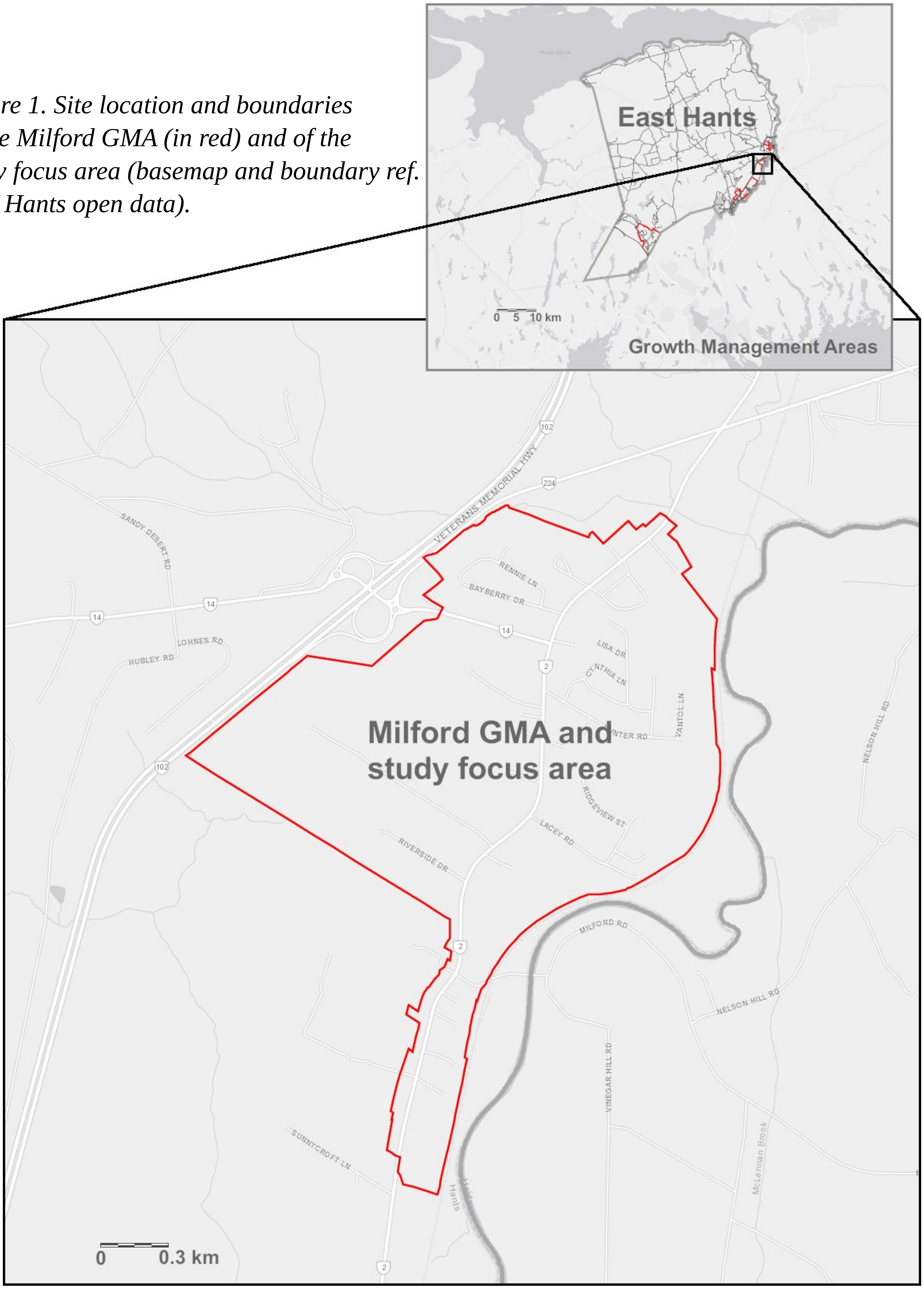
1.2 Scope of the study

The study’s terms of reference were for a desktop review (no ground investigation work requested) of currently available data, with mapping to be included as required to help support its findings.

East Hants indicated that doing a feasibility study to provide the Milford GMA with Municipal water service may by considered in the future if development pressure warrants such a study. However, for now the expectation is that drinking water would continue to be supplied from on-site wells. So while this study needed to look more broadly at the regional geology to properly define nearby aquifer characteristics, its area of focus (see Figure 1) is on the local aquifer units at the Milford GMA, to:

- Identify groundwater supply issues for the existing property owners within the community.
- Identify known water quality issues within the GMA and note whether these issues are costly for homeowners to treat.
- Characterize the general availability of water in the community, such as:
    - areas where water quantity/quality would provide challenges to existing and new residents of that area,
    - areas where water is plentiful and be be promoted for development, and
    - expected impacts to existing and potential future water supply as the community develops.
- Recommend any further investigation or study as warranted.

Figure 1. Site location and boundaries of the Milford GMA (in red) and of the study focus area (basemap and boundary ref. East Hants open data).



2. A primer on aquifers

The Milford GMA well water supply (groundwater) comes from an aquifer. But aquifers are are underground, out of sight, not in most school curriculum, so there are many misconceptions about what aquifers are and how they work. The next few pages explain what aquifers are in the broad context of the Milford GMA – the aim is to inform readers so they can gain more value from this study.

2.1 An encyclopedic definition

An aquifer is a body of rock or sediment that holds groundwater. Groundwater is the word used to describe precipitation or other surface water that has infiltrated into the subsurface and collected in tiny empty spaces underground – between the sand grains that make up the soils or sandstone bedrock, or in narrow cracks and in bedrock fractures.

Because of the depths to which groundwater may exist, groundwater represents about 97% of the earth's fresh liquid water, compared to less than 3% for water in lakes and rivers.

2.2 Visualizing groundwater

Figure 2 shows how the ground can become saturated with water (shaded blue). Only this saturated area is considered to be an aquifer. The "unsaturated zone" above the water table still contains water (after all, plants' roots live in this area), but it is not totally saturated with water, so it is not aquifer.

A common misconception about aquifers is that they are underground rivers or lakes.

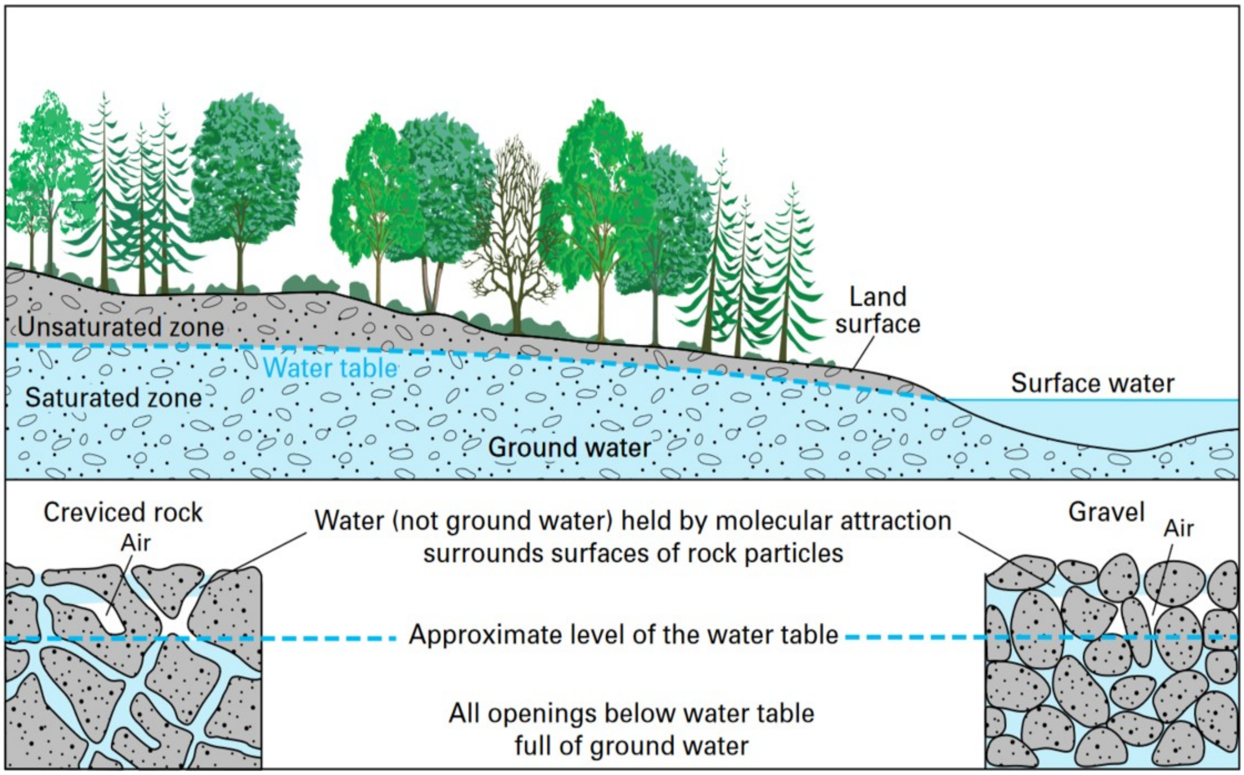


Figure 2. How groundwater occurs in soil and rocks. (USGS, 2019).

While groundwater can seep into or out of aquifers due to their porous nature, because of the very tiny spaces in which it exists and the tortuous pathways though which it must flow between those tiny spaces, groundwater cannot move fast enough within aquifers to flow like a river. And groundwater also isn't found in "seams". The best analogy is to think of an aquifer as a household sponge; different sponges can hold different amounts of water and allow it to soak into and be removed from it at rates that depend entirely on what that sponge is made of.

The two drawings at the bottom of Figure 2 show close-ups of how water is stored in between underground soil and rock particles or within bedrock fractures. Figure 3 shows the three principle types of pore spaces that may be present in aquifers to store water.

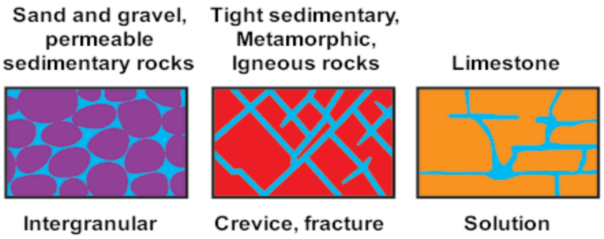


Figure 3. Main types of porosity. (EC, 2013)

Porosity is the space in which groundwater may be stored; as in household sponges, the rate that groundwater can flow trough an aquifer depends on levels of interconnection between pore spaces, or permeability of the aquifer matrix (the soil and/or rock and pore spaces that make up the aquifer). Note that permeability and porosity, although related (i.e. there can be no permeability in an aquifer if there is no porosity it), are two very distinct aquifer properties that are not mutually inclusive in all soil or rock.

For example, while clay may have 40-70% porosity (Freeze and Cherry, 1979) (this high porosity is why clay settles when it is built on and as water present in it is squeezed out over time due to the structure's weight), due to the extremely small (microscopic) grain size and shape of the materials that make up clay, water cannot easily move between its pore spaces. By contrast, well-sorted coarse sand and gravel deposits, having 25-40% porosity, can allow groundwater to flow quickly since the pore spaces have better interconnections.

For the reasons above, at larger local and regional scales at and around the Milford GMA, aquifer permeability can vary significantly both horizontally and vertically depending on where and what types of soil and/or bedrock are present underground.

Permeability (more specifically, hydraulic conductivity (K) is used in groundwater science), is defined as the velocity at which water will pass through an earth material of unit area and unit gradient (change in water height). Table 1 lists typical values for K (Freeze and Cherry, 1979) in conventional centimetres per second (cm/s) and for readers, in easier-to-grasp metres per day (m/d).

Table 1. Typical hydraulic conductivity values.

Aquifer matrix	cm/s	m/d
Clean sand	$1 - 10^{-3}$	86 - .86
Silty sand	$10^{-2} - 10^{-5}$	8.6 - .0086
Glacial till	$10^{-4} - 10^{-9}$	.086 - .00000086
Sandstone	$10^{-4} - 10^{-8}$	.086 - .0000086
Limestone	$10^{-3} – 10^{-7}$	.86 - .000086
Shale	$10^{-7} - 10^{-11}$	.000086 - .00000001

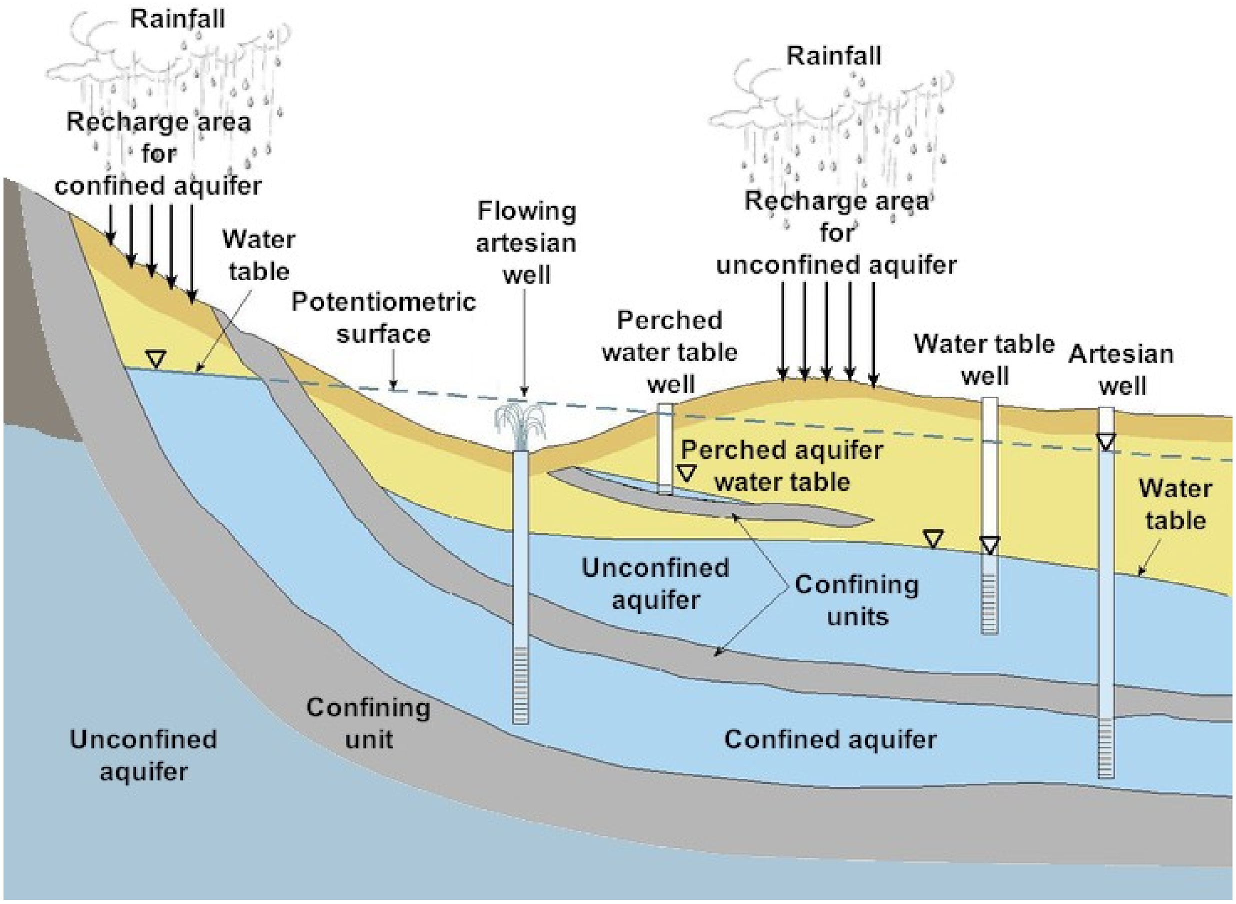


Figure 4. Geological and topographical groundwater flow controls on wells drilled in confined and unconfined aquifers. Modified from NGWA (2007).

Saturated soil or bedrock materials with high permeability are referred to as aquifers. Those with low permeability with very slow or no groundwater flow are referred to as aquicludes. Both aquifers and aquicludes are present in and around the Milford GMA.

2.3 Confined vs unconfined aquifers

There are three general types of aquifers: confined, unconfined, and perched. Figure 4 shows the geologic and topographic controls affecting groundwater flow from wells drilled into all three types, and related terminology.

In Figure 4, the saturated zones are shaded blue and grey, unsaturated zones are yellow.

Confined aquifers have an impermeable rock or clay layer above them, while unconfined aquifers consist of or lie below a permeable layer of soil in hydraulic communication with the surface. Perched aquifers – another form of unconfined aquifer – have impermeable rock or clay under them that prevents infiltrating waters (groundwater recharge) from reaching deeper aquifer materials. Drilling through the layers below perched aquifers may also cause them to drain.

Some confined aquifers may not be confined over their entire extent, but are in hydraulic contact with the surface to receive recharge at locations of higher elevation. Figure 4 shows an example of that. The potentiometric (also called piezometric) surface shown by the dashed line is the level at which water would rise in wells drilled into the confined unit. Wells drilled into confined aquifers where the ground surface is below that piezometric surface will naturally flow.

Some confined aquifers may be buried so far underground that they cannot receive direct recharge from surface. Those produce what's often called prehistoric water (water becomes trapped in aquifer sediments as confining deposits are laid over-top) that can be tens to hundreds to thousands of years old. The Shubenacadie-Milford Aquifer Complex (SMAC) just north of the Milford GMA which serves as water supply to the village of Shubenacadie may be one such type of confined aquifer (more on that later).

2.4 What drives groundwater flow?

We all know surface water runs downhill according to slope and shape of the land. It's no different for groundwater flow.

2.4.1 Flow in unconfined aquifers

In unconfined aquifers, the water table (surface of the saturated zone) generally follows surface topography, but in a subdued manner. That's because the depth and shape of the water table are controlled by recharge rates and aquifer permeability; the higher the aquifer permeability, the more quickly groundwater can flow and thus, the flatter the water table can become.

The resistance to flow in aquifers also creates sloped gradients in water tables. Groundwater will flow in the direction and at velocities that are defined by those gradients. Thus in the examples in Figures 2 and 4, the slope of the water tables follow the lay of the land, so too will groundwater flow, from left to right in both Figures, at rates that are relative to aquifer permeability and water table gradient.

2.4.2 Flow in confined aquifers

In confined aquifers, groundwater also flows down-gradient, from areas of high piezometric elevations to areas of lower piezometric elevation. However, unlike water table surfaces in unconfined aquifers, piezometric gradients do not follow surface topography, but are controlled by water withdrawal.

That withdrawal may occur where the aquifer becomes exposed at surface (is no longer confined), such as at springs, in streams and in stream-beds, at or beneath lakes, or ultimately as discharge to the ocean, or by pumping at wells. Sections 2.4.3 and 2.4.4 below give brief descriptions.

2.4.3 General surface-water and groundwater interactions

Groundwater's role in the hydrologic cycle is huge, not only in terms of water removals by overland infiltration, which can range from 14% of total annual precipitation at and around the Milford GMA, to 25% in parts of Cape Breton, the Eastern Shore, and South Nova Scotia (Kennedy et al, 2010), but also through groundwater's direct interaction with surface water bodies and the hydrologic cycle generally by other means.

Some examples include:

- the reintroduction of water to atmosphere by evaporation and evapotranspiration from plants where aquifers are shallow,
- direct influx/outflows of groundwater at wetlands,
- seepage of water from streams and lakes into aquifers as groundwater recharge,
- discharge as springs (initiating streams) at breaks in land topography, or as baseflow (groundwater can contribute up to 100% of a steam's flow during droughts periods and maintain temperatures for fish) at river banks and stream-beds, or as springs at lake bottoms, and
- seepage of groundwater to the ocean.

Figure 2 shows one instance of groundwater interacting with surface water (i.e. lakes can serve as windows onto groundwater tables). Figures 5 and 6 (modified from Winter et al, 1998) show examples of spring/wetland and river/lake interactions.

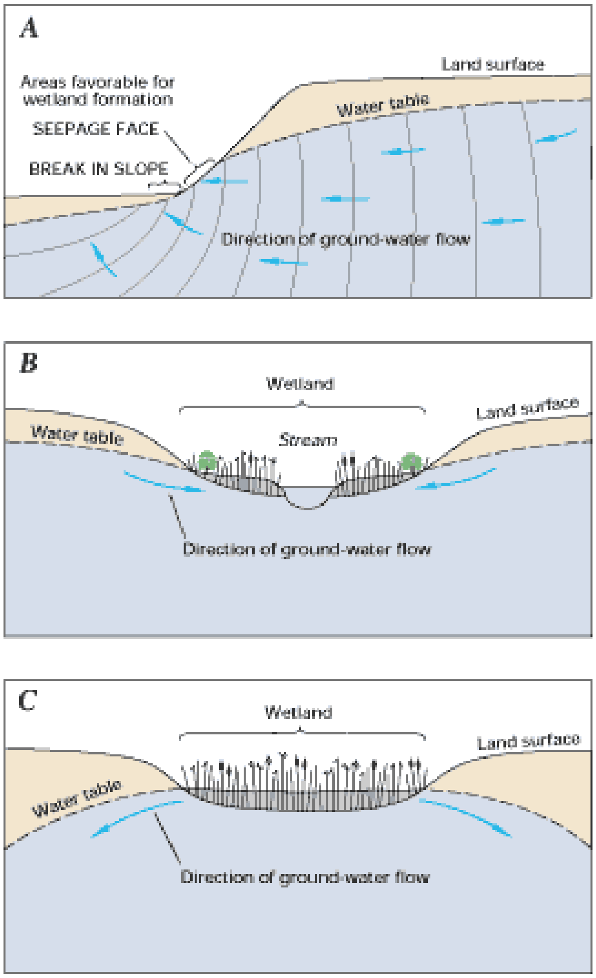


Figure 5. Wetlands (A) at breaks in slopes, (B) fed by groundwater at low elevations, and (C) serving as groundwater recharge.

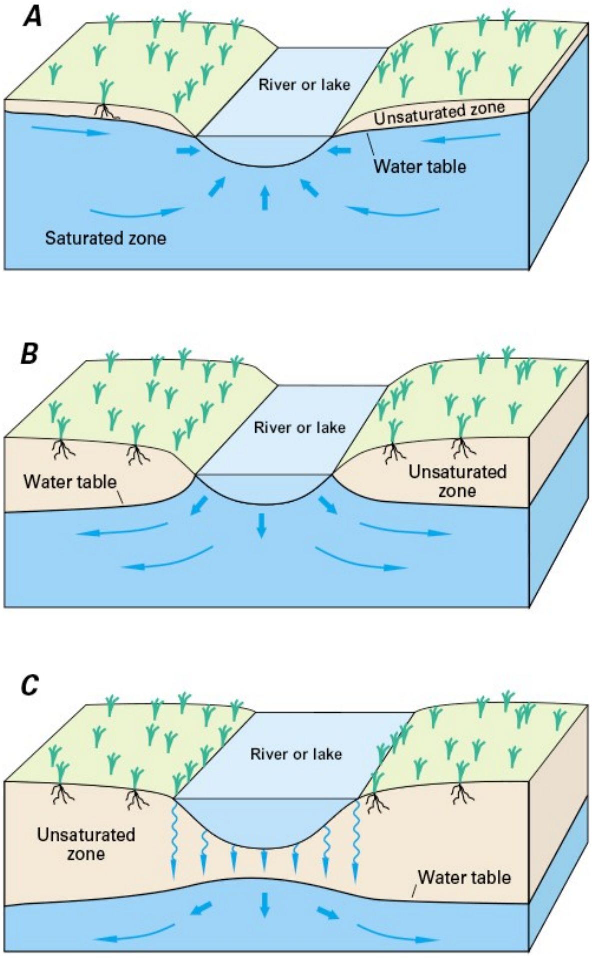


Figure 6. Groundwater and (A) gaining streams, (B) loosing streams, and (C) loosing streams disconnected from the water table.

2.4.4 General effects of pumping wells

Where aquifers are shallow and permeable enough to allow water to move in them at a rapid-enough rate, then people can drill wells into them and withdraw water. The level of the water table can naturally change over time due to changes in weather cycles and precipitation patterns, stream-flow and geologic changes, and even human-induced changes, such as the increase in impervious surfaces (roofs, roads) on the landscape.

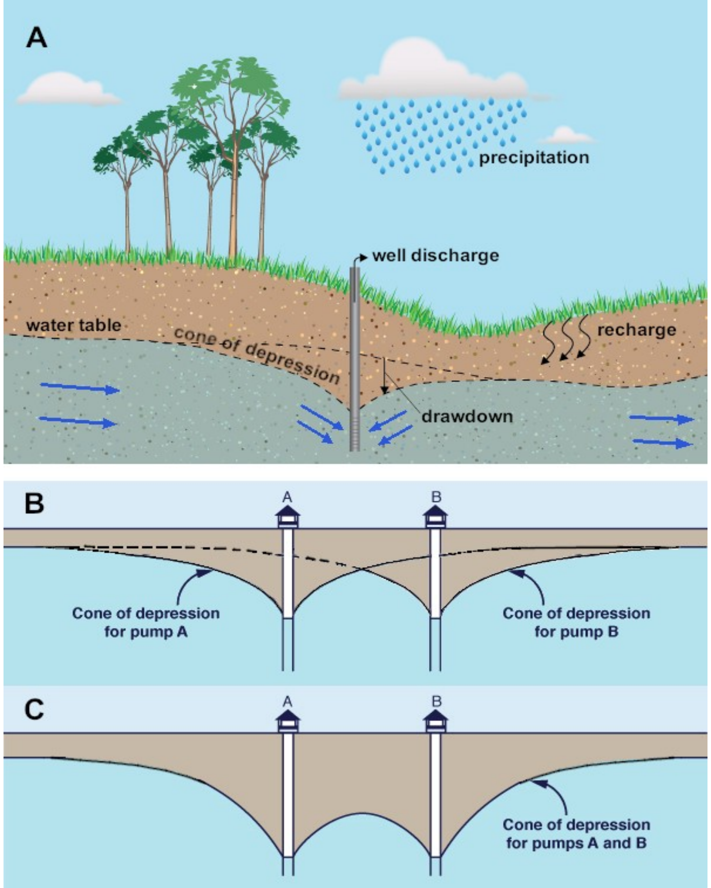


Figure 7. Schematics showing (A) cone of depression around a pumping well (note change in groundwater flow direction from pumping), (B) drawdown from pumping at either well A or well B, and (C) drawdown interference from pumping at wells A and B together. (Modified from USGS, 2019)

The pumping of wells can also have a great deal of influence on water levels in aquifers, especially in the vicinity of the wells, as the diagram in Figure 7 shows.

If water is withdrawn from the ground at a faster rate that it is replenished by infiltration from the surface or from streams, then the water table can become lower, resulting in a "cone of depression" or drawdown around the well. Depending on the geologic and hydrologic conditions of the aquifer and the pumping rates used, the drop in groundwater levels can be small, or several tens of metres. The total amounts of drawdown and lateral extent of cones of depression can be determined from well pumping tests and use of observation wells.

The pumping of wells can cause groundwater flow to change direction locally, as shown in the top (A) in of Figure 7. The bottom (B and C) shows that where two or more wells are pumping together and their cones of depression overlap, the amount of drawdown at each well is equal to the sum of the drawdown from each cone of depression produced with the wells pumping individually. This is referred to as well interference – essentially a situation where “Peter robs Paul”.

Over pumping wells can lower the water table so much that wells can “go dry” and no longer supply water. The impact on the water table level can be short-lived or last for decades depending on the nature of the aquifer and availability of recharge.

2.5 General groundwater quality

The natural chemical reactions that affect the geochemical characteristics of groundwater include (1) acid-base reactions, (2) mineral dissolution and precipitation, (3) sorption and ion exchange, (4) oxidation-reduction reactions, (5) biodegradation, and (6) the dissolution and exsolution of gases.

Rain and snow-melt typically contain low concentrations of dissolved solids and have low pH. When that water first infiltrates the land surface, microorganisms in the soil have a significant effect on the evolution of the water chemistry. Organic matter in soils is degraded by microbes, producing high concentrations of dissolved carbon dioxide (CO_2). This process further lowers the water pH by increasing the carbonic acid (H_2CO_3) concentration in the soil water.

The production of carbonic acid starts a number of mineral-weathering reactions, which result at first in bicarbonate (HCO_3^-) usually being the most abundant anion in groundwater. Where contact times between water and minerals in shallow groundwater flow paths are short (typically the case for dug wells constructed in glacial till), then the dissolved solids concentration in the water generally is low. In such settings, limited chemical changes take place before groundwater is discharged either to surface water or is pumped from wells.

But in deeper groundwater flow systems, the contact time between water and minerals is much longer than in shallow flow systems. As a result, the initial importance of reactions relating to microbes in the soil zone are superseded over time by chemical reactions between minerals and water (geochemical weathering). As weathering progresses with age and flow distance, the concentration of dissolved solids increases, and depending on the chemical composition of the minerals that are weathered, the relative abundance of the major inorganic chemicals dissolved in the water changes – the groundwater chemistry evolves – bicarbonate generally decreases and sulphate (SO_4^{2-}) and then chloride (Cl^-) increase with time and distance travelled.

At and around the Milford GMA, those minerals which may become dissolved and naturally affect groundwater quality include:

- calcium and magnesium carbonates (the building blocks for the limestone and dolomite bedrock that underlies the area), which make groundwater hard,
- gypsum, anhydrite and halite (rock salt) evaporite minerals, which can elevate sulphate, sodium, and chloride concentrations in groundwater, and
- soluble iron and manganese oxides and carbonates, and other trace metals and elements present in the carbonate rocks and interbedded shale and mudstone present beneath the community.

Human land use around the Milford GMA can also affect (detrimentally) groundwater quality by introducing unwanted chemicals into groundwater recharge: automotive fuel, heating oil, and chemical storage tank leaks and spills; fertilizer and pesticide use; road salt; leaky sewage collection systems; and outside of the community, failed septic systems and leaky manure pits.

3. Study approach

Completing this study meant drawing from and expanding upon earlier work by Giles and Boehner (1982), Dickie (1986), Lay (1979), Matheson (1999), Stea and Pullan (2001), Pe-Piper et al (2004, 2004a), Pe-Piper and Piper (2018), and others. This required first doing a careful review of the regional bedrock and surficial geology, borehole data, water well data, and other information at different scales in order to help gain a clear understanding of the locations of the area aquifer units and their characteristics.

Armed with this regional knowledge, it was then possible to zoom in and focus on the Milford GMA – to delineate and characterize the local bedrock and the Cretaceous (the SMAC) aquifer units at/near the community, to identify the water supply options available to its residents and businesses, and thus to define any related water quality and quantity concerns relating to current water use and to possible future water use with development.

3.1 Extent and scale of the map and data reviews carried out

3.1.1 Initial, small-scale reviews

The initial review of the regional bedrock geology and related general well water quality encompassed the approximately 70 km (east-west) by 50 km (north-south) area of the Shubenacadie and Musquodoboit sedimentary basins as mapped by Giles and Boehner (1982). This served to review the general distribution of the local geologic units, define what data was available for this study, and how best to proceed with the more detailed aspects of the study.

3.1.2 Mid-scale reviews

Then an area that included approximately 5 km all around the Milford GMA boundaries was used to do further bedrock mapping, to:

- expand upon the work completed by Matheson (1999) to delineate where the lateral edges of SMAC are and where it might extend to along its axis beyond his thesis area and this study area, and
- look at well production (yield) and water quality characteristics in finer detail within the SMAC and bedrock aquifer units in this mapping area.

It was important for this phase of the work to use only data for which mapping locations were accurately known and defined. Therefore, the mapping reviews that were done at this scale looked only at those water wells within the well log database records (NSE, 2016, 2018; NSDEM, 2020) for which UTM coordinate locations[1] were accurately defined to within 30 metres.

3.1.3 Final, larger-scale reviews

Finally, the map study area was tightened to include an area extending about 1 km around Milford GMA boundaries (slightly larger than the map in Figure 1), to summarize all that was learned during the earlier phase reviews for general statistical analysis of all wells (both accurate and non-accurate locations) that are understood to be located inside the boundaries of Milford GMA.

---

[1] Wells drilled before 2004 were located by map roaming number; in the NS well log database, their locations have been projected to the centre of 1 km UTM grids. Wells drilled after mid-2004 were located by drillers using hand-held GIS instruments, so their locations are accurate to within about 30 m.

3.2 Study information sources

This study made extensive use of Geographic Information System (GIS)[2] to compile and manage, review, and interpret all relevant publicly available and some privately available information. The following general data sources were used for this study:

- published bedrock and surficial geology maps in paper and digital formats,
- reports published for other places in Nova Scotia on stratigraphically similar or equivalent geologic units to those present at and near the Milford GMA,
- local published and unpublished technical studies and reports on water resources as done by consultants on behalf of different levels of government,
- mining assessment reports relating to the bedrock and/or shallower sand and gravel and clay resources of the area, and
- numerous digital databases, including but not limited to:
    - the NS Well Log database (NSE, 2016, 2018; NSDEM, 2020), for general well construction information, depths to bedrock, casing lengths to assess production zones, and general well performance and well yields,
    - the NS Well Pumping Test database (published (Kennedy, 2020a) and unpublished (John Drage, pers. comm., 2017) versions), for more detailed well and aquifer performance information than can be obtained from the Well Log database,
    - the NS database on Groundwater Chemistry (from private sources and mined from public sources (Kennedy, 2020b)), for general groundwater quality, and
    - NS Exploration Borehole Database (O'Neill and Poole, 2016), for depths to bedrock.

Searches were done of the GeoScan and NovaScan bibliographic databases to locate and retrieve Geological Survey of Canada and Nova Scotia Natural Resources Geoscience and Mines Branch publications and relevant mineral assessment reports on the Carboniferous, Cretaceous, and Pleistocene Age geologic deposits of the greater study area, which constitute the local bedrock aquifer and the SMAC.

Follow-up Google searches were done to help retrieve documents referenced in these databases that were not directly accessible for download from the government Web sites.

3.3 Datum used in this study

Unless noted otherwise, all coordinates and elevations and all maps presented in this report are in reference to UTM datum NAD 83 CSRS Zone 20 and to vertical datum CGVD2013.

---

[2] Using GRASS GIS (2020).

4. Area geology

The Milford GMA is situated at the very southern edge of the Shubenacadie-Musquodoboit sub-basin, which itself is located at the southern edge of the Maritimes Sedimentary Basin (see Figure 8).

4.1 Brief history of Maritimes Basin

The Maritimes Basin is a product of continental drift. It was created when the prehistoric continents Laurasia and Gondwana drifted together and started to collide during the Late Devonian to Middle Mississippian Epoch (Lower Carboniferous Period) about 335 million years ago (Ma) to create the supercontinent that we call Pangea.

Sedimentary deposition at and north of the Milford GMA within the Maritimes Basin began shortly following the start of that collision and continued:

- during the start of the early breakup of Pangea in the Upper Triassic to Middle Jurassic Periods (200 to 175 Ma) when volcanic activity associated with the early rifting extruded the North Mountain basalt now exposed in west Nova Scotia from Scots Bay to Digby, and

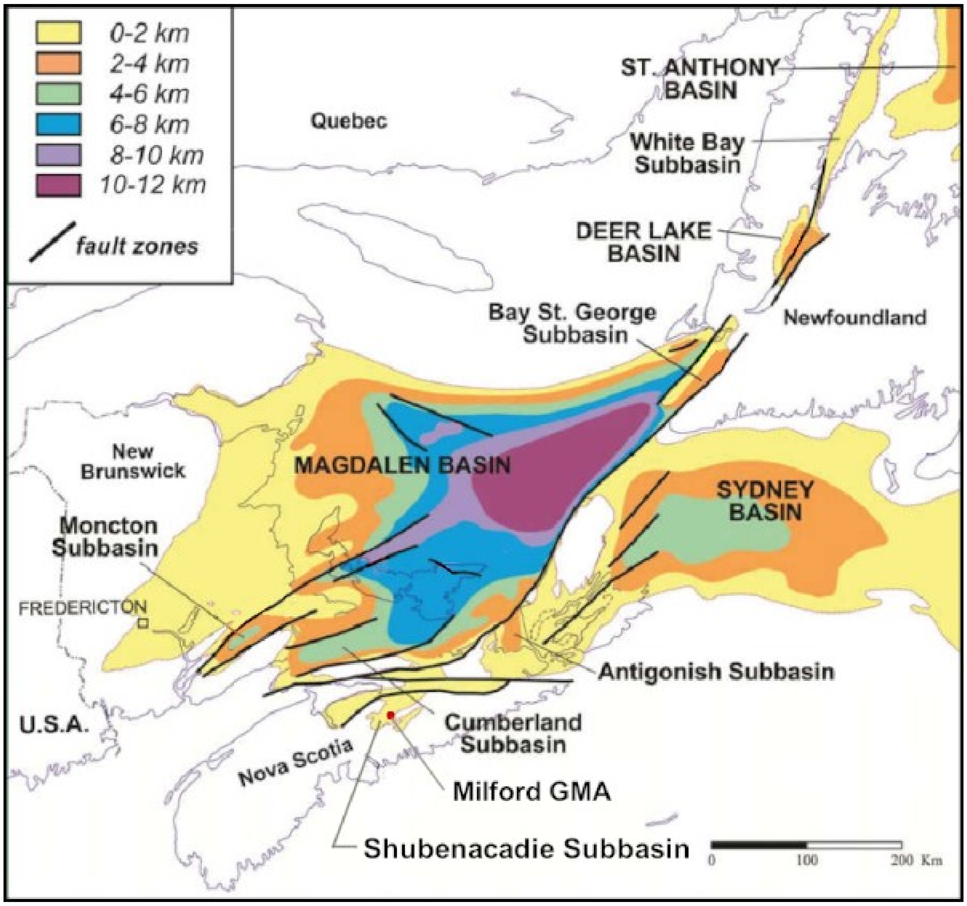


Figure 8. The Maritimes Basin, its sub-basins, location of the Milford GMA, and current basin sediment thickness (after MacMulin et al, 2017).

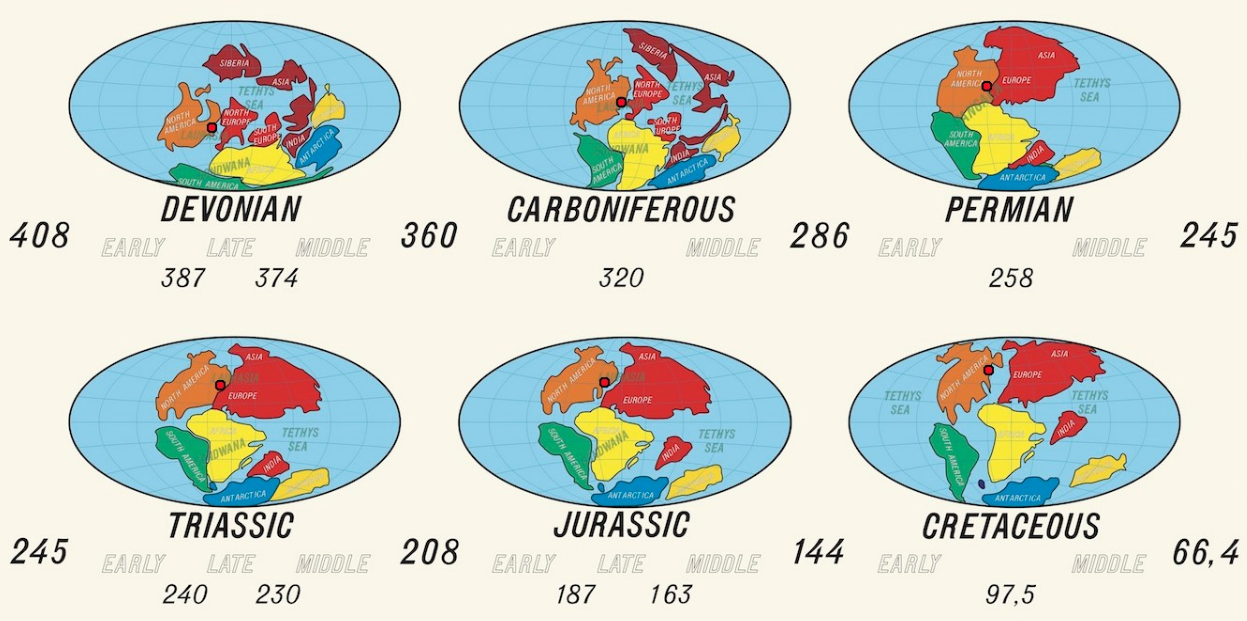


Figure 9. Tectonic evolution of Pangea. (values in millions of years, red dot shows Nova Scotia).

- to the final breakup of Pangea as rifting restarted off the continental shelf at the proto-Atlantic Ocean during the Early Cretaceous Period (145-100 Ma).

Deposition has continued at the present off-shore of Nova Scotia to this day.

The early continental reconstructions in Figure 9 show that what was to become Nova Scotia was located at very near the equator[3] from the start of the Devonian Period to the Triassic and end of the Jurassic Periods (at about the time that dinosaurs went extinct). The Maritimes Basin existed as a tropical inland sea during a period of rapid sediment supply from a mountain range in the south (the Meguma Supergroup meta-sediments) and another mountain range in the north (crystalline rocks of the Avalon Terrain and Appalachians) within a progressively deepening basin due to faulting from significant tectonic stresses. Figure 8 shows the current thickness for Maritimes Basin sediments that ranges from zero to 2 km at the basin edges to over 10 km at its centre.

The tropical climate that existed at the time, the tectonic changes to land elevations, and fluctuating global sea-levels, resulted in the development of numerous trapped marine bays, where evaporation allowed anhydrite and halite (rock salt) and associated limestone to precipitate at the bottom of the bay, which along with shale, mud, and coarser clastic sediments from nearby streams and rivers, now form the bedrock that underlies the Milford GMA today.

---

[3] The locations of ancient land mass over time are known from paleomagnetic studies. This is a branch of geophysics where the azimuth and declination of rock remanent magnetism (the permanent magnetism in rocks resulting from the orientation of the Earth’s magnetic field at the time of rock formation – which is locked into rocks as sediments are deposited or as basalt cools) of oriented rock samples of known age are modelled backwards over time.

4.2 Local stratigraphy and table of Formations

Figure 10 shows local bedrock stratigraphy with reference to the the mid-scale mapping (5 km) area around the Milford GMA. Figure 11 shows the local bedrock stratigraphy for the Carboniferous Period in the same area.

Notwithstanding the odd 1 to 5 million year hiatus in Nova Scotia's geologic record (due to falls in sea-level and marine regression[4]), there is a nearly continuous record of deposition at one location or another for the Maritimes Basin (Keppie, 2000).

However, terrestrial environments prevailed in Nova Scotia following the Carboniferous Period, and there is a general absence of any geologic record on-shore Nova Scotia from the start of the Permian Period (300 Ma) to about the Middle Triassic Period (240 Ma), from about the mid-Early Jurassic Period (195 Ma) to the start of the Early Cretaceous Period (145 Ma), and again from the end of the Lower Cretaceous Period (about 100 Ma) to the Pleistocene Epoch about 2.6 Ma (start of the most recent ice age).

The Holocene (post-glaciation) Epoch (not shown in Figure 10) contains a relatively good record of the last of four glaciations.

4.3 Basement rock units

The rocks of the Meguma Terrane form the basement complex for the Shubenacadie and Musquodoboit Basins.

The Meguma Terrane encompasses all of Nova Scotia south of the Avalon Terrane (the Cobequid Hills) at the Minas Fault zone, which runs east-west from Chedabucto Bay to Cobequid Bay and the Minas Basin. The Meguma Supergroup consists of two groups: the lower Goldenville Group, and the upper Halifax Group, that were deposited in mostly a transgressive marine environment.

The rocks of the Meguma are not exposed at the Milford GMA, but are exposed in the southeast corner of this study's mapping area and farther south into Halifax County.

The Goldenville Group consists largely of Cambrian-Age turbidite (submarine slide and avalanche) and related continental shelf sediments deposited on the west coast of what is now Africa (Gondwana). The younger Halifax Group conformably overlies the Goldenville Group and consists of more distal marine sediments.

During the Acadian Orogeny (closure of the pre-Hercinian Ocean as Gondwana and Laurasia collided), the Meguma sediments were tightly folded and uplifted to create a formidable mountain system.

4.3.1 General Meguma lithostratigraphy

The Goldenville Group is comprised mostly of massive grey to greenish-grey, generally poorly sorted quartzose sandstones, with chlorite-rich matrix, interbedded with

---

[4] A marine transgression is a geologic event during which sea-level rises relative to the land and the shoreline moves toward higher ground, resulting in flooding. Flooded environments generally provide for better preservation of sediments and thus, of the geologic record. Marine regressions are the opposite. They are times during which sea-levels fall relative to the land, exposing former sea bottom. During those drier environments, erosion is prevalent and depositional processes (or their preservation) are reduced, thus leaving blanks in the geologic record.

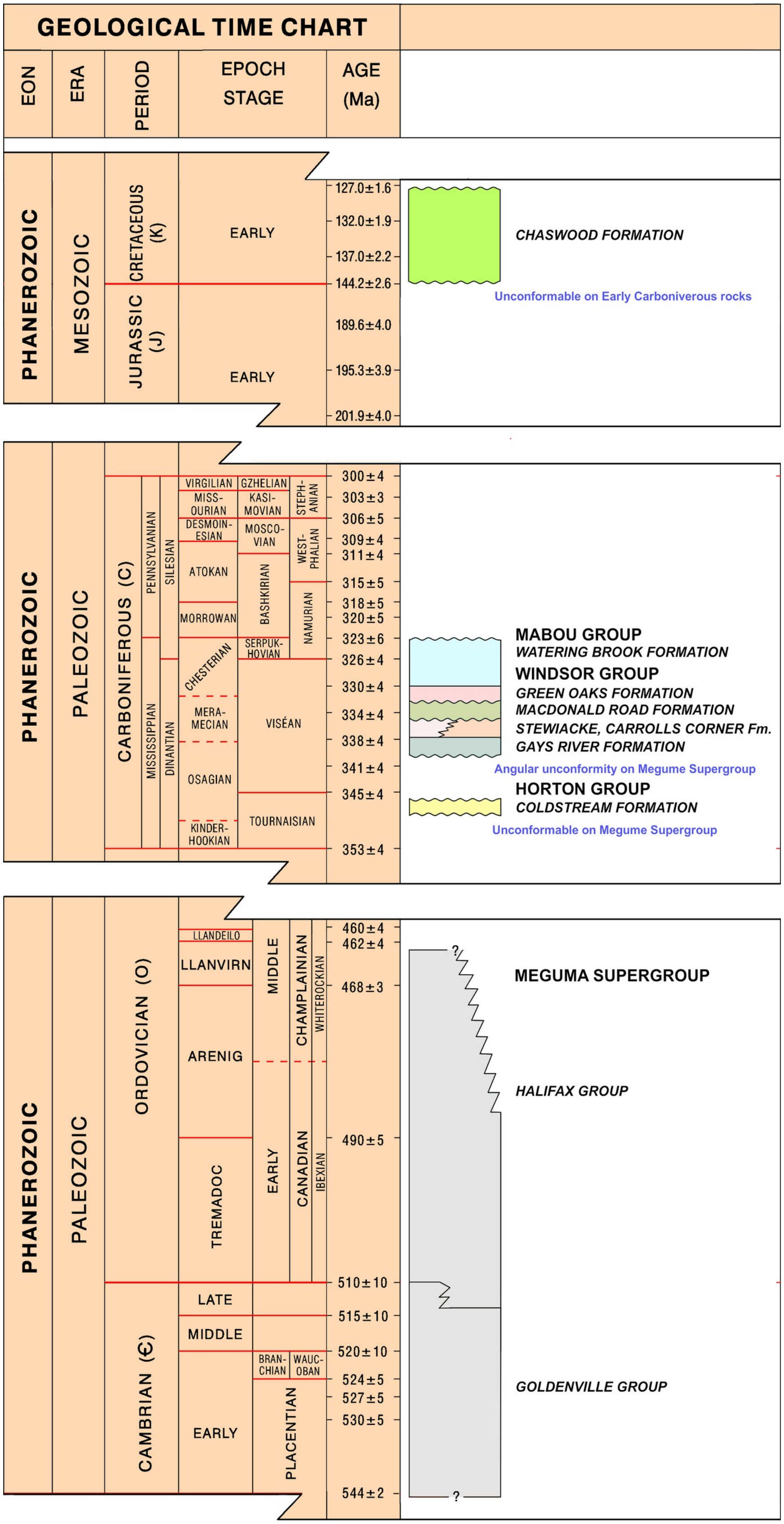


Figure 10. Local bedrock stratigraphy and table of Formations (after Keppie, 2000; Giles and Boehner, 1982).

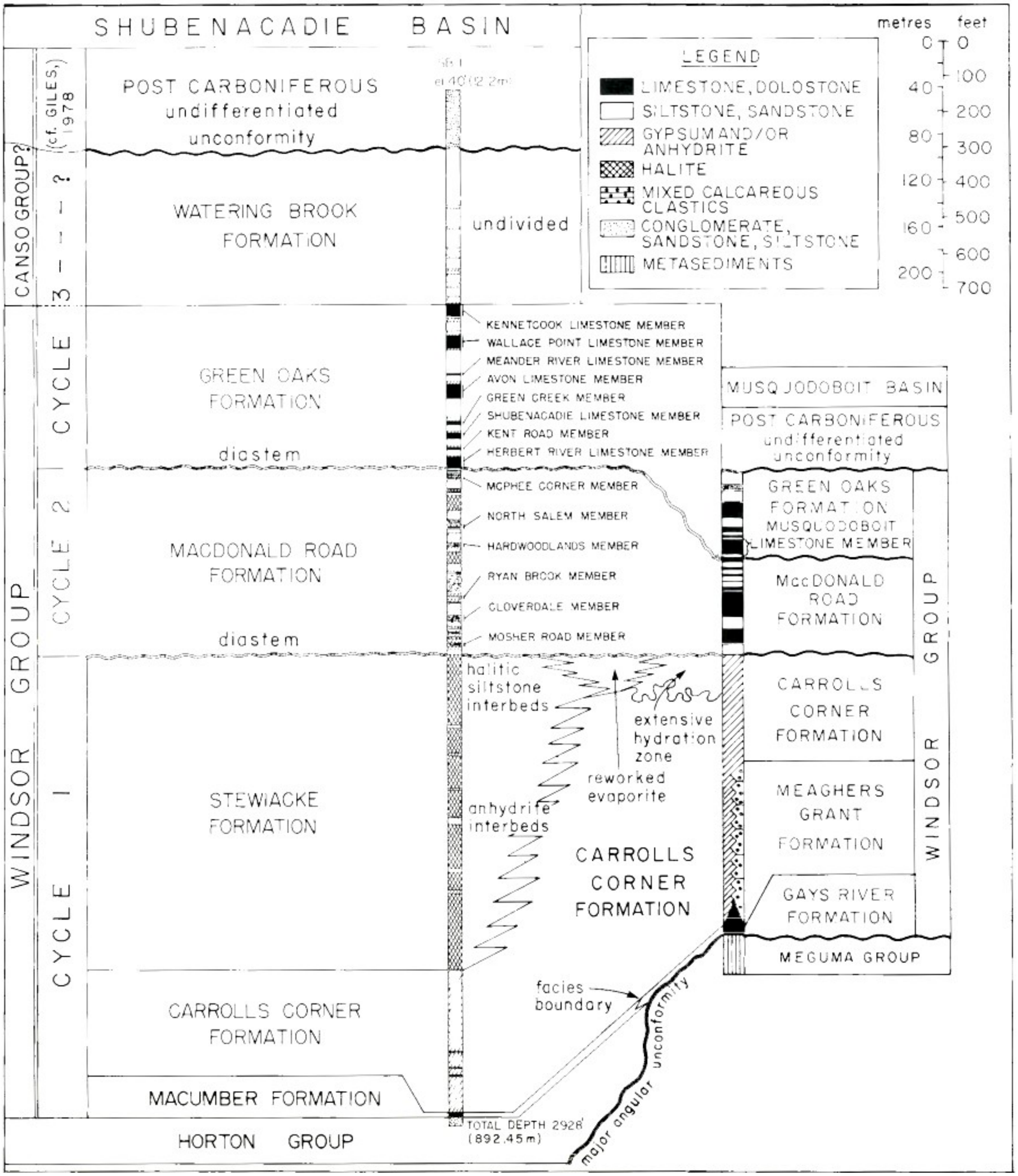


Figure 11. Stratigraphic correlation for the Carboniferous within the Shubenacadie Basin and at the Milford GMA (copied from Boehner, 1981).

generally subordinate grey to black slate. The rocks have been regionally metamorphosed to green-schist and, locally, amphibolite facies. Gold-bearing quartz veins occur at many localities (Williams et al, 2018).

The maximum measured thickness is about 5,400 m, with the base not exposed. The Goldenville Formation is overlain conformably by the Halifax Group, although some have suggested that the two are in part contemporaneous. It is intruded by Upper Paleozoic granitic plutons. Where the Halifax Formation is absent, the Goldenville is unconformably overlain by the Lower Carboniferous Horton and Windsor groups and by the Upper Triassic Wolfville Formation of the Fundy Group.

The Halifax Group is comprised mostly of greyish-green to black and, locally, red slate, siltstone, and minor sandstone, generally thinly bedded and strongly sheared. The slates (some acid generating) locally contain abundant pyrite and arsenopyrite. The formation is regionally metamorphosed to green-schist and, in places, amphibolite facies, and is locally schistose. Hornfels is developed close to granitic plutons.

The Halifax Group thickness varies from about 3,600 m in the type area (Halifax) to about 500 m in southwest Nova Scotia. The Halifax Group conformably overlies the Goldenville Group, and as with the Goldenville, the Halifax Group has also been intruded by Upper Paleozoic granitic plutons and unconformably overlain by the Lower Carboniferous Horton and Windsor groups and the Upper Triassic Wolfville Formation of the Fundy Group.

4.4 Carboniferous geology

The map in Figure 12 shows the local bedrock Carboniferous[5] geology present within the mid-scale (5-km) area around the Milford GMA, as mapped by Giles and Boehner (1982). Figure 13 is cross section C-C’ from Figure 12. It shows the general vertical relationship of the formations present near and beneath the Milford GMA.

4.4.1 Depositional setting

The Carboniferous Age bedrock formations present at the Milford GMA were deposited in a predominantly tropical environment (the paleoequator was where Amherst is today) at the western edge of the Mid-Euramerican inland sea (Gibling et al, 2008), bounded to the north and west by the Appalachians and to the south and southeast by mountainous Meguma Terrane (Wittenburg Mountain and Chaswood Ridge (Jutras et al, 2006) east and south of the Milford GMA), then Gondwana.

The Shubenacadie Basin comprises a stratified sequence of sedimentary rocks with an estimated thickness of about 800 m locally, with a distinct angular unconformity on rocks of the Meguma Group.

The Shubenacadie Basin is traversed by a series of high-angle normal faults with northeast-southwest orientations. These faults define a graben in the axial regions of the Basin and merge toward the northeast with the major east-west Minas Fault system.

---

[5] The name *Carboniferous* means "coal-bearing". The Carboniferous, which spans about 60 million years, was a period when vast swaths of forest covered the land, to eventually be laid down and become coal beds characteristic of the period. All of Nova Scotia’s coal beds are of Carboniferous Age.

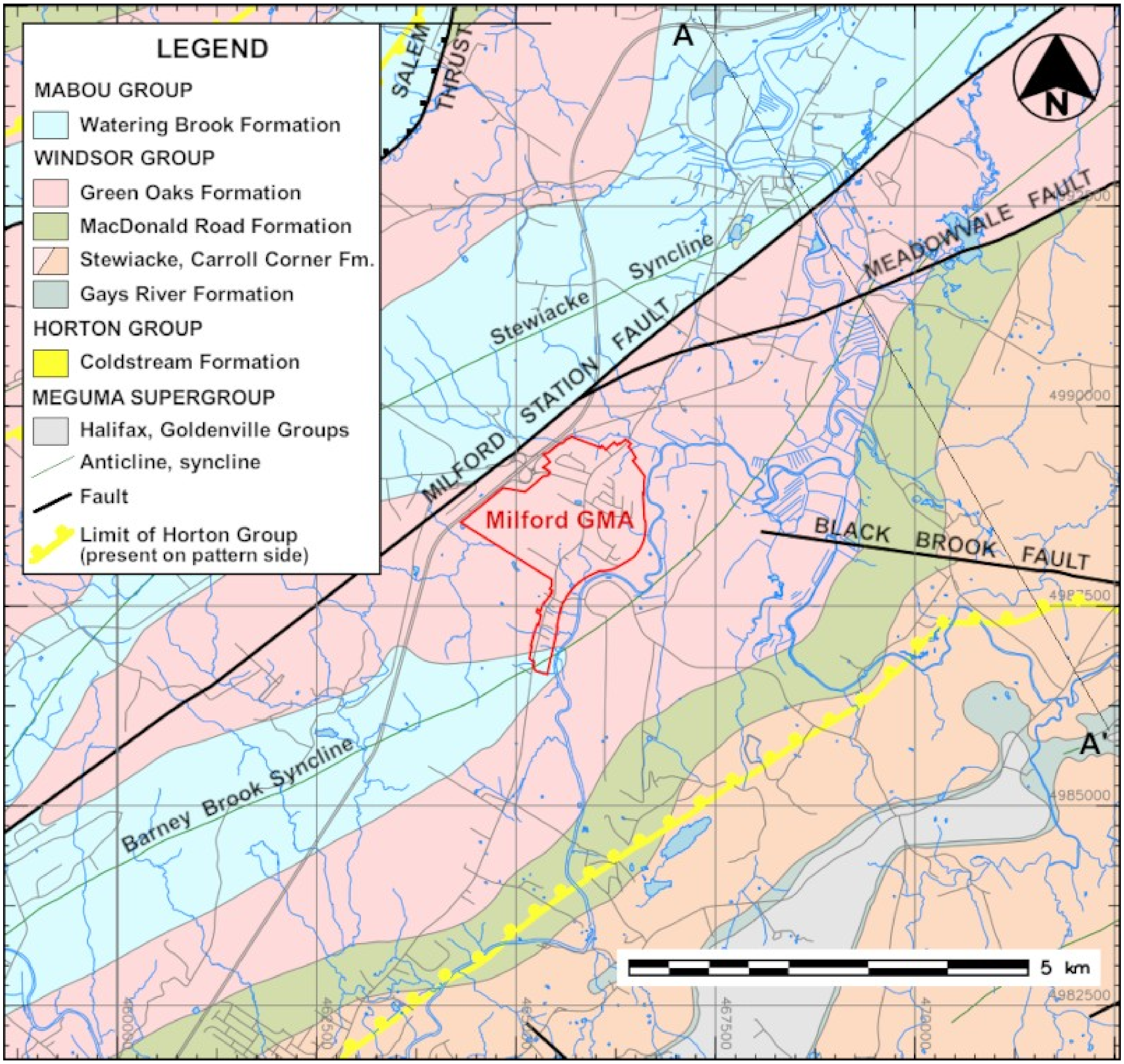


Figure 12. Carboniferous bedrock geology (from Boehner, 1982; basemap Geonova, 2020).

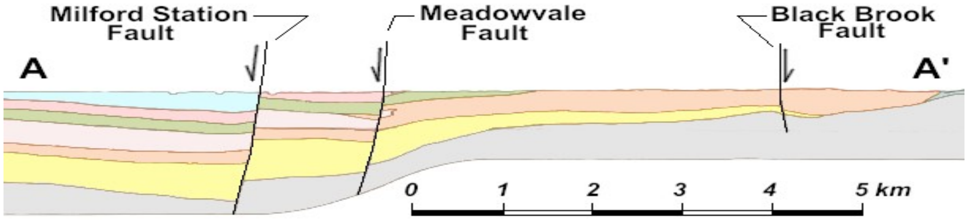


Figure 13. Cross-section A-A' from Figure 12 (no vertical exaggeration).

The Carboniferous section of the Basin encompasses three groups[6]: the Horton, Windsor, and Mabou Groups (referred to by Boehner (1981, 1982) as the Canso Group).

The initial Carboniferous deposition in the Shubenacadie Basin includes terrigenous piedmont and fluvio-lacustrine flood plain sediments of the Horton Group, which locally lies concordantly beneath the Windsor Group, but may be separated from the Windsor Group by a significant hiatus.

The Windsor Group in the Shubenacadie Basin was deposited in three major cycles (Boehner, 1981).

The lower cycle is dominated by restricted hypersaline subaqueous marine evaporite deposition in a preformed basin, and is characterized by a thin basal dolostone overlain by a thick massive anhydrite and halite with thin anhydrite and siltstone interbeds. In marginal areas the anhydrite locally inter-tongues with terrigenous sediments; basin-ward, anhydrite precipitation precedes halite deposition in localized shrinking basins adjacent to contemporaneous sub-aerially exposed anhydrite surfaces.

The middle and upper cycles are more complex, with repeated minor cycles of extensive transgressive-regressive marine carbonates and terrigenous rocks, with a large proportion of evaporite including anhydrite (as nodules in siltstone or carbonate) and minor halite. The more massive and laminated anhydrite was precipitated in hypersaline shallow coastal lagoons.

Thick evaporites of the lower cycle progressively infilled the initial basin and effectively levelled topographic irregularities. The resulting surface of low relief and gentle slope favoured shallow water and evaporite deposition throughout the latter two cycles.

The uppermost member of the Green Oaks Formation is conformably overlain by a sequence of interbedded terrigenous and evaporites of the Watering Brook Formation (Mabou Group).

4.4.2 Coldstream Formation

The Coldstream Formation overlies the Meguma Group with pronounced angular unconformity, and is concordant and

---

[6] Stratigraphic units are subdivided on the basis of their shared lithology and depositional environment in a hierarchy of lithostratigraphic rank, with higher ranks comprising two or more units of the lower rank, which going from smaller to larger are: Bed, Member, Formation, Group, and Supergroup.

A Bed is a distinct layer within a member or formation; beds are not normally named, but may be in the case of marker horizons.

A Member is a distinct part of a formation with a unique distinguishing characteristics, but which may not be mappable at the same scale as a formation.

Formations are the primary units used in the subdivision of a sequence and may vary in scale from tens of centimetres to kilometres. They should be distinct lithologically from other formations, although the boundaries do not need to be sharp. To be formally recognized, a formation must have sufficient extent to be useful in mapping an area.

A group is a set of two or more formations that share certain lithologic characteristics. A group may be made up of different formations in different geographical areas and individual formations may appear in more than one group.

A Supergroup is a set of two or more associated groups and/or formations that share certain lithologic characteristics. The groups that make up a Supergroup may be in different geographical areas.

apparently conformable with the overlying Windsor Group. Its lithologic character and relationship with the Windsor suggest that it is a probable correlation with the Cheverie Formation (upper Horton Group).

The Coldstream formation is comprised of reddish-brown conglomerate and coarse-grained sandstone, with minor shale and siltstone, variably stratified.

It ranges in thickness from 3 to 67 m near the southern end and southeastern margin of the Shubenacadie sub-basin, thickens basin-ward, and is believed (Boehner, 1981) to underlie the entire Shubenacadie sub-basin, although the basal units of the overlying Windsor Group extend beyond the edge of the Coldstream Formation at several areas of the Shubenacadie Basin. Its exposure is limited to eroded areas at the basin margin.

The Coldstream Formation is believed to represent braided stream sedimentation on surfaces of alluvial fans peripheral to the Shubenacadie sub-basin.

4.4.3 Gays River Formation

The Gays River Formation is the basal unit within the mapping area in Figure 12. It conformably overlies the Coldstream Formation and Meguma Supergroup with angular unconformity where the Horton Group is absent. It is conformably overlain by the Carrolls Corner Formation.

The Gays River Formation comprises a complicated suite of dolomitic carbonates, including algal boundstone and bafflestone with associated skeletal packstone and wackestone and locally developed basal breccia-conglomerate. At the type section[7] (Imperial oil Ltd. diamond-drill hole GR 256 (45 deg 01'54" N, 63 deg 20'31" W; NTS 11 E/3W), between 15.5 and 48.2 m, near the Gays River Mine), the formation is 32.7 m thick where it is a bank facies, but may be as thin as 3 m in the flanking inter-bank facies.

Boehner (1977) and Giles and Boehner (1982) correlated the Gays River Formation with a part of the Macumber Formation.

4.4.4 Carrolls Corner Formation

The Carrolls Corner Formation is comprised of nodular mosaic to massive anhydrite with minor, intercalated dolostone and argillaceous dolostone with rare halite. Hydration to gypsum is common in near surface areas.

Locally, the Carrolls Corner Formation is capped by a substantial thickness of gypsum; about 2.5 km south of the Milford GMA, the National Gypsum Company has been exploiting it since the mid-1950’s.

The basal anhydrite of the Carrolls Corner Formation is conformable with the underlying Gays River formation and inter-fingers with and is conformably overlain by the Stewiacke Formation.

At the type section (Imperial Oil Limited diamond-drill hole IJ 76-1 (45°03'37" N, 63°23'07" W; NTS 11 E/ 3W) between 121.9 and 366.2 m (400 and 1,201.5 ft), near Carrolls Corner, Halifax County), the

---

[7] A type location is the locality where a rock type, stratigraphic unit, or mineral species is first identified. A stratigraphic unit’s site location usually serves to define and formally document that strata.

Carrolls Corner Formation is 244.3 m thick, but locally it may exceed 300 m in thickness. The formation is present throughout the Shubenacadie Basin.

4.4.5 Stewiacke Formation

The Stewiacke Formation is comprised of bedded and banded rock salt with irregularly intercalated and subordinate beds of anhydrite. Beds of grey-green and red siltstone become increasingly abundant towards the top of the formation.

The thickness of the Stewiacke Formation ranges from 190 to 310 m, and is typically around 270 m thick. It is present throughout the axial regions of the Shubenacadie Basin where it is known only from boreholes. The Stewiacke Formation halite conformably overlies anhydrite of the Carrolls Corner Formation and is overlain disconformably by the MacDonald Road Formation.

4.4.6 MacDonald Road Formation

The MacDonald Road Formation is comprised of cyclically intercalated evaporates and marine carbonate rocks with minor fine-grained terrigenous rocks. Anhydrite and gypsum are predominant where this Formation outcrops.

Marine carbonate bands in the Formation form marker horizons, and are formally identified as members in several areas. In the Shubenacadie Basin, the MacDonald Road Formation includes, in ascending order, the Mosher Road, Cloverdale, Ryan Brook, Hardwoodlands, North Salem, and McPhee Corner members.

At the type area (St. Joseph-Noranda borehole 153-1 on the MacDonald Road, about 1.9 km northwest of Shubenacadie, East Hants), the formation ranges in thickness from 150 to 164 m, where it disconformably overlies salt of the Stewiacke Formation, or anhydrite (gypsum) of the Carrolls Corner Formation.

4.4.7 Green Oaks Formation

The Green Oaks Formation directly underlies all but the very southern tip of the Milford GMA. In the Shubenacadie Basin it is the most broadly exposed Windsor Group unit.

Its composite type section begins south of Anthony's Nose on the east bank of the Shubenacadie River (just south of the Fundy Tidal Interpretive Centre), at the base of the first major carbonate bed exposed in the river bank and on the tidal flat. It extends south to the mouth of Green Creek in Colchester County, along Green Creek to the steel road bridge, then upstream to the well exposed red siltstones. Exposures on both banks of the Shubenacadie River at Urbania, East Hants, form part of the composite type section.

The Green Oaks Formation is characterized by successive marine carbonates, each representing transgressive-regressive cycles separated by relatively thick, volumetrically dominant red-brown siltstones and fine-grained sandstones of continental origin.

The base of the Green Oaks Formation is the Herbert River Member – it documents the first transgression, as indicated by green siltstones, marginal marine carbonates, sub-tidal carbonates, marginal marine carbonates, anhydrite, and red siltstones. The red siltstones suggest a continental or high supra-tidal flat environment (Giles, 1981). The formation includes, in ascending order, the Herbert River, Kent Road, Shubenacadie, Green Creek, Avon, Meander River, Wallace Point, and Kennetcook members.

Gypsum and anhydrite are locally associated with the marine carbonate rocks but are not seen at the type area; these evaporites are a significant lithologic component of the Green Oaks Formation (drill hole evidence) in the Shubenacadie Basin south of the type area.

In the type area, the Green Oaks Formation is estimated to be 680 m thick, although it is incomplete in the upper part of that section. It occurs throughout the axial region of the Shubenacadie Basin. Lithologic correlatives extend throughout Nova Scotia, such as the Murphy Road Formation in the Windsor area (Giles, 1981), and strata on Port Hood Island. It has also been recognized elsewhere in Atlantic Canada.

The Green Oaks Formation disconformably overlies the MacDonald Road Formation. Its upper boundary is not preserved in the type area, but elsewhere in the Shubenacadie Basin it is conformably overlain by rocks of the Watering Brook Formation (Giles, 1981). The Kennetcook Member is defined as the top of the highest bed of marine limestone (or dolostone) of the Green Oaks Formation, and is equated with the top of the Windsor Group in the Shubenacadie Basin.

4.4.8 Watering Brook Formation

The Watering Brook Formation is the other bedrock unit that directly underlies study area and the very southern tip of the Milford GMA. It is the second of the most broadly exposed bedrock units within the Shubenacadie Basin.

The Watering Brook Formation belongs to the Mabou Group. It is differentiated from the rocks of the Windsor Group by its lack of any marine carbonate beds beds (Utting, 1980), and unlike for rocks of the Windsor Group, no marine fossils have been reported regionally from the Mabou Group or from the Watering Brook Formation (Giles, 2009).

The Watering Brook Formation is comprised of light to medium grey, greenish-grey and minor red, variably calcareous siltstone, mudstone and shale. Near the base, the clastic rocks are locally interbedded with anhydrite, gypsum and rare salt, which are thought to represent a continuation of the transgressions and regressions that existed during Windsor Group deposition.

The Watering Brook Formation ranges from 50 to 260 m in thickness. While it is distributed throughout the Shubenacadie Basin, complete outcrop or cored drillhole sections are not present in the Basin.

The Watering Brook Formation conformably overlies the Green Oaks Formation. In the Shubenacadie Basin, the Watering Brook is the only formation of the Mabou Group. Elsewhere, it is unconformably overlain by the Upper Carboniferous Scotch Village Formation of the Pictou Group, but at the Milford GMA and in the Shubenacadie Basin generally, it is overlain with a distinct angular unconformity by only much younger Cretaceous and Pleistocene deposits.

4.5 Relation of the Carboniferous deposits to the Milford GMA

As was noted in Sections 4.4.7 and 4.4.8, only the Green Oaks Formation and a small bit of the Watering Brook Formation are found directly below overburden within the boundaries of the Milford GMA. Their presence is known from observations made by Giles and Boehner (1982) at less than 20 surface outcrops along the Shubenacadie River, Barney’s Brook, and Highway 2 west of Rennie Lane, plus from information obtained from eight drill holes located roughly within the same area, with interpolations made from that limited data.

However, all of the Carboniferous formations described in Sections 4.4.2 to 4.4.8 are also known to be present in below overburden and at depth beneath the Milford GMA based on drill hole evidence. The stratigraphic units present below the Milford GMA should be expected to approximately match those in Figure 13 between the Meadowvale and Milford Station Faults, likely in about the same thicknesses, except perhaps the Green Oaks Formation, which may be thicker under the Milford GMA than is shown in Figure 13.

4.6 Cretaceous geology

The Cretaceous Period is represented by the Chaswood Formation only (Keppie, 2000), as isolated outliers in northern Nova Scotia (see Figure 14) and eastern New Brunswick. It is a 200-m-thick succession of non-marine (Eisnor, 2002), loosely indurated fluvial conglomerate, sandstone, and mudstone.

The Chaswood Formation has been documented in detailed studies since the 1950's, and general mapping projects from as early as the 1900's have postulated that the deposits are of Cretaceous age.

Many of the studies of the Chaswood Formation were aimed at identifying and characterizing the provenance and source for offshore reservoir rocks (Pe-Piper et al, 2004; Piper et al, 2007; Piper et al, 2008; Pe-Piper and Piper, 2010; Reynolds et al, 2010).

However, the Chaswood Formation has been the target of commercial interest in its own right regarding exploration efforts near the Milford GMA for silica sand and kaolin (Stea et al, 1996; Gillis, 1997, 1998; Price, 2000; Wightman, 2012). The Shubenacadie water supply wells are also drilled into the Chaswood Formation (which constitutes the more significant part of the SMAC).

The Chaswood Formation outcrops in only two sand and gravel pits and one clay pit locally, and is thus known mostly from around 250 boreholes throughout Nova Scotia and New Brunswick.

4.6.1 Depositional framework

The early Cretaceous was a period of rapid sediment supply from crystalline rocks of the Appalachians as a result of fault reactivation related to the opening of the North Atlantic Ocean. In addition, uplift of the Labrador Rift supplied large amounts of sediment from the Canadian Shield via the then “Sable River” to the Sable sub-basin of the Scotian Basin (Pe-Piper and Piper (2018).

The resulting thick deltaic sandstones that were deposited are the reservoir rocks of the offshore gas and oil fields of the Scotian

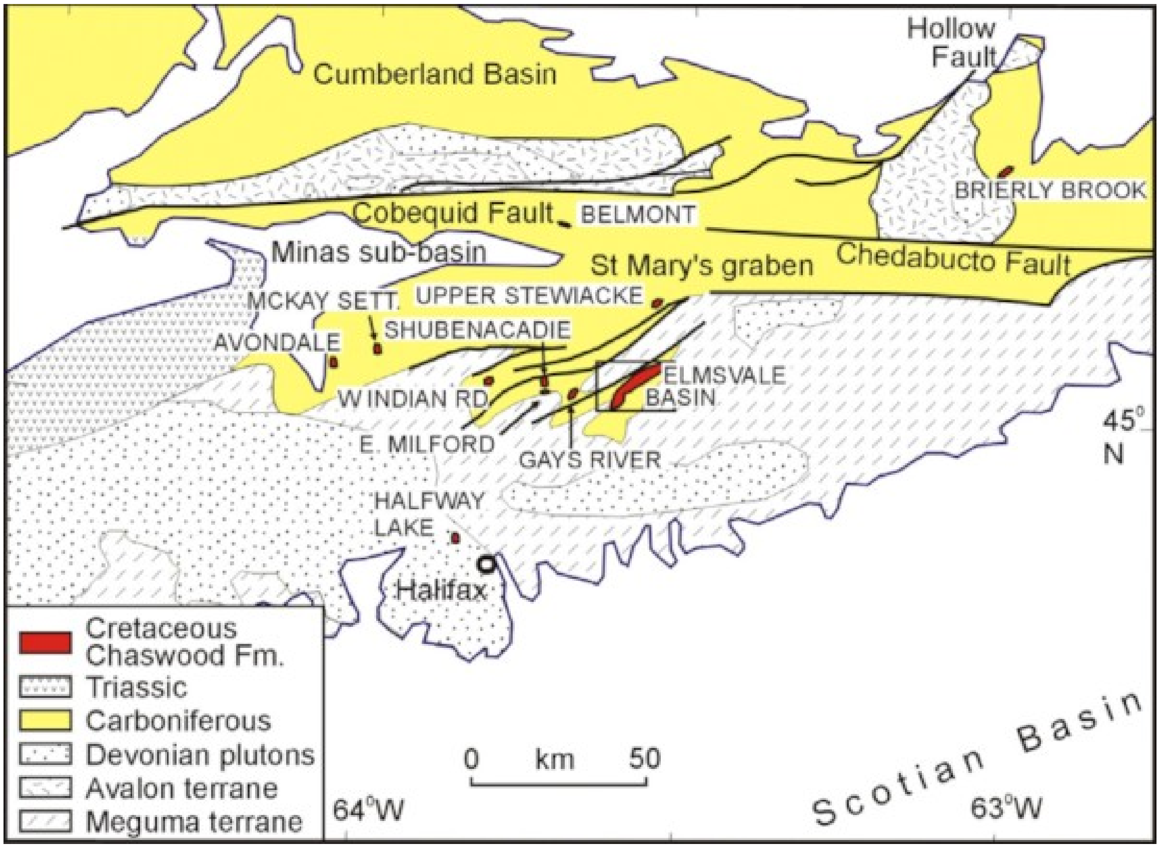


Figure 14. Map showing the distribution of the Chaswood Formation in Nova Scotia (from Pe-Piper et al, 2004).

Basin (Gobeil, 2002; Pi-Piper et al, 2004, 2004a); the on-shore Chaswood Formation is stratigraphically equivalent to the offshore Alogan Canyon, Naskapi, and Missisauga Formations of the Scotian Basin (Pe-Piper et al, 2004).

Chaswood Formation deposition was synchronous with progressive tectonic deformation along NNE-trending strike-slip faults in basement rocks, basin formation, and uplift of horsts that shed local detritus (Stea et al, 2003, 2004; Pe-Piper and Piper, 2004), although some karst from underlying Carboniferous evaporite dissolution is thought to have had some control also on deposition (Fletcher, 2004; Falcon-Lang et al, 2007). Synsedimentary tectonic deformation along strike-slip faults also led to local uplift that created intraformational unconformities (Gobeil et al., 2006), which can be used for regional correlation (Hundert et al., 2006).

Price (2000) has divided their sand deposit exploration targets in two groups, where larger deposit targets were found to be located in low-lying channel and basin areas (possibly karst?), and smaller deposit targets were located in higher elevations, appearing to be either fault, thrust, or fold controlled.

Gobeil et al (2006) suggested an east-southeasterly depositional flow direction for the Chaswood Formation at West Indian

Road, but the sediment provenance suggested by Pe-Piper et al (2008) and Pe-Piper and Piper (2018) and the orientation of the depositional valley near the Milford GMA would suggest a west-southwesterly flow for Chaswood Formation deposition locally.

4.6.2 Chaswood Formation lithology

The Chaswood Formation is composed mainly of terrestrial clastic sediments, with a dominance of quartzose sand (silica clay), multicoloured kaolinitic clays and lignitic clays and lignite. Purple, yellow and red in the clays reflect ferric oxide. Feldspar and gypsum may be present.

Stea and Pullan (2001) subdivide the Chaswood into three informal members: the lower, middle and upper. The lower and upper members show fining-upward cycles of coarse- to fine-grained quartz sand and silt, grading upwards into multicoloured, mottled and light-grey silty clays. The middle member has thick sequences of laterally continuous black and grey, lignitic clays and lignite. The lignite horizons vary from a few centimetres to 1.5 m thick.

The fining-upward cycles of the lower and upper members of the Chaswood Formation are characteristic of fluvial systems (Miall, 1992). Stea and Pullan (2001) did not see evidence for deltaic sedimentation, such as coarsening-upward facies and progradational clinoform bodies. Perhaps the most promising scenario is an anastomosing river system.

Rhythmically laminated organic muds near the base of the lower member may indicate tidal deposition (Dalrymple, 1992), although Eisnor (2002) found no evidence of marine foraminifera in the Windsor area outlier, and marine foraminifera found at other localities is thought to have been reworked (Warringer, 1996).

The middle member is dominated by organic-rich, fine-grained sediments indicating lacustrine or estuarine environments. Freshwater algae suggest terrestrial swamp and shallow lakes with changing water levels (Stea and Pullan, 2001). From the abundant charcoal, Scott et al. (1998) deduced that forest fires were common; these authors also suggested that there were alternating wet and dry periods denoting seasonality.

The red and white mottled clays and red massive clays at the top of some fining-upward cycles may represent zoned paleosols (Stea and Pullan, 2001). According to these authors, the formation represents the erosional remnants of a formerly thick and extensive basin, which overstepped local highlands. This is based on the mineralogy, the relationship with faults, and thermal maturation studies (Hacquebard, 1984).

4.6.3 Chaswood Formation distribution

The Chaswood Formation unconformably overlies rocks of the Windsor Group and unconformably underlies Quaternary sediments. Gobeil et al (2006) and Reynolds et al (2010) show a maximum thickness for the Chaswood formation of approximately 130 m in drill holes at West Indian Road. Stea and Pullan (2001) show a maximum thickness for the Chaswood Formation of approximately 110 m in drill holes in both, the Musquodoboit (Elmsvale) Basin, and in drill holes located south of Shubenacadie,

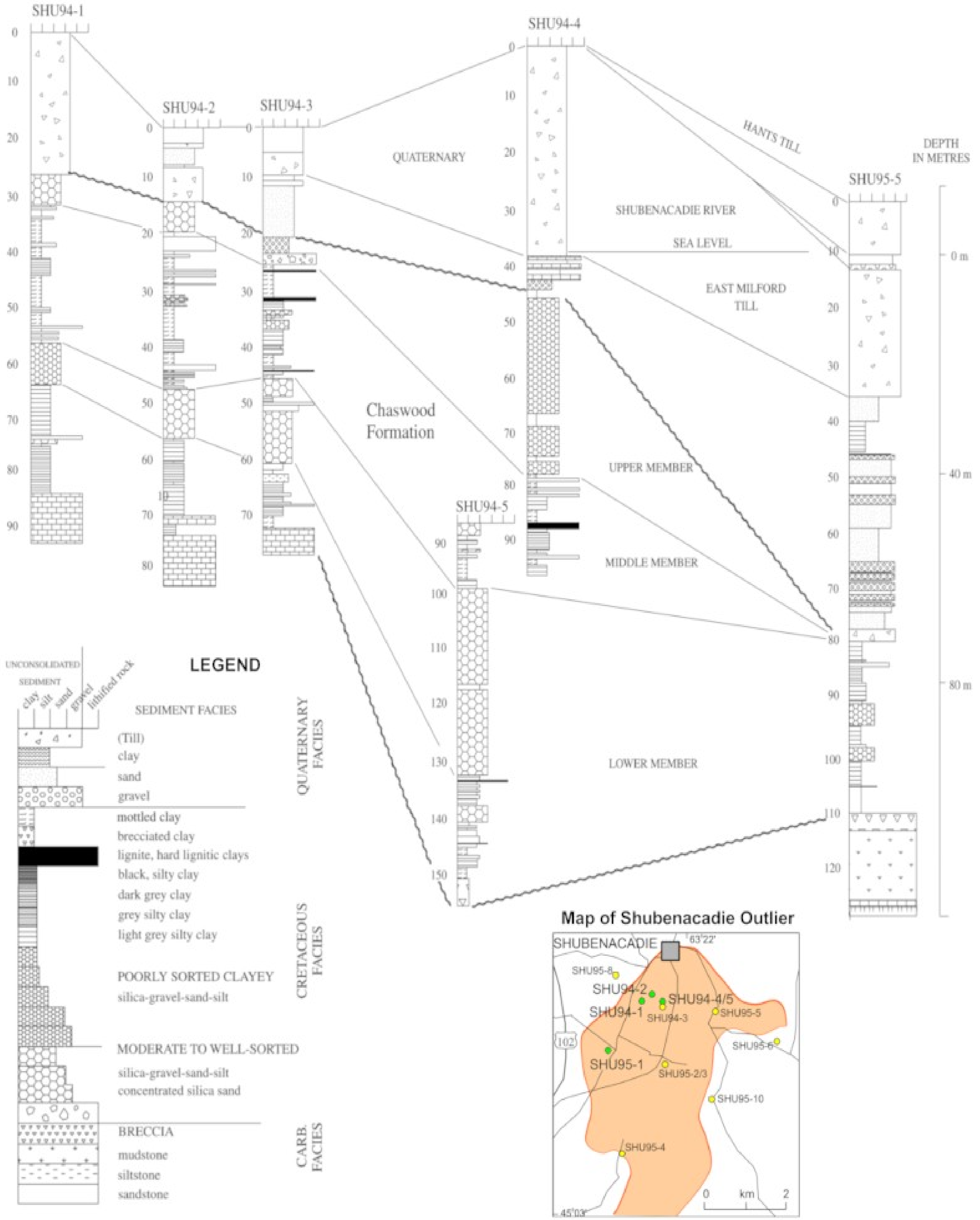


Figure 15. Cross section west-to-east in the north part of the SMAC just south of Shubenacadie (from Stea and Pullan, 2001; location index map from Pe-Piper et al, 2004a).

with thicknesses of roughly 50, 25 and 35 for the lower, middle and upper members of the Chaswood Formation, respectively (see Figure 15). However, within the Chaswood Formation south of Shubenacadie (the SMAC), the middle member does not appear to be present everywhere within the southern-most parts of the depositional body (Stea et al, 1996; Matheson, 1999).

The distribution of the Chaswood Formation is thought by all earlier researchers to have been much more extensive during its deposition during the Cretaceous Period than has been preserved in the known outliers.

Stea and Pullan (2001) have proposed a hypothesis to explain the “hidden” nature of the Chaswood Formation, based on what they have identified as the sequence of events recorded at the Elmsvale basin (Figure 16):

1. Early Cretaceous deposition of the Chaswood Formation ca. 140–110 Ma (age range).
2. Post-Early Cretaceous faulting; regional uplift and erosion ca. 110–80 Ma.
3. Mesozoic–Tertiary exhumation, erosion, and nondeposition ca. 80–2 Ma.
4. Quaternary deposition.

Their hypothesis requires a thick cover of Mesozoic sediment (1–2 km) to account for the survival of Cretaceous deposits while also accounting for ~80 million years of exhumation or erosion occurring since the mid-Cretaceous, the inferred timing of the tectonic event, and the last record of deposition before the Quaternary. Freshwater deposits (Chaswood Formation) in lowlands far below present sea level imply regional uplift to account for the lack of marine incursion during Mesozoic and Cenozoic periods of higher eustatic sea levels. Tertiary sediments are absent in Maritime terrestrial basins, so Cenozoic cover was probably minimal, but a large Tertiary basin offshore implies considerable Cenozoic erosion. A rough estimate of the 1.6 km of Mesozoic cover can be derived by simply multiplying a conservative estimate of the denudation rate for the Appalachians (20 m/Ma) by the elapsed time of erosion (80 million years).

Thermal maturation studies support the idea of substantial Mesozoic cover. The depth of burial of lignite beds within the Chaswood Formation has been inferred to be 1 km based on vitrinite reflectance values between 0.31 and 0.48% (Hacquebard 1984; Stea et al. 1996) and forward modelling of apatite fission-track data, assuming an average geothermal gradient of 30°C/km. Others have estimated a Mesozoic cover of about 2 km based on thermal maturation indices in the Fundy Basin.

The structural-exhumation hypothesis by Stea and Pullan (2001) infers that Carboniferous and Mesozoic sediment was eroded from the tops of Mesozoic horst blocks, such as Wittenburg Mountain, made of resistant older rocks (Figure 16). Early Cretaceous sediments were “hidden” or preserved in the structural valleys adjacent to the horsts, whereas Mesozoic and Cenozoic erosion largely exhumed the pre-Carboniferous accordant upland “peneplanes” across Nova Scotia.

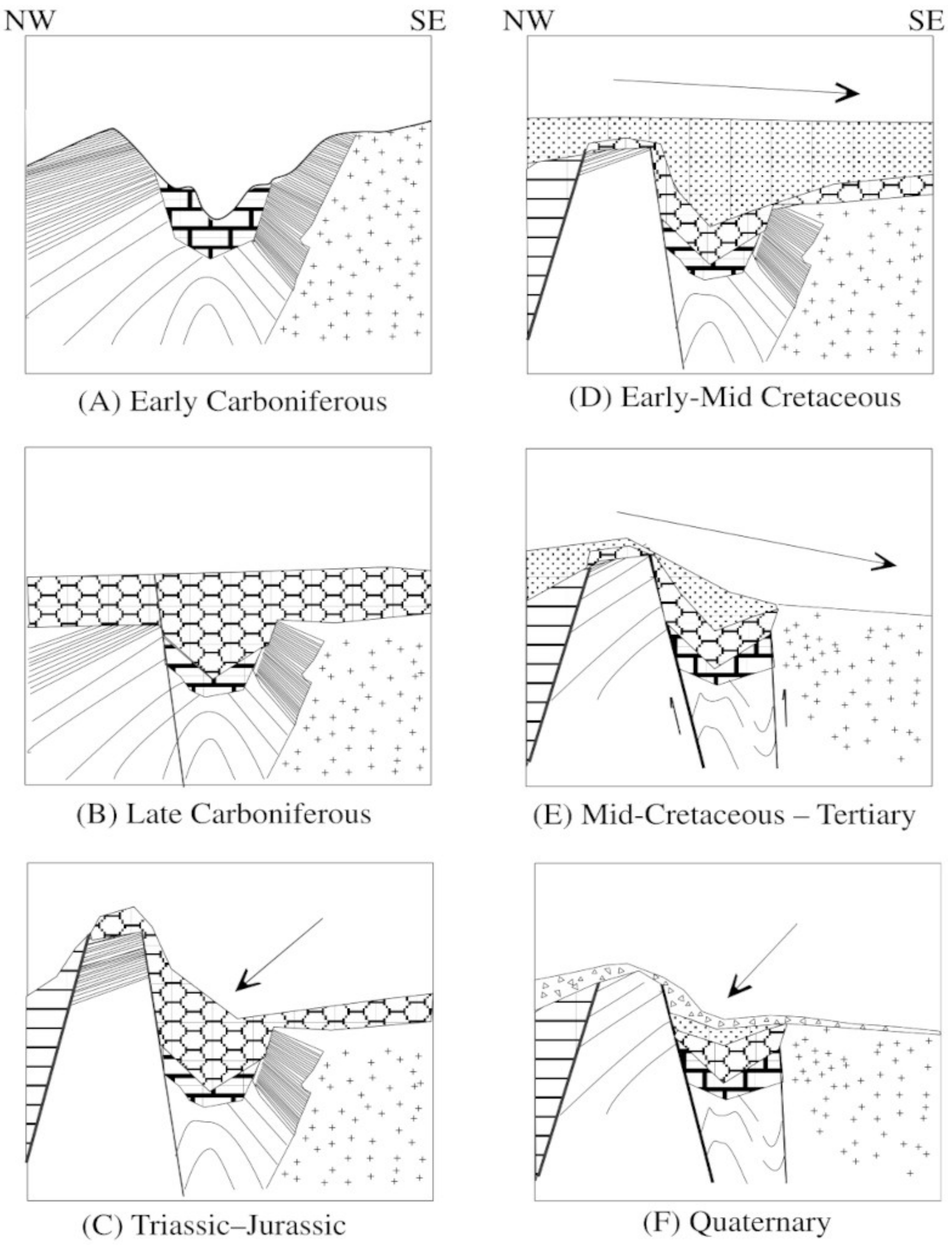


Figure 16. Structural-exhumation hypothesis for the evolution of Nova Scotia landscapes (from Stea and Pullan, 2001). (a) Carboniferous sediments deposited in continental-epeiric basins, with (b) Peneplane formation in the Late Carboniferous. (c) Triassic rifting and landscape rejuvenation. Deposition of Triassic–Jurassic sediments in the Fundy Basin. (d) Deposition of Early Cretaceous sediments in a low-relief coastal plain fluvial environment. North–south regional consequent drainage. Residuum in upland areas feeds the deltas and provides kaolin and quartz. (e) Mid-Cretaceous diastrophism creates or reactivates basin faults forming structural valleys followed by further Tertiary uplift and denudation. Subsequent valleys formed. Regional subsidence. (f) Quaternary modification, valley incision. Note: Arrows denote drainage directions.

4.7 This study's mapping of the Chaswood Formation

Matheson (1999), Stea et al (1996), Stea and Pullan (2001), Price (2000), Pe-Piper et al (2004a), Whightman (2012), and Kennedy (2014) show the sub-aerial extent of the Chaswood Formation south of Shubenacadie (the SMAC, as defined by Matheson, 1999) only to approximately the northern boundary of the Milford GMA.

In light of the significance of the SMAC as water source for the village of Shubenacadie and surrounding farms, the potential for it to perhaps also serve the Milford GMA, should it extend into the community, and also to help identify the need to protect it if it does, mapping was carried out as part of this study to assess if and where the Chaswood Formation might be present farther south.

That mapping was done at the mid-scale, covering a 5 km area around the Milford GMA, following these steps:

1. data was extracted[8] from the NSE (2016, 2018) and NSDEM (2020) well log databases to include only those records for drilled wells and for which the well location UTM coordinate accuracy was indicated to be better than 30 m,
2. records without depths for casing or bedrock were removed from the data-set, and Boolean math and calculations were applied to assign and qualify bedrock depth values (i.e. actual bedrock depth given, or assumed "greater-than depth" where well casings did not penetrate bedrock, as would be the case for wells completed in unconsolidated material),
3. similarly, data was extracted from the NS Exploration Borehole Database (O'Neill and Poole, 2016) to included only records for which depth to bedrock[9] was given,
4. records from steps 2) and 3) were merged to produce a bedrock-depth database with 691 valid data points within the mapping area,
5. LiDAR data from Geonova (2020) and HRM (2018) was imported and patched to create a continuous map area DEM,
6. ground surface elevations were "picked" from the DEM at each well/borehole record location from step 4), and top-of-bedrock elevation, soil thickness were calculated and added to their attributes,
7. working at 3 m resolution to speed up computations while still giving sufficient accuracy, interpolation of the the data from 6) was performed using bilinear spline interpolation with Tykhonov regularization using the Cholesky solver, a 1000 m NS step, 1x10^{-6} error break criteria, and Lambda_i of 0.01 for smoothing, to generate the 3D surface raster maps in Figures 17 and 18.

---

[8] First, for future larger-scale mapping, UTM coordinates were applied to records in the database for those few wells within 1 km of the Milford GMA for which Civic addresses were given. The UTM locations for those wells were "picked" as being between roads and what appeared to be the main building at those Civic addresses.

[9] Since the Chaswood Formation appears to be poorly indurated generally within the mapping area, well logs and exploration borehole logs appear to have all treated it as overburden, with the depths to bedrock recorded actually representing the more competent, Carboniferous rock.

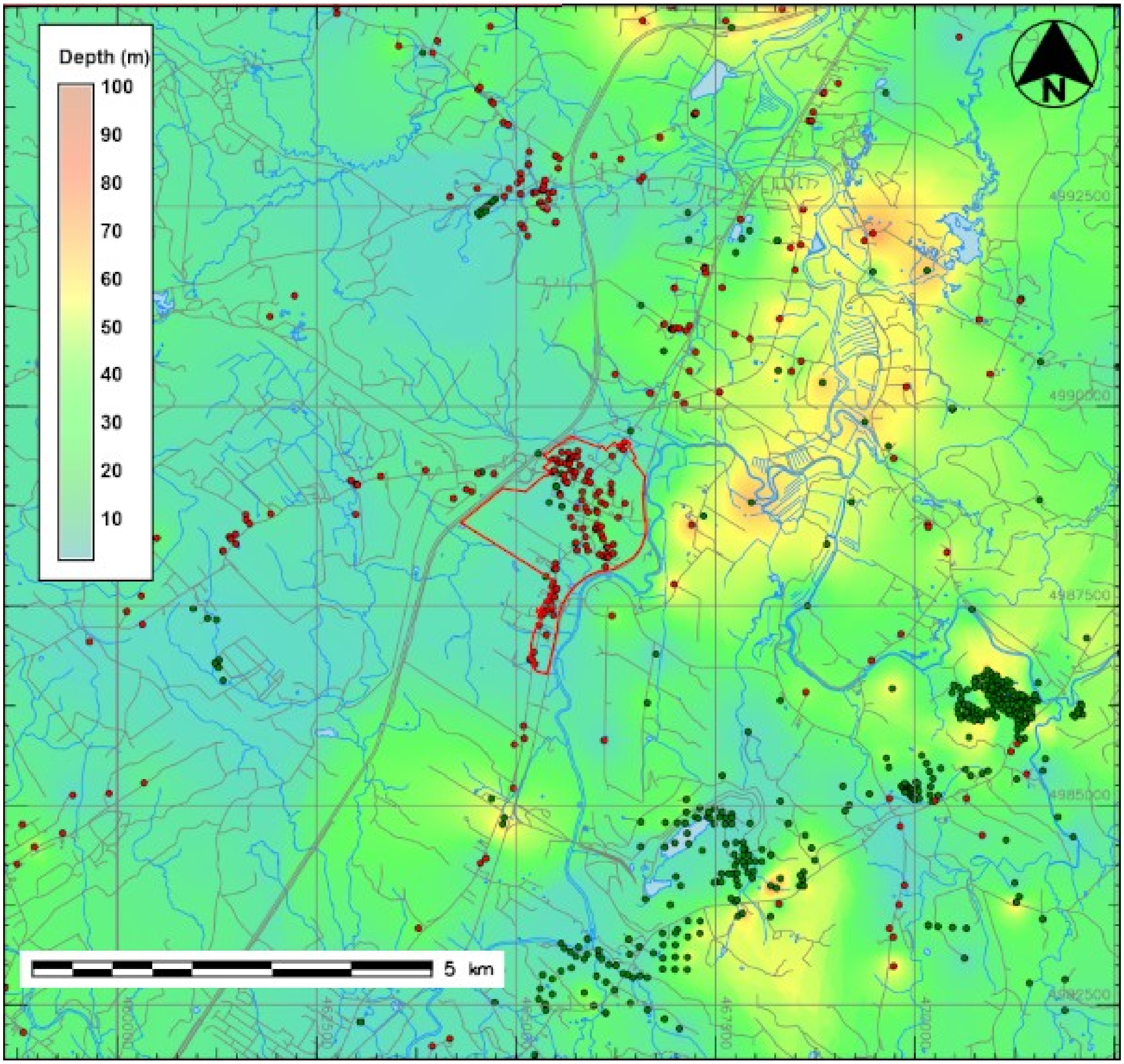


Figure 17. Depths (m) below ground surface to the top of Carboniferous rocks. Green dots represent exploration borehole locations with overburden depth information, red dots represent water wells with depths to bedrock (see text) available and for which UTM coordinates are accurate to within 30 m. Basemap from Geonova (2020), Carboniferous bedrock depth data from NSE (2016, 2018), NSDEM (2020), and O'Neill and Poole (2016).

Extreme anomalies in the early interpolations were verified against source data to ensure the accuracy of the Boolean decisions made on well log information; only about a dozen data points needed correcting.

Figure 18 shows the outline of the Early Cretaceous structural/erosional valleys that had been carved into Carboniferous rocks (as depicted by card c) in Figure 16) into which Chaswood Formation deposits might be able

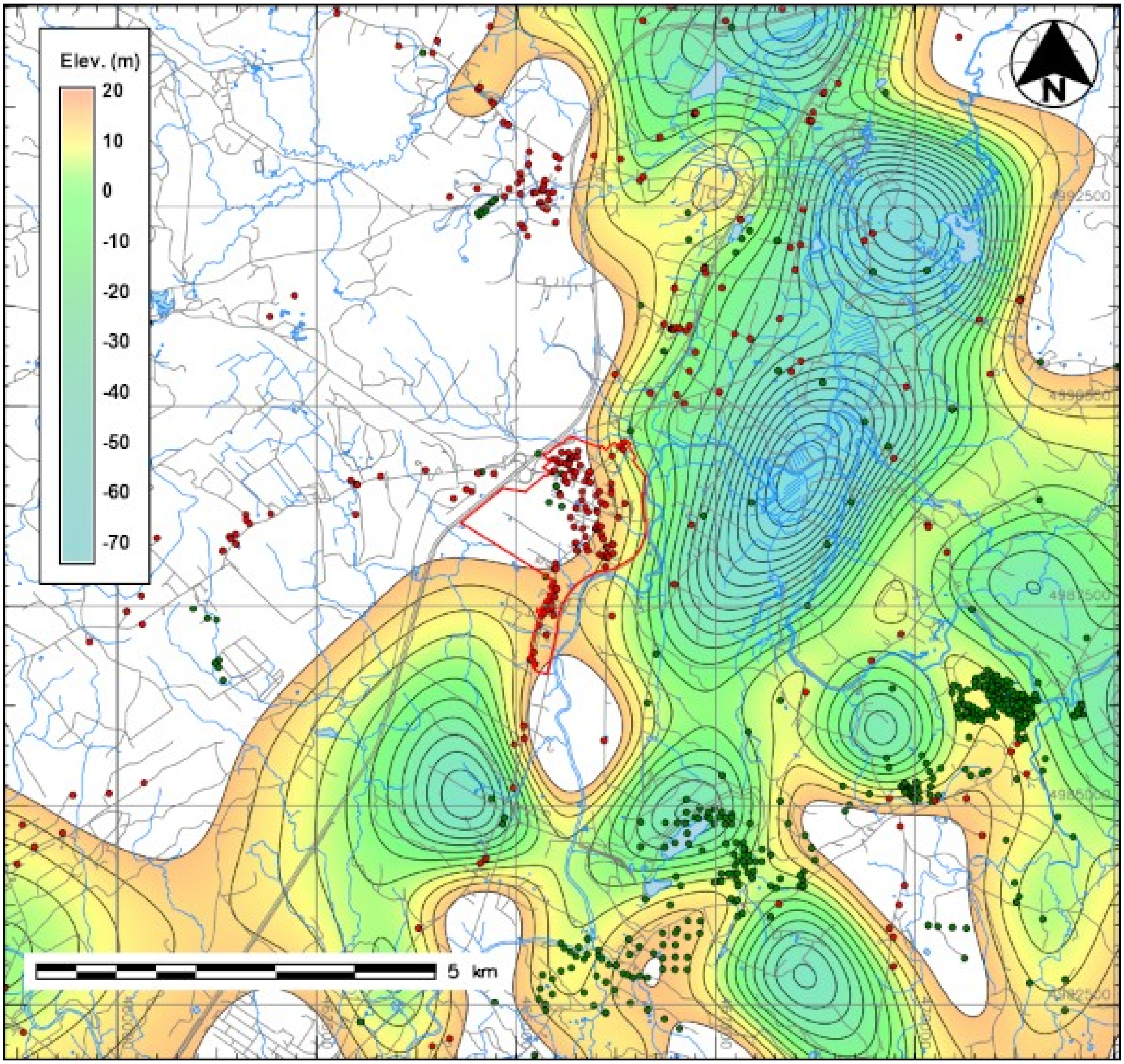


Figure 18. Elevation (m) below 20 m (mean sea level) of the top of Carboniferous rocks. Green dots represent exploration borehole locations with overburden elevation information, red dots represent water wells with depths to bedrock (see text) available and for which UTM coordinates are accurate to within 30 m. Elevation contour intervals = 5m. Basemap from Geonova (2020), Carboniferous bedrock depth data from NSE (2016, 2018), NSDEM (2020), and O'Neill and Poole (2016).

to accumulate and be preserved (as depicted by cards d) to f) in figure 16). However, the Milford GMA is situated on a Carboniferous bedrock high, right on the edge of what appear to be the Early Cretaceous erosional valley, so Chaswood deposits are less likely to have been deposited or preserved beneath the community.

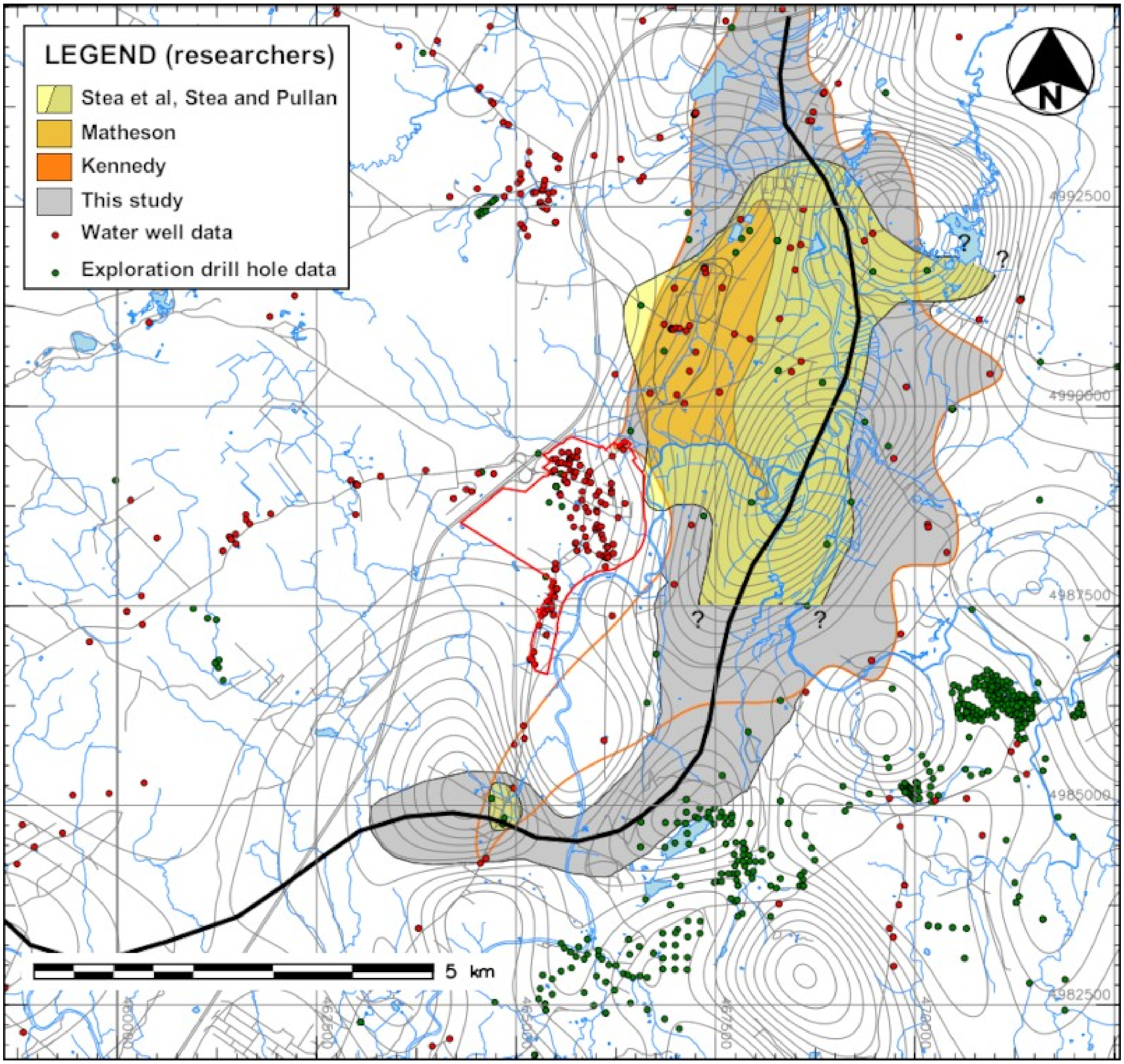


Figure 19. Sub-aerial distribution of the Chaswood Formation sand-bearing channel deposits near the Milford GMA (boundaries in red), from Stea et al (1996) and Stea and Pullan (2001), Matheson (1999), Kennedy (2014), East Hants (2021a), and as interpreted for this study. The green and red dots are as per Figures 17 and 18, with the eroded Carboniferous rock surface elevation contours (5m interval) carried over from Figure 18. Basemap from Geonova (2020).

Figure 19 shows the sub-aerial distribution of the Chaswood Formation channel deposits as defined by Stea et al (1996), Stea and Pullan (2001), Matheson (1999), and Kennedy (2014), and as reinterpreted for this study.

Interpreting the sub-aerial lateral extent of the Chaswood Formation for this study was done based on the more recent overburden depth and Carboniferous rock surface elevation data presented in Figures 17 and

18, followed by confirmation of Chaswood Formation type deposits by reviewing individual well logs and borehole information where lithologic descriptions were provided.

Previous researchers did not give clear explanations on why they ended their mapping where they did within the greater Milford GMA – Shubenacadie area. The mapping coverage by Stea et al (1996) and Stea and Pullan (2001) included large parts of the Shubenacadie and Musquodoboit Basins, so their mapping limits of the Chaswood Formation near the Milford GMA appears to have been due to data availability limitations (as evidenced by the question marks on their maps). The limits of the mapping done by Matheson (1999) may have been due to some degree to data availability constraints, but mostly to political boundaries; his study was limited to areas within East Hants.

Kennedy gives no explanation for why he extended the Chaswood Formation to the north or south beyond what Stea et al (1996) and Stea and Pullan (2001) had shown, but it is apparent that his southern delineation of the Chaswood Formation was done as an attempt to join the small southern bit shown by them at UTM 464865E/4985040N, to the rest of the depositional body farther north by linear extrapolation simply without regard to the well or borehole lithology descriptions or underlying Carboniferous bedrock topography. The interpretation in this study satisfies both of those criteria.

The Chaswood Formation channel axis as shown in Figure 19 was drawn based on the Carboniferous bedrock surface valley topography and relative amounts of sand reported where lithologic descriptions were available in well log and/or exploration drill hole logs; the channel axis was extended following general bedrock topography to other sand deposits that had been reported in the Elmsdale area which description matched those of the Chaswood Formation.

4.8 Quaternary geology

The Quaternary Period (about 2.6 Ma to today) includes the Pleistocene Epoch (the period of latest glaciation, which started about 2.6 Ma and started to end 18,000 to 12,000 years ago), and the Holocene Epoch (the period following the last glacial melt).

The major features of the landscape of Nova Scotia – the overall relief, the distribution of highland, upland and lowland areas – are all the product of its long geological history. The minor features – the final rounding of surface features, the alignment of surface lineations, surficial deposits and sea-level changes – are the product of glacial activity that involved ice flows up to 1 km thick over Nova Scotia during the Quaternary Period.

The last phase of glaciation ended about 10,000 years ago and left behind, during the Holocene, an unconsolidated mantle of sediment. On it, drainage patterns were reestablished and soils were developed.

Much of the following is from Stea and Mott (1990) and Davis (1998). Deep-ocean-sediment core samples provide evidence that there were more than sixteen glaciations during the Quaternary. They generally each lasted about 100,000 years and progressed slowly until huge ice sheets covered most of Canada. But in Nova Scotia, only the last two glaciations (the Illinoian and the Wisconsin) have been identified. The Wisconsin glaciation started about 75,000 years ago and ended 12,000 to 10,000 years ago. Each major glacial advance, by its nature, tends to destroy evidence of previous glaciations. The glacial deposits and features in Nova Scotia are therefore almost all of Wisconsin age.

The main events of the Wisconsin glaciation have been interpreted from their deposits and from striation patterns which indicate ice-flow patterns. The Wisconsin glaciation occurred in four phases, with each leaving new deposits stacked over older ones where the older deposits were preserved, or onto bedrock where they were not. These stacked till sheets and superimposed striations helped to interpret the changes in ice flow.

Phase 1 striations, erratics, and till fabric suggest that the earliest and most extensive ice flow in Nova Scotia was eastward then southeastward. The majority of the drumlin fields in Nova Scotia were formed during this phase and modified during Phase 2.

Phase 2 ice flow was southward and southwestward from from the Escuminac Ice Centre in the Prince Edward Island region and established much of the drumlin topography and alignment of the geomorphological features in Nova Scotia.

Phase 3 included development of thick ice and an ice divide in southern Nova Scotia, with northward and southward ice flow.

Phase 4 saw mostly westward ice flow from remnant ice caps from Phase 3 and which formed over the Chignecto Peninsula, and where eskers and striations cut across features formed by earlier ice flows.

None of the advances in the late Wisconsin were as strong as those before, and they became progressively weaker, until the ice caps finally disappeared from Nova Scotia about 10,000–12,000 years ago.

These events left behind surficial deposits both regionally and locally, consisting of: ground moraine or sheet tills; drumlins; fields of erratics; glaciofluvial deposits such as eskers, kames and stratified kame terraces, ice outwash and river channel deposits, lacustrine deposits; and other water-lain and wind-sorted sand. Figure 20 shows their distribution at and around the Milford GMA.

4.8.1 Ground moraine and drumlins

Nearly 60% of the map area is covered by ground moraine – a smooth to hummocky glacial drift cover that is mostly composed of sub-glacial lodgement or melt-out till made of unsorted boulders and compact sand and mud, derived from both local and distant sources, and deposited under a glacier.

Within the Figure 20 mapping area, the silty till plain is a flat to rolling, with mostly thick glacial cover, composed of multiple tills with intervening layers of gravel, sand or mud (glaciofluvial deposits). The plain completely masks underlying Carboniferous bedrock undulations, ranging in thickness generally from 3 to 30 m – reaching a maximum thickness up to 70 m. The predominant till formations of the silty till plain are the Hants and Milford tills, which are characterized by silty-clay matrix.

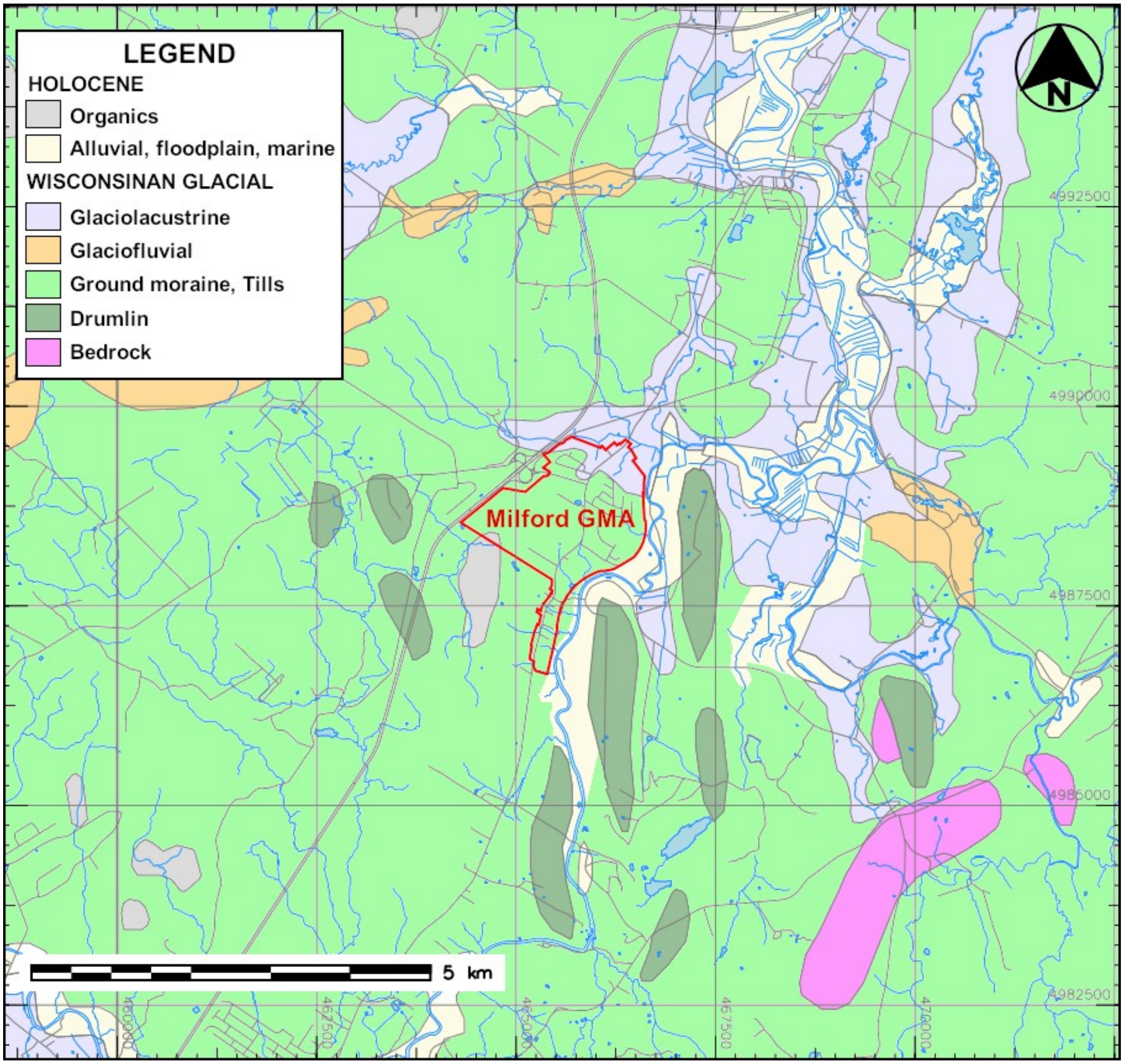


Figure 20. Quaternary (surficial) geology (Stea et al, 2006; Stea and Kennedy, 1998). Basemap from Geonova (2020).

The drumlin facies contain siltier till and a higher percentage of distant source material, including red clay. Drumlins are streamlined, elongate hills with a steeper, up-glacier facing slope, consisting of layers of glacial till up to 30 m thick. Although there are no modern examples of drumlins, they are thought to have formed as material released from the base of an ice sheet by melting, reworking, and moulding by ice action, often where there are large changes in the bedrock surface topography. The Nelson Hill drumlin east of the Milford GMA rises approximately 33 m above the surrounding land. The two drumlins south of the Milford GMA rise about 45 and 30 m above the river floodplain, respectively. Other smaller drumlins are apparent immediately to the south of and within the eastern half of the Milford GMA.

4.8.2 Glacial melt-water deposits

Around 30% of the Figure 20 map area is covered by sediments deposited by glacial melt-water – glaciofluvial, kame field and esker deposits that were often reworked in places by glacial lake currents or waves.

The glaciofluvial deposits are comprised of brown gravel, sand and silt, and diamicton layers that are poorly to well bedded, with horizontal to angular beds. Faulting and collapse features are common.

The glaciofluvial deposits present at surface are typically steep-sided, occurring as 4 to 20 m high mounds or hummocks (moulin kames), as 3 to 30 m high pitted terraces on valley sides (kame terrace), or as 5 m high sinuous, steep sided ridges (eskers). They were developed as streams of glacier melt-water depositing material in holes in ice (moulin kames), between glacier and valley slopes (kame terrace), in water (kame deltas), or in tunnels in or under the ice (eskers).

Also, between Shubenacadie and the Milford GMA, Matheson (1999) identified four distinct sets of 5-12 m and 35 m thick glacial channel sequences that have been buried under up to 25 m of Hants/Milford till. These buried channel-fill deposits are from earlier, phase 1, 2 and 3 glacial advances and ice-melts (Stea and Kennedy, 1998). The buried channels appear to have scoured and cross-cut each other and stacked vertically with and separated by up to 10 m thick till (the Miller creak till, per Matheson, 1999) and other laterally contiguous, penecontemporaneous channel deposits, all of which have incised into the underlying Chaswood Formation.

The glaciolacustrine deposits north and northeast of the Milford GMA in Figure 20 are generally present below 30 m elevation and are comprised of brown, varved (winter and summer deposits) fine-grained sand, silt and clay, and laminated, massive or crudely stratified diamictons (mixtures of gravel, sand, and mud). They are generally under 2 m thick, but can attain 30-40m along major valley streams. They were deposited in a ponded body of water either in direct contact with ice, or fed by glacial melt-water.

4.8.3 Holocene deposits

About 10% of the Figure 20 map area is underlain by Holocene sediments, where were deposited after the retreat of glaciers and sea-level rise starting 10,000 years ago. These consist of marine estuary, river (alluvial) and organic (bog, fen) deposits. The tidal bore extends well past the village of Shubenacadie and marine estuarine sediments are intercalated with alluvial deposits along the Shubenacadie River floodplain and its tributaries.

The alluvial deposits consist of rivers, abandoned channels, oxbow lakes, and flat floodplain gravel, sand and mud that are generally bedded – coarse at the base, finer at top. They form thin veneer less than 1 m thick in small streams, up to 20 m in large floodplains.

Locally, the organic deposits consist of sphagnum moss, peat, gyttja, and clay, in fens and swamps and in swamps along river valleys. They can range in thickness from 1 m at the edges to 5 m in the centre. They develop by infilling of ponds or river courses by vegetation.

4.9 Structural geology

As per Section 4.4.1 and Figure 12, the primary area geologic structures include:

- the steeply dipping northeast-southwest Milford Station and Meadowvale normal Faults, long which there has been about ½ km of vertical displacement,
- the northwest trending sinistral strike-slip Black Brook Fault, along which there has been an apparent ½ to 1 km of lateral displacement,
- the Salem Thrust Fault at Indian Road, at which there has been an apparent displacement of 1½ to 2 km, and
- anticlines and synclines, which axis are generally parallel to the Milford Station and Meadowvale Faults.

Stea and Pullan (2001) and Piper et al (2005) describe a northeast-trending tension fault in the Elmsvale basin southeast of the Milford GMA that post-dates Cretaceous sediments.

However, these faults have all been identified from borehole evidence – their locations are inferred from the relative location of surrounding stratigraphic units[10]. As such, they are likely an over-simplification of the structural geology that actually exists in the Milford GMA region. The relative shape, size and location the the Chaswood Formation valley northeast, east and south of the Milford GMA, plus the relative elevation of the bedrock surface under the community, are a testament to that and suggest that there are many more faults in the area than is shown in existing mapping.

With the exception of the recent exploration work done locally for sand and clay, since the downturn of the gypsum mining industry in Nova Scotia a few decades ago, there has been little to no economic incentive to better define the structural geology of the Milford GMA and immediate surrounding area.

However, since the public release of once-confidential oil and gas industry drilling and seismic information, new structural research has been published on the Kennetcook Basin north of Rawdon (Waldron et al, 2010; Keppie Sr, (undated); Javaid, 2011; and Keppie Jr, 2012).

Those recent reports show the presence of numerous northeast trending thrust and tension faults, along with also numerous intersecting northwest-trending dextral strike-slip faults, which were active before, during, and after Carboniferous deposition within the Kennetcook Basin, and which are likely to also extend south into the Shubenacadie Basin. Their work gives a very good insight on the extreme complexity of the structures that are likely to be present more locally.

---

[10] For example, Giles and Boehner show only three locations with structural data within 1 km of the Milford GMA – which show structural features striking at 11°, 111°, and 350°, and suggest a very complex local structural geology. The rest of their interpretations were made from core samples, which may be used to define dips, but not their strike.

5. Available aquifer units

With the exception of the very northern edge of the Milford GMA (at 2382 and 2394 Hwy. 2 and possibly 2367 Hwy. 2), the Chaswood Formation is not present below the Milford GMA to serve as a possible aquifer source for the community.

The aquifer units that are available for individual wells within the Milford GMA include Pleistocene glaciolacustrine deposits, which are present in the northern 10-15% of the community (beneath 25 to 30 of the existing homes), Pleistocene till, which underlies the rest of the community, and Carboniferous age bedrock – the Green Oaks Formation, which is present under most of the community, and the Watering Brook Formation, which is present at the very southern tip of the Milford GMA.

The following two sections give general descriptions of these aquifers in terms of their accessibility and viability to serve private well demands within the community. More detail on well yields and groundwater quality is given later in Sections 6 and 7.

5.1 Pleistocene aquifer units

Although there are no records of their permeability locally, the glaciolacustrine deposits are expected to be quite clayey and have a generally low permeability – probably with hydraulic conductivity values that are similar to those for till.

For the till, hydraulic testing was done by Stantec (2010) at three monitoring wells located behind the Shubenacadie water treatment building, about 1.8 km north of the Milford GMA. Those rising head slug tests yielded hydraulic conductivity values for till ranging from 1.6×10^{-7} to 3.7×10^{-6} cm/s in the three wells, with geometric mean of 7.5×10^{-7} cm/s . These values are about a mid-range for glacial tills (Freeze and Cherry, 1979). There are no known reports indicating any changes in till composition regionally or locally, so similar hydraulic conductivity values for till may be expected also at the Milford GMA.

Hydraulic conductivity values in the 7.5×10^{-7} cm/s range typically would not allow wells dug into the till to produce enough water to meet most residential needs. Where dug wells constructed in tight till are successful generally is when they are dug down to the till/bedrock interface – at which water slowly permeates though the till to recharge a thin layer of weathered bedrock at the interface, which can them flow more easily into wells. This (and also to allow more water storage in the well) is why most dug wells are generally excavated down to the bedrock surface. Due to the maximum reach of larger excavators, this typically also limits the depths for dug wells to 7 or 8 metres.

Figure 21 is a larger-scale (zoomed-in) version of Figure 17 that shows soil thickness (distance from ground surface to the top of bedrock) in greater detail within the Milford GMA. Again, Figure 21 is limited to using only those water well records (NSE, 2016, 2018) for which UTM coordinates are known to be accurate to within about 30 m.

On the basis of not exceeding excavator reach limitations (i.e. where overburden thickness is under 8 m), Figure 21 suggests that higher yielding dug wells may be viable

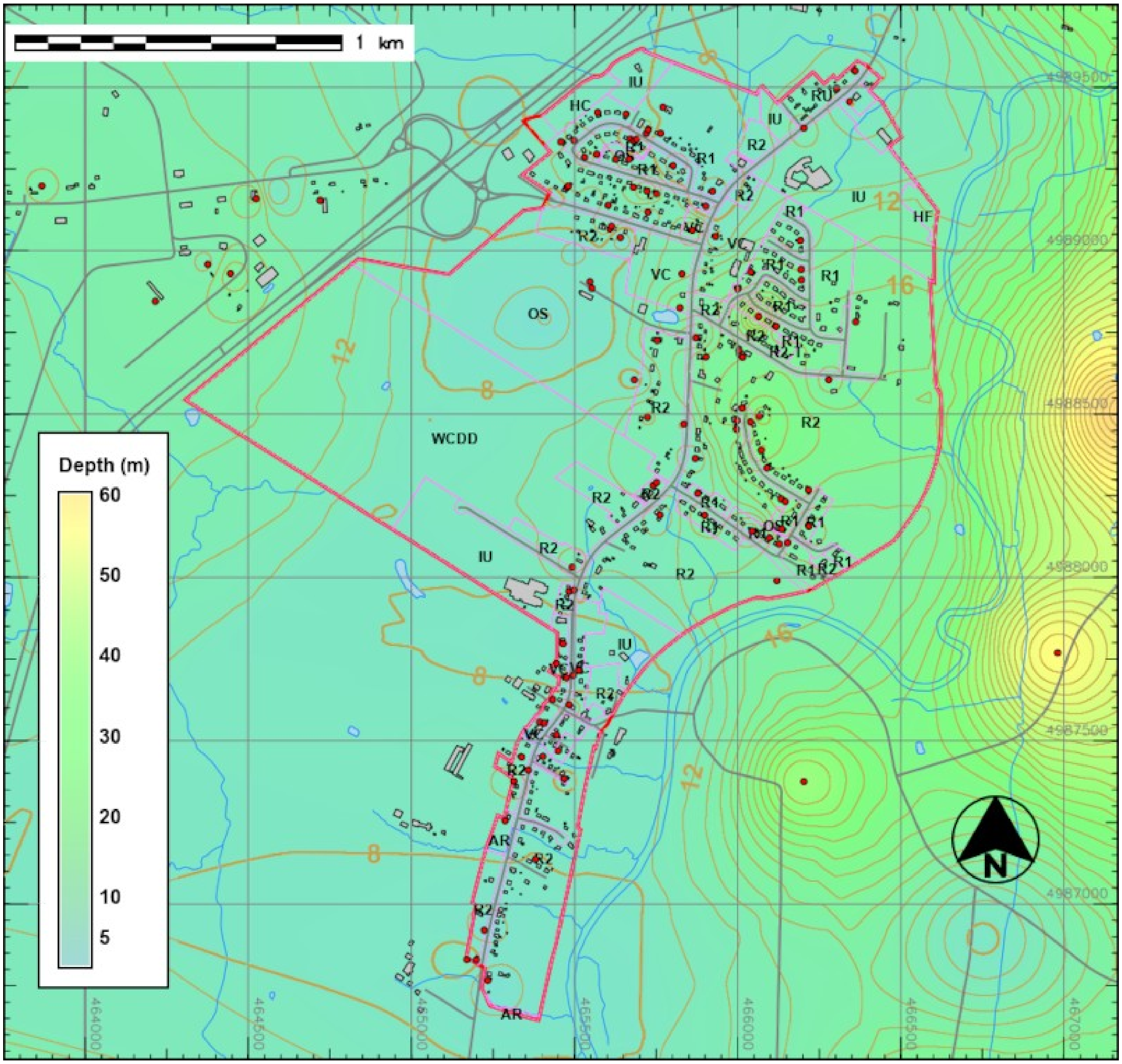


Figure 21. Overburden thickness (contour interval 2 m) within the Milford GMA (red boundary). Red dots show data sources (wells with UTM coordinates accurate within 30 m). Purple lines are municipal zoning boundaries. Base maps from Geonova (2020) and East Hants (2021b).

only within part of the open-space lands at the west edge of the Milford GMA, at the institutional and R1-zoned properties along the northwest edge of the community, or at two locations at institutional and R2-zoned properties south of Riverside Drive.

Notwithstanding the possible viability of constructing dug water supplies at these locations, dug wells are prone to surface contamination, and due to short groundwater travel and residence times, water pH and total dissolved solids are often quite low, making water from dug wells more corrosive to plumbing systems. Also, the depths to the groundwater table in surficial deposits can vary based on topographic relief, material permeability, and recharge. Groundwater levels in dug wells can fluctuate 1 m to 2 m seasonally, with larger fluctuations causing problems with wells going dry in summers. These issues may be exacerbated by reduced recharge in paved urban areas, and by gravel-filled trenches for storm and sanitary sewer systems that may act as groundwater drains.

There is only one dug well reported in the NSE (2016, 2018) well log database – it is reported to be 4.6 m deep but no well yield is given – it at an undetermined location (a UTM accuracy within 800 m is reported in the database record) somewhere probably in the Lacey Road to Hunter Road area.

5.2 Bedrock aquifer units

Based on the well log records (NSE, 2016, 2018), all but one of the water supply wells that are located within the Milford GMA have been drilled into the bedrock aquifer units (hydrostratigraphic units, or HU's[11]).

The NS well log database contains records for 374 drilled wells that have either been confirmed to be present within the Milford GMA based on UTM coordinates (there are 100 wells which UTM coordinates are accurate to within 30 m), or which are strongly understood to be within the Milford GMA based on how their geographic locations are defined.

There may be more than 374 drilled wells in the community – newly drilled wells may not be in the database yet as there can be an 18 to 24 lag time from drilling, to reporting by drillers, to data entry, to the public release of the data. Also, not all wells find their way into the database due to lost records or failure by drillers or well diggers to report newly constructed wells (this is a particular concern for dug wells).

Wells that are drilled into the bedrock of the Shubenacadie Basin are known for their potential to produce groundwater that is hard, with elevated values for total dissolved solids (TDS) and sodium, chloride (both derived from halite) and sulphate (derived from gypsum and anhydrite). Also, because of the chemically reducing conditions that are often prevalent within these bedrock HU's (due to their high organic and in some places the petroliferous nature of Windsor and Mabou Group formations), iron and manganese can be readily dissolved from aquifer materials to negatively affect well water quality.

These are issues that can also affect well water quality from the bedrock HU's (the Watering Brook Formation, the Green Oaks Formation, and the MacDonald Road Formation beneath it), which directly underlie the Milford GMA (more details on well water quality are provided in Section 7 of this report).

---

[11] A Hydrostratigraphic Unit (or HU) is defined as a part of a body of rock or a soil unit that forms a distinct hydrologic unit with respect to the flow and the quality of groundwater. For example, the SMAC, which contains both Cretaceous and Pleistocene channel sequences, has at least two HU's since the flow and chemical characteristics for groundwater in either of them is likely to be different. Separate channels of each geologic age may be considered as different HU's also if groundwater flow and chemical characteristics vary channel to channel. Likewise, each bedrock formation, and each member within each formation, may be considered as separate HU's.

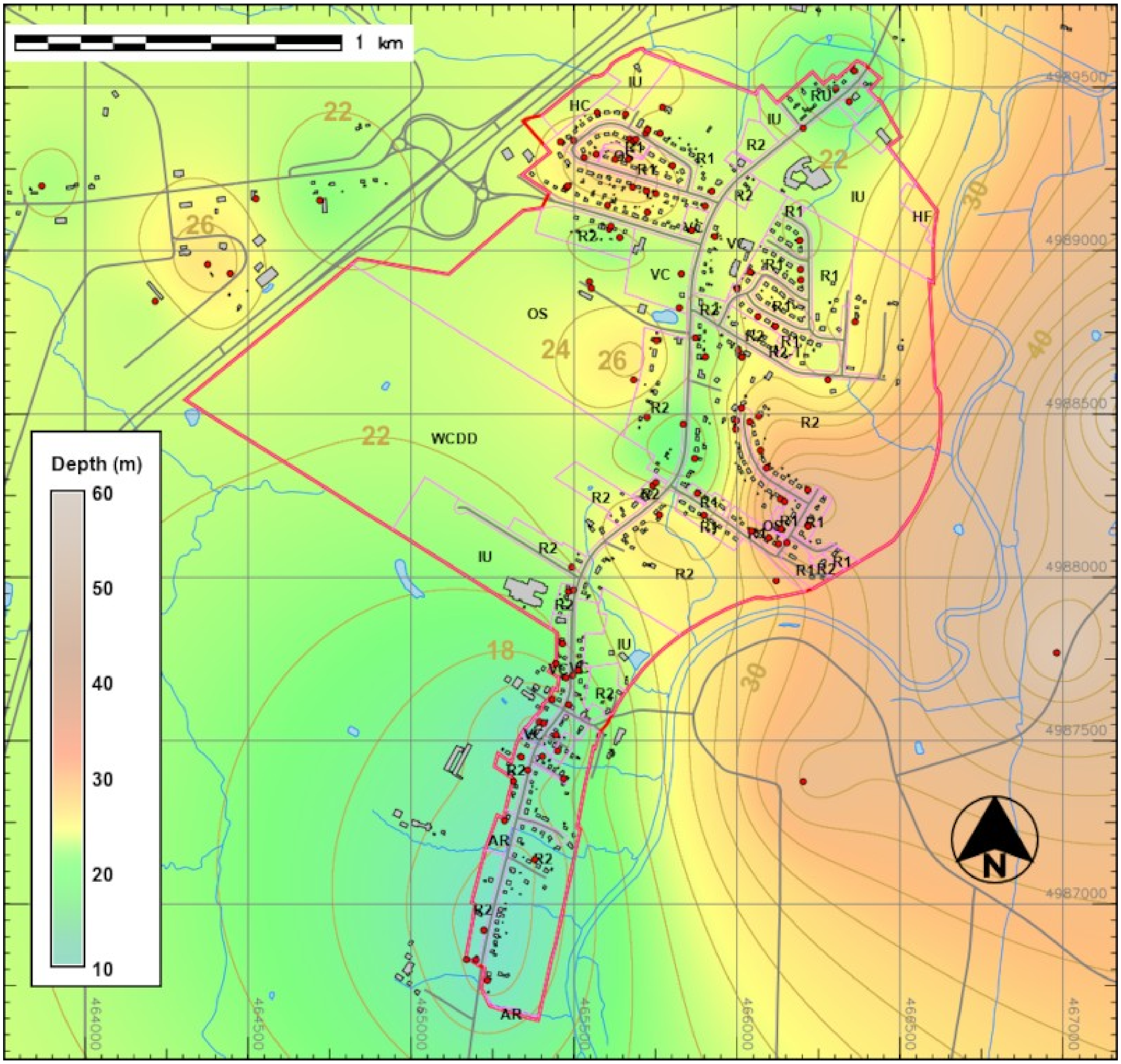


Figure 22. Well casing depths (contour interval 2 m) within the Milford GMA (red boundary). Red dots show data sources (wells with UTM coordinates accurate within 30 m). Purple lines are municipal zoning boundaries. Base maps from Geonova (2020) and East Hants (2021b).

While the map in Figure 21 shows depths to the bedrock surface, Figure 22 shows well casing[12] depths below the ground surface as interpolated from wells with known locations within the Milford GMA.

---

[12] Well casing is used generally to hold back overburden to prevent it falling down into the well. However, well casing can also be used to seal off shallow heavily fractured bedrock that could allow surface water to leak into the well, either as recharge through soil, or as water flowing directly along the outside of the casing. Well casing may also be used to seal out zones within wells that can negatively affect water quality, such as bedrock horizons that may contain gypsum, halite, or petroliferous material.

Depths to the bedrock surface range from 1 to 35.4 m (average 12.6 m, from 92 wells with data) for wells with known UTM coordinate locations, and 0.3 to 47.3 m (average 12.0 m, from 323 wells with data) for all wells located within the Milford GMA. However, well casing depths range from 6 to 49.1 m (average 23.1 m, from 99 wells with data) for wells with known UTM coordinate locations, and 1.5 to 56.1 m (average 20.4 m, from 338 wells with data) for all wells drilled within the Milford GMA.

Figure 22 shows that well casing depths, which are nearly consistent between 20 and 24 m within the western ¾ of the community, deepen to the east to more-or-less follow overburden thickness. Together, the two data sets and figures suggest that the bedrock surface is probably quite fractured, thus requiring that well casings be advanced on average 12 to 14 m into the bedrock before competent casing seals are possible to avoid possible surface water contamination.

The map in Figure 23 shows well total depths (TD) below ground surface as interpolated from wells with known locations within the Milford GMA. Generally, well depths are fairly shallow in the community, and as in the earlier figures, well TD appears to generally follow bedrock topography, in that most of the wells in the west ¾ of the Milford GMA should be expected to be under 40 m deep, whereas wells along the eastern edge of the community may be expected to have depths around 50 m below surface.

The actual data from NSE (2016, 2018) shows values for well TD within the Milford GMA ranging from 9.2 to 61.6 m (average 37.2 m, from 100 wells with data) and that for all wells drilled within the community, values for TD range from a very shallow 4.6 m to 61.6 m (average 33.5 m, from 365 wells with data).

Table 2 summarizes the well record data from which the bedrock surface, casing, and well depths in Figures 21, 22 and 23 were interpolated.

Table 2. Summary of bedrock and well construction depths in the Milford GMA.

Statistical parameter		Depths (m)		
		Bedrock surface	Casing	Well TD
Wells with known UTM	Maximum	35.4	49.1	61.6
	Minimum	0.9	6.1	9.1
	Average	12.6	23.1	37.2
	n	92	99	100
All wells in Milford GMA	Maximum	47.3	56.1	61.6
	Minimum	0.3	1.5	4.6
	Average	12.0	20.4	33.5
	n	323	338	365

It should be noted that wells constructed for residential purposes or for businesses with small water needs are typically drilled only as deep as drillers judge necessary to meet those specific needs. This includes a combination of actual well yield (water entrance velocity into the well) and the amount of well borehole storage (often referred to as cold-water storage) available, to allow meeting water needs during busy water-use times, while allowing water levels in wells to recover overnight during periods of lower water demand.

Wells constructed for commercial, municipal, and/or institutional purposes, on the other hand, are typically advanced to much greater

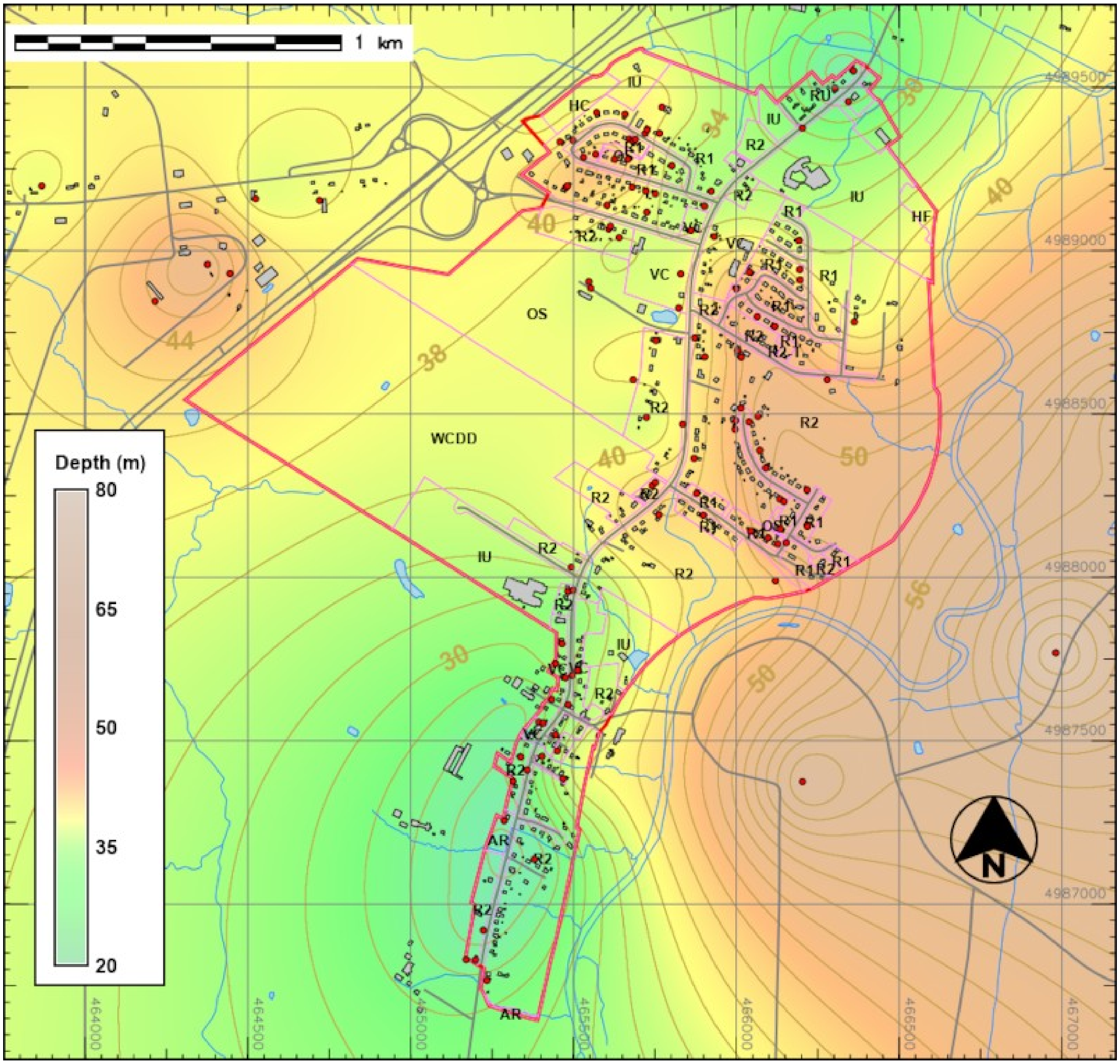


Figure 23. Total well depths (contour interval 2 m) within the Milford GMA (red boundary). Red dots show data sources (wells with UTM coordinates accurate within 30 m). Purple lines are municipal zoning boundaries. Base maps from Geonova (2020) and East Hants (2021b).

depths in attempts to maximize and obtain larger well yields by intercepting greater numbers of water-bearing zones or fractures, and also to maximize the amount of available drawdown in boreholes so as to increase long-term production yields.

The Green Oaks Formation may produce slightly better quality water than the other Windsor Group formations because it is composed primarily of carbonates and is said to contain fewer gypsum and halite beds than the other bedrock units.

However, the Green Oaks Formation is only approximately 140 m thick at the Milford GMA (see Figure 13). Therefore, attempts to obtain larger yields by drilling wells deeper within most of the Milford GMA that is underlain by the Green Oaks Formation may result in drilling through the formation into the MacDonald Road Formation below. The MacDonald Road formation is said to typically contain more gypsum and halite (salt) than the Green Oaks Formation. This could, therefore, result in deeper wells having poorer water quality.

On the other hand, wells drilled into the Watering Brook Formation, which is present under the southern part of the Milford GMA, should be expected to produce poorer quality water because it is known to contain more gypsum and/or halite than the Green Oaks Formation. However, the Watering Brook Formation onlaps onto and pinches out on top of the Green Oaks Formation within and at the far east end of the Barney Brook Syncline (see Figure 12). So it may be possible to drill through the Watering Brook Formation (advancing well casing into that part of the well that intercepts it, to seal out any gypsum or halite it may contain), into the Green Oaks Formation beneath it, which may produce slightly better quality water.

5.3 Bedrock well drilling costs

Based on the data presented in Table 2 and in the maps in Figures 22 and 23, to meet typical residential water needs, assuming a cost of $75 to $80 per metre for 150 mm wells for both well casing materials, labour and equipment for drilling (spring 2021 cost estimates), and casing shoes, well caps and well grouting, then wells drilled in the west ¾ of the Milford GMA may be expected to cost somewhere between $5,200 and $6,000 before the installation of pitless adapters, water lines, pumps, and related in-home equipment. Wells that are drilled in the east ¼ of the community may in general be expected to cost somewhere between 33% and 44% more, or $7,500 to $8,000 before pump installations and such.

Readers must note that the drilling depths reported in the well log databases and shown in the figures above are based on constructing wells to meet water needs within an existing community, with existing well interference and static well water levels. Development and increasing population density will increase aquifer stresses, which could lower groundwater levels in existing wells such that they may need to be deepened to compensate for possible well interference issues (there is more discussion on this later in this report).

6. Milford GMA well yields

This section considers the key parameters that can affect well yields for existing and/or possible future well owners. These include:

- static groundwater levels,
- individual well yields as defined from well development testing by drillers,
- general aquifer capability as defined from pumping tests,
- estimates of aquifer groundwater storage,
- estimates of the aquifer replenishment by recharge from surface, and
- issues relating to well interference form pumping many wells together within a relatively densely populated community.

6.1 Static groundwater levels

Static groundwater levels are the depths at which the groundwater surface in wells will stabilize under non-pumping conditions. They are of significance in that together with well TD, they define the amount of cold-water storage available in wells. Also, together with well yield (see section 6.3), static water levels also define what the minimum pump capacity should be for a well to properly satisfy water demand. Finally, static groundwater levels can change over time, seasonally, and also over time with water withdrawals (especially if withdrawal volumes exceed recharge). So static water levels (or their rate of change over time), if measured carefully, may serve as indicators of groundwater source/aquifer sustainability.

Static groundwater levels range from zero (flowing well conditions) to 36.9 m (average 17.4 m, from 72 wells with data) for wells with known UTM coordinate locations, and from zero to 39.6 m (average 17.9 m, from 253 wells with data) for all wells located within the Milford GMA.

With a few exceptions, groundwater levels within the community generally follow the ground surface topography (see Figure 24). However, due to the subdued nature of the groundwater surface topography relative to surface topography, as illustrated by the map in Figure 25, actual groundwater level depths are greater at the locations of highest land surface topography within the Milford GMA.

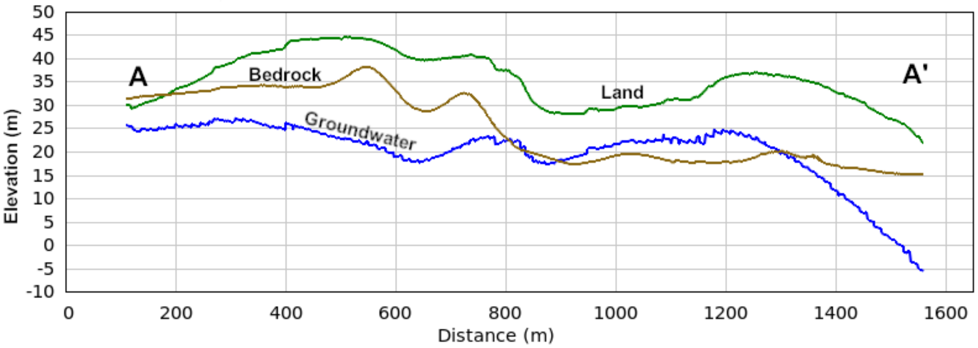


Figure 24. Cross-section of the land, groundwater and bedrock elevations from the southern Hwy. 102/14 traffic circle to the end of Riverview Drive.

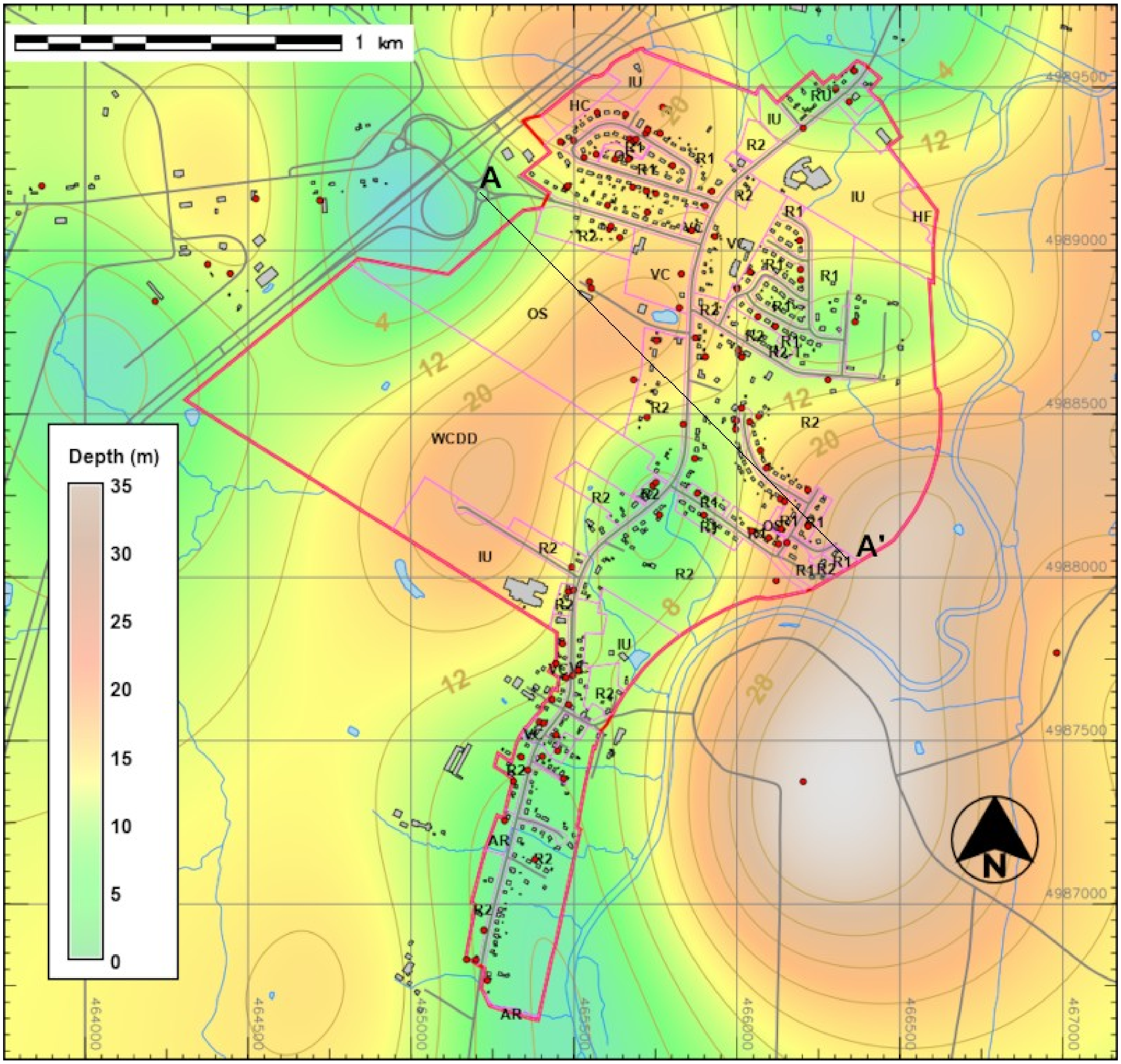


Figure 25. Static groundwater level depths (contour intervals 4 m) in wells in the Milford GMA (red boundary). Red dots show data sources (wells with UTM coordinates within 30 m). Purple lines are municipal zoning boundaries. Base maps from Geonova (2020) and East Hants (2021b).

Of all the wells drilled within the Milford GMA, 8 are reported to have had flowing conditions when they were drilled. Three of those are among the 100 wells with accurate UTM locations – in the areas with lower topography on Edward Kerr Dr., at the top of Milford Rd., and on Lacey Rd.

In the Milford GMA, 249 well records give both total well depth (TD) plus static water levels. The water column heights (cold-water storage in wells) calculated from those (TD minus static water level) range from 3.1 to 46.3 m (average 14.3 m). With no safety margin applied, this represents total cold-water storage volumes ranging from 56 L (way too little storage) to 864 L, and an average of 323 L. For reference, a typical household of four is assumed to require about 1,350 L of water per day (NSE, 2011).

Readers are advised that static water levels are usually measured right after wells have been drilled, developed, and drilling tools pulled from wells. Therefore, water levels often have not stabilized when measured. Further, few drillers use proper water level measuring tapes to record water levels, but instead may estimate static water levels by dropping rocks into wells and timing the splash when they hit the water. So the static water levels as reported by NSE (2016, 2018) must be used with caution.

Further, typically, static water levels are measured only when wells are newly drilled, or when pumps are installed in them (which data does not make it into the well database), and are very rarely measured afterwards. Therefore, while they may serve as a guide, the static water level values reported in the well log databases should not be used to make definitive assessments on pumping effects or source/aquifer sustainability.

6.2 Driller blow test results

Driller blow tests are typically carried out during well development at the end of well drilling. In Nova Scotia, wells are typically developed (to remove drill cuttings, water with high turbidity, and to clear water-bearing zones of debris) for periods of about one hour. During that time, depending on borehole conditions, the driller may raise and lower the drilling rods and bit in an effort to clear as many zones as may be thought to produce water. But at the end of the well development, the drilling bit is usually kept a the very bottom of the hole to blow[13] all debris from the bottom of the well.

During this final stage of well development, drillers will estimate the volume of water produced by, and blown out of, the well using a bucket and stopwatch, but at times also by simply estimating the volume of water flowing on the ground away from the well.

Blow testing is a crude method of evaluating what water volumes wells may be able to produce. Because blow testing is done with the drilling bit sitting at the very bottom of the hole, blow test results never represent true well pumping conditions[14], because the groundwater gradients at and in the aquifer around the well that drive water into the well during blow testing are not the same. Further, driller blow tests are of too short a duration to reliably define long-term well capabilities.

However, depending on depths to the water-bearing zones in a well, multiplying driller blow test results by 0.50 to 0.75 can help to give a general estimate of possible longer-term well yields.

---

[13] Today’s rotary-percussion drilling rigs use air-actuated drilling bits. Compressed air is blown down inside hollow threaded drilling rods to the drilling tool to make the carbide hammer-bit reciprocate. That compressed air, which then leaves the bit, forces rock drill cuttings and water back up the annular space between the drilling rods and the borehole to surface to be shovelled away from the well.

[14] Well pumps are typically kept 3 to 5 m off the bottoms of wells, and with proper well pumping the goal is to never allow drawing the water level down to the pump, whilst the pump would draw air, which can damage pump impellers and motors.

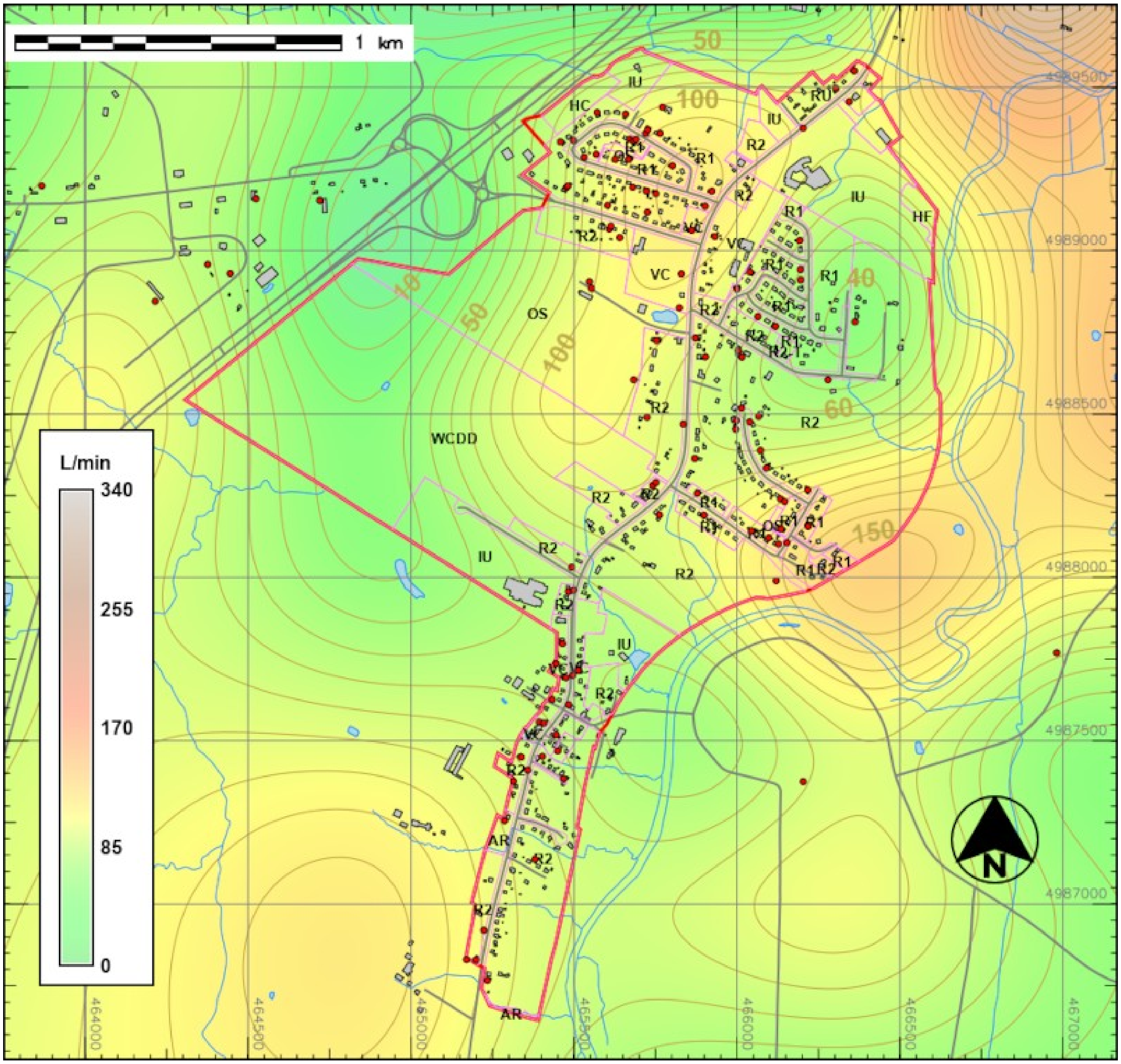


Figure 26. Driller blow test yields (contour intervals 10 L/min) for wells in the Milford GMA (red boundary). Red dots show data sources (wells with UTM coordinates within 30 m). Purple lines are municipal zoning boundaries. Base maps from Geonova (2020) and East Hants (2021b).

The driller blow test yield rates reported in the NS well log database range from 11 to 455 L/min (average 92 L/min, from 94 wells with data) for wells with known UTM coordinate locations, and 2.3 to 455 L/min (average 66 L/min, from 357 wells with data) for all wells located within the Milford GMA. The map in Figure 26 shows the relative distribution of these values (subdued somewhat by the interpolation parameters used) for wells with known locations – the higher values reported are for two wells on Bayberry Drive and a third southwest of the Highway 2 and Lacey Road intersection.

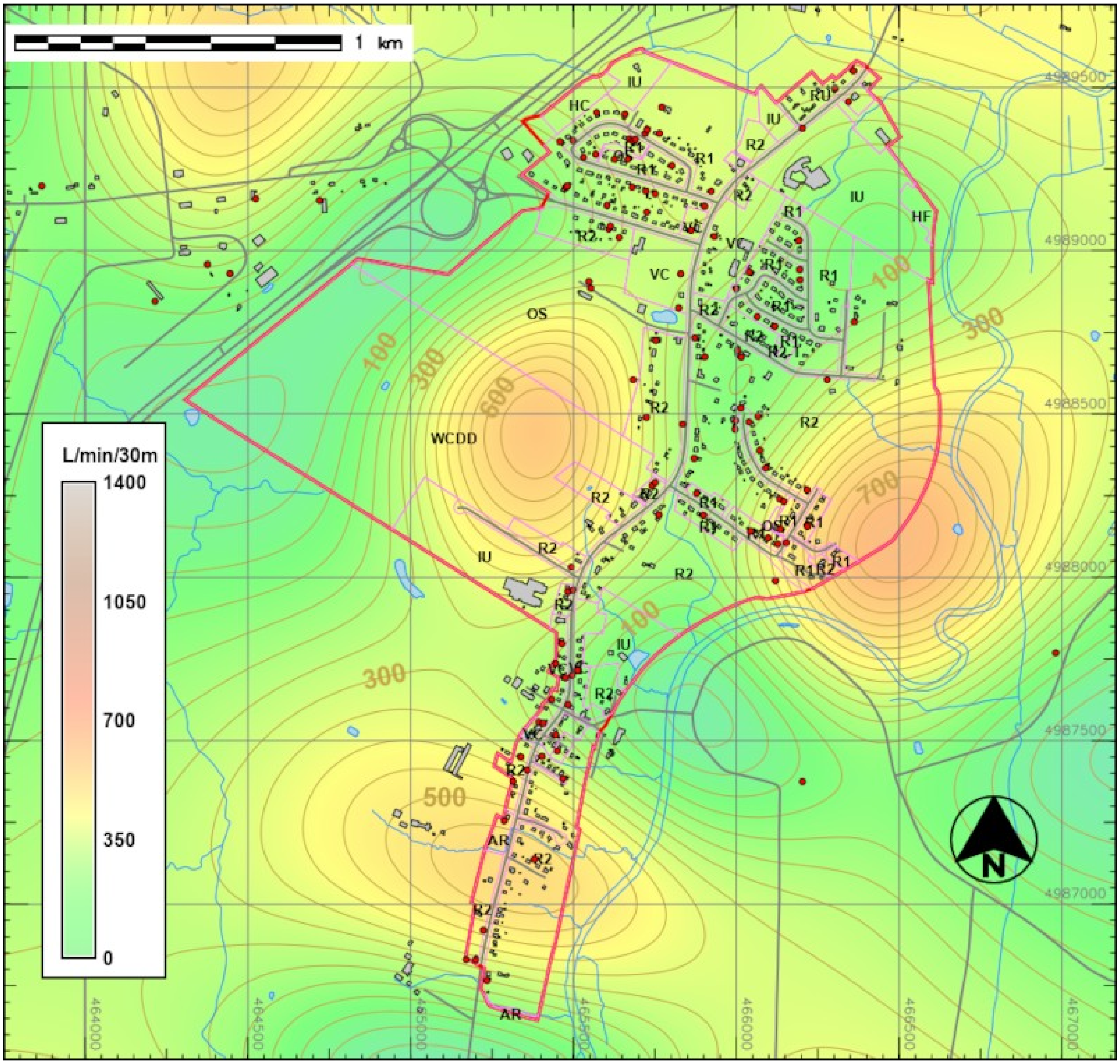


Figure 27. Calculated driller blow test yield rates per 30 m (contour intervals 50 L/min/30m) for wells in the Milford GMA (red boundary). Red dots show data sources (wells with UTM coordinates within 30 m). Purple lines are municipal zoning boundaries. Base maps from Geonova (2020) and East Hants (2021b).

Knowing driller blow test yields can be used to crudely define aquifer characteristics, but those values are also a function of well depth as well as the number of water-bearing zones intercepted. To help better define true aquifer characteristics, the reported blow test rate values were normalized by calculating yield rates per 30 m of open borehole (distance from bottom of well casings to TD), which as can best can be done with the well log data, is akin to well specific capacity. Figure 27 shows their relative distribution.

While Figures 26 and 27 show similar trends, Figure 27 does serve to confirm a possible southerly extension of higher yields from the Green Oaks Formation HU that also matches the apparent north-south to southwesterly trend of higher yielding wells noted earlier.

Notwithstanding the exceptional well yields noted in the well logs and Figures 26 and 27, there are two or three wells in the Milford GMA with reported yield rates that are under 10 L/min (still enough for average residential needs) and one with a reported yield rate of only 2.3 L/min, which is just able to meet average residential needs assuming there is sufficient cold-water storage. Based of the 100 wells with known UTM coordinates within the Milford GMA, some of the lower-yielding wells appear to be located very close to wells with extremely high yields.

The overall presence of high yield wells in close proximity to wells with lower yields suggests that fracture flow[15] (or flow through karst[16]) is prevalent within the Green Oaks Formation HU beneath the Milford GMA.

While details on the locations and frequency of faulting and associated fractures is sparse (Giles and Boehner, 1982) and mapping them in greater detail was not in the scope of this study, well log records suggest that drillers have in general encountered numerous water-bearing fracture zones while drilling. The NSE (2016, 2018) database includes records of these, and for the 100 wells with known UTM locations, water-bearing fractures are reported to have been intercepted as follows:

- first fractures were encountered at depths of 6.1 to 54.9 m (average 29.3 m, 39 m for the 3rd quartile, on average 77% of TD in 92 of 100 wells),
- second fractures were encountered at depths of 8.8 to 59.8 m (average 34.8 m, 43.4 m for the 3rd quartile, on average 90% of TD in 75 of 100 wells), and
- third fractures were encountered at depths of 10.4 to 59.8 m (average 37.2 m, 48.3 m the for 3rd quartile, on average 93% of TD in 16 of 100 wells).

Fourth fractures are reported at depths that are similar to third fractures, but in only 3 of 100 of the wells with known UTM locations.

The fact that the first fractures were generally encountered at 77% of well TD[17] suggests that for most wells within the Milford GMA, those first water-bearing fractures were able to produce sufficient water to meet well owner needs.

---

[15] Fracture flow is groundwater flow through cracks and fractures in the aquifer, as opposed to flow through tiny spaces in aquifer matrix (i.e. interstitial flow, such as may occur between sand grains in sandstones). Fractures propagating through aquifer matrix can serve as pathways to collect water from interstitial flow, thus increasing aquifer yields. Well developed fractures may allow huge volumes (at times hundreds of L/min) to flow through them.

[16] Karst is a topography formed from the dissolution of soluble rocks such as limestone, gypsum and halite. It is characterized at surface as sinkholes, and in the subsurface as broadened fracture zones and in extreme cases, as caves.

[17] Note: It is preferable for fractures and other water-bearing zones to be as deep as possible in wells. The reason – it is bad practice to dewater water-bearing zones, since doing so may cause air to enter those zones, thus negatively affecting zone hydraulics. Therefore, the deeper the water bearing zones or fractures, the better, since those zones are less likely to become dewatered. Deeper fractures also allow for greater available drawdown in wells and thus, greater long-term yields (see next section).

6.3 Pumping test data

The Nova Scotia pumping test database (Drage, pers. comm., 2017; Kennedy, 2020a) includes pumping test records for only 5 wells drilled into the Green Oaks Formation within the Shubenacadie Basin.

Two of those wells are said to be located near the northern boundary of the Milford GMA. One of them is at the Colchester-Hants East Rural High School. The other, which was pump tested on behalf of the NS Housing Commission/Housing Authority, has no given NSE well number or location. The third well is said in the database to have been tested for the Milford Station middle School, but the testing date and approximate well location (plots off-property, likely due to coordinates being in reference to datum Nad-27) match those of the Riverside Education Centre.

The other two wells are located off-site, at the LaFarge Canada Inc. quarry west of Brookfield, on the other side of the Shubenacadie Basin.

Table 3 summarizes the relevant data from the three wells tested at the Milford GMA.

6.3.1 Pumping tests and data – defined

Pumping tests, as are summarized in Table 3, are typically done for periods of 6, 12, 24, 48, 72 hours, or longer, using constant pumping rates. The wellheads are set up with a meter and throttle valve to measure and regulate (keep constant) the test pumping rate as the water level in the well is measured as it drops over time with pumping.

Table 3. Summary of available pumping test data for wells tested within the Milford GMA.

Database record	NS Housing	East Hants High School	River-side Educate Centre
PumpTest_ID	HAN-16	HAN-11	HAN-20
NSE Well No.	--	640238	972405
Well depth (m)	27.74	51.82	62
Casing (m)	--	7.62	49
Tests start	28-Dec-89	18-Mar-73	--
Recovery start	31-Dec-89	21-Mar-73	--
Duration (hrs)	72	72	73
Ave. pump rate (m^3/d)	120.44	294.55	399.27
Static water level (m)	5.87	5.43	26.5
Pump set (m)	--	48.77	--
Available DD	18.29	42.67	27.9
Maximum DD	11	16.15	11.5
% of avail. DD	60.13	37.86	41
DD stable	N	Y	N
Tot. recovery (m)	10.82	--	--
Recovery minutes	180	--	--
% Recovery of max. DD	98.39	--	--
Transmissivity (T, m^2/d)	2.77	12.68	64
Specific capacity	10.95	18.23	36.5
Hydr. Cond. (K, m/d)	--	0.287	1.73
Q_{20} (m^3/d)	27.49	294.55	418.9
Q_{20} (L/min)	19.1	204.5	290.9
Note: DD = drawdown.			

During pumping tests, water levels in the pumping well (and in as many non-pumping observation wells as can be made available) are carefully measured (usually to within the nearest millimetre), typically over the base-10 log of time (every minute first, with progressively longer periods between readings) during the course of the test. After a predetermined test duration, or upon reaching a predefined available drawdown[18], the pump is stopped and the rate of water level rise during well recovery is also measured (also on the log of time).

The water level/time data collected during the pumping tests is plotted on log-log or semi-logarithmic paper, depending on the interpretation method used (the Theis (1935) or the Jacob (1947) Hantush (1964)), and the shape of the curves or slopes of the lines in the plots are used to calculate a value called Transmissivity (T), which along with Storativity (S), are the two parameters used to describe an aquifer's ability to contain and transmit water though it and into wells.

The coefficient of Transmissivity (T) is the aquifer hydraulic conductivity multiplied by aquifer saturated thickness penetrated by the well. It is the rate at which water will flow through a vertical strip of the aquifer.

Storativity (S), the coefficient of storage (values for S were not obtained for any of the pumping tests that are summarized in Table 3, but S is significant for section 6.7 of this report), represents the volume of water released per unit of aquifer storage area per unit change in aquifer head. In confined aquifers, S is a result of compression of the aquifer when the head is reduced during pumping. In unconfined aquifers, S is the same as the specific yield of the aquifer.

Values for S, which require that water level measurements and, thus, values for T be obtained from non-pumping observation wells, are defined by:

$$S = \frac{2.25 \bullet T \bullet t_0}{r^2}$$

where;

T = Transmissivity obtained at the observation well of interest,

r = distance from the pumping well to the observation well ,

t_0 = time (in days) at the zero drawdown intercept at the observation well.

The values for S for unconfined fractured bedrock aquifers are poorly defined in the literature (Neilsen, 2002), but may range from around 0.006 (Maréchal et al, 2006) to 0.3 (Driscoll, 1986; Freeze and Cherry, 1979), whereas values are typically much lower for confined aquifers.

With T calculated, then the safe long-term pumping rate for the well being tested can be determined from (Farvolden, 1959):

$$Qs_t = \frac{0.7 \bullet T \bullet s}{0.183 \bullet \log(t)} \qquad (m^3/d)$$

or,

$$Qs_t = \frac{0.7 \bullet T \bullet s}{264 \bullet \log(t)} \qquad (igpm)$$

---

[18] The available drawdown of a well is the maximum desired depth beyond which the water level should be allowed to drop due to pumping. Often available drawdown is defined as the top of the pump (to avoid the pump drawing air). But better practice is to set available drawdown to avoid dewatering major water-bearing zones (to avoid hydraulically damaging them). The ideal pumping test will use a pumping rate estimated such that the water level in the pumping well is brought down to at least 75% of the available drawdown to properly stress the well, and recovery should be at least 80% of that drawdown.

where;

Q = sustainable yield over time period (t)
s = available drawdown (in m or feet),
t = time since the start of pumping (in minutes)

The multiplier 0.7 serves as a safety factor and the values 0.183 and 264 are constants relevant to one log cycle of pumping time (t) for metric and imperial units, respectively.

The values obtained for Qs_t (where t is usually 20 years, or Qs_{20}), is the pumping rate at which the tested well may in theory be pumped continuously 24/7 for a period of 20 years. The values for Qs_{20} are usually conservative in that they assume no recharge occurs during the 20 year period of pumping.

The Qs_{20} values given in Table 3 (particularly for the school wells) are about at par with or slightly higher than the average driller blow-test yield rates reported for the Milford GMA. This is probably because the drilling locations for the schools would have been targeted for and the wells drilled at greater depths (for greater available drawdown) to meet those larger institutional demands.

6.4 Groundwater recharge

The information needed to assess possible water availability to aquifers from recharge at any well field or community with on-site of centrals supply wells requires defining:

- the watershed or capture area size,
- total annual precipitation,
- a groundwater recharge coefficient for the capture area, and
- total water demand by others already within the capture area, which for new development, must be subtracted from the total recharge estimated.

Except for the latter, these are discussed in the following sections.

6.4.1 Groundwater flow, potential water capture areas

Estimating groundwater capture areas requires identifying surface watershed boundaries and defining regional and local groundwater flow regimes.

Groundwater flow can be differentiated as regional, intermediate, or local (Freeze and Cherry, 1979) – with flow between each being possible without distinct boundaries.

Regional flow involves recharge at the top of the province and deep, long-distance flow toward the ocean, and long residence times. Regional flow in reference to the Milford GMA (which is near the provincial water divide) would be south-southeasterly toward the Atlantic Ocean to some degree, but mostly north-northwest to the Minas Basin.

Intermediate flow would include recharge in areas just north and west of the Milford GMA, and discharge towards the Shubenacadie River immediately to the south, and also to some degree towards the north. The groundwater-sheds for both regional and intermediate flows can and often do transcend surface watersheds.

Local-scale groundwater flow includes

recharge at local knolls and discharge in nearby valleys. Local flow groundwater surfaces usually parallel surface topography in a subdued manner.

The Milford GMA is situate at a 4-point surface water divide, therefore local-scale groundwater flow at the community would include recharge originating right within the community, as well as some recharge originating in tertiary sub-watersheds:

- 1DG-1-K (the east part of the Milford GMA, extending 870 ha south),
- 1DG-1-J (the northwest quarter of the Milford GMA, extending north 880 ha), and
- 1DG-1-L (the southwest quarter of the Milford GMA, extending over 2,850 ha west and southwest).

Where there is no empirical data, the concept above and ground surface elevations may be used to make rough estimates of groundwater flow directions and to define approximate local groundwater recharge areas.

In the greater community area, regional and intermediate groundwater flows would be expected to contribute directly to water for the Milford GMA wells from sub-watersheds 1DG-1-J and 1DG-1-L over an area possibly encompassing 15 to 20 km^2.

A more conservative approach to defining a groundwater recharge area for wells within the Milford GMA might be to consider only the areas of more direct influence (areas with possible drawdown) from wells pumping within the community.

Past experience with wells completed carbonate aquifers suggests that under steady state (long-term) pumping conditions, that area of influence may extend 250 m to 500 m beyond wells located at the boundaries of the community. This could include Hwy. 102 up to where it curves south and north, the business park and part of Route 14 up to Hubley Road or Scotch Pine Drive, to where Routes 2 and 224 cross, and along both sides of the Shubenacadie River valley.

Therefore, a conservative groundwater recharge area for wells in the Milford GMA may be considered to be about 1,000 ha.

6.4.2 Precipitation

At Halifax Airport, Environment Canada (2020) reports a 30-year normal (period 1981-2010) annual precipitation of 1,396.2 mm (includes snow-water equivalent).

For the Milford GMA, we estimate that value to be 1,362.1 mm (which is roughly the province-wide average) based on a GIS precipitation model[19] for Nova Scotia that employs data from the 57 Environment Canada climate stations (20 in Nova Scotia, 37 in New Brunswick) that meet the United Nation's World Meteorological Organization (WMO) standards for the period 1981 to

---

[19] The modelling was done by spatial approximation analysis using climate station point data to floating-point raster format (10 m x 10 m resolution) by regularized spline interpolation with tension (factor 30, zero smoothing) in GRASS GIS (2020). Measures were not needed to incorporate elevation-dependence, as local orographic effects were likely inherent to the climate station locations. However, anisotropy (ratio 2:1, azimuth 70 degrees) was applied to represent prevailing storm advance directions across Nova Scotia.

2010 (the latest period for which this type of data is available).

6.4.3 Recharge coefficient

Kennedy et al (2010) have published values for groundwater recharge coefficients for the entire province, and have ascribed a value of 0.14 for the Shubenacadie Basin and the Milford GMA. Their value closely matches values obtained for other projects using similar water balance analytic methods.

6.4.4 Estimated groundwater recharge

Table 4 summarizes the estimated volumes of groundwater recharge and the approximate number of homes (or home equivalents) that may be served applying the noted of recharge areas as discussed above.

Table 4. Estimates of groundwater recharge and number of homes (or equivalent) that could be served within the Milford GMA.

Ground-water recharge area	Possible recharge[1] (m^3/yr)	Possible allocation[2] (m^3/yr)	No. of homes[3] served
15 km2	2,860,410	1,430,205	2,902
20 km2	3,813,880	1,906,940	3,870
1,000 ha	1,906,940	953,470	1,935
291.6 ha	556,167	278,083	564[4]

1 Assuming 1,362.1 mm/yr precipitation and a groundwater recharge coefficient of 0.14.

2 Half the value in column 2, as required by NSE for permitting if approvals were sought-after.

3 Proportion of total allocation based on 1,350 L/day per home (or equivalent), 365 days/year.

4 Considered very conservative and unrealistic since recharge is unlikely to be limited to within the Milford GMA boundaries.

6.5 Aquifer water storage

The Green Oak Formation HU (and likely also the Watering Brook Formation HU) present beneath the Milford GMA appear to depend in large part on fractures and/or karst for groundwater flow and water storage.

Fracture density may be expected to vary significantly one place to the other under the community. Also, how the fractures behave to store groundwater will depend largely on whether the aquifer HU's are confined or unconfined, which although there are some reports of flowing wells, based on the very limited number of pumping test done locally, is something that remains unclear currently, although the values for Storativity values of 0.0005 and 0.00031 obtained from testing of the two LaFarge wells in Brookfield suggest semi-confined conditions for those wells.

Notwithstanding, assuming that there may conservatively be around 2.5% to 5% porosity within the Green Oaks Formation HU (Freeze and Cherry (1979) suggest ranges of 0-20% for limestone, 5-50% for karst limestone, and 1-10% for shale), for a 140 m thick aquifer unit (assuming no bottom leakage) and 10 to 20 km^2 as recharge areas as noted in Table 4, then the volume of water potentially in storage within the bedrock HU at the Milford GMA may be 35,000,000 m^3 to 140,000,000 m^3. The amount of water potentially in storage within the bedrock HU immediately beneath the community's footprint is conservatively estimated to be between 10,206,000 m^3 and 20,412,000 m^3.

Additionally, the till material of the surface HU above the bedrock will also hold water and supply it to the bedrock HU beneath it.

The till material present within the surficial HU at the Milford GMA is expected to be variably sorted and as such, the net porosity for it may be expected to range from 20% to 30% (Freeze and Cherry (1979) suggest 35% to 50% for silt). Also, at the Shubenacadie water treatment plant north of the Milford community, the static water levels in the till monitoring wells has ranged between 1.2 and 2 m below ground surface, so assuming the groundwater in till at the Milford GMA is 2 m below the ground surface, then depending on location, there is likely to be 1.8 to 66 m of saturated till beneath the Milford GMA.

Assuming a slightly more conservative area of influence for the soil HU of 250 to 500 m around the boundaries of the Milford GMA, then using GIS to calculate the saturated soil volumes and total water stored, an estimated 10,777,500 m^3 to 27,997,700 m^3 of water may be in storage within the till HU to feed the Green Oak and Watering Brook Formation HU's below.

6.6 Aquifer recharge/water storage vs community water demand

In their infrastructure study on waste water needs, Vaughan Engineering (2001) had counted 323 homes and 13 businesses and institutional structures in the Milford GMA, and projected that there might be 452 homes and 15 commercial and institutional buildings in the community in 2021. Based on the number of wells (374) present in the community in or around 2015 from the NSE (2016, 2018), Vaughan (2001) may have overestimated the 2021 projections. Based on their assertion of peak waste water flows of 1,740 to 1,880 L/day per person equivalent, they also appear to have overestimated mean daily water demand perhaps by twice.

Nonetheless, assuming there is an increase of 40% as suggested for the Vaughan study period in the number of water users to the year 2040, notwithstanding individual well problems and possible well interference issues (see next section), the numbers in Table 4 suggest there should be sufficient groundwater recharge available to meet that growth at the Milford GMA. Also, assuming severe drought conditions, based on the water storage estimated between the surficial till HU (which is not being directly used) and the bedrock HU's, there appears to be many decades of stored water available within the aquifer units serving the Milford GMA.

6.7 Well interference

In any community or subdivision with many closely-spaced wells, there is a potential for well interference problems – namely, the cumulative pumping effects from all wells, which can result in the lowering of the water table and groundwater levels.

NSE (2011) recommends the use of the Theis (1935) equation as one means to assess well interference. But their criterion to determine if the calculated interference is acceptable is somewhat arbitrary, very conservative, and may not be suitable for all sites. That said, other methods typically involve doing complicated and costly aquifer modelling, for which there is insufficient well pumping test information at the Milford GMA at this time.

Use of the Theis method is subjective and time consuming because it involves complex curve fitting, so NSE provides a spreadsheet on their Web site to facilitate the calculations. However, the spreadsheet contains password-protected macros that cannot be verified. In light of the liability safeguard claims made by NSE and the developer of that spreadsheet regarding support, bug fixes, and use of their spreadsheet, earth-water Concepts inc. must also extend those safeguards[20] to the users of any data the spreadsheet generates.

The method suggested by NSE to assess well interference is to estimate the cumulative drawdown at the centre of a community or subdivision by adding the affects of pumping at all wells (at 1,350 L/day for 365 days) to a well located at the centre of the subdivision.

If the predicted drawdown is less than 50% of the available drawdown for the central well (or for another average well located on-site), then the site is deemed to have met the NSE well interference criteria.

The method proposed by NSE assumes a square or circular-shaped community or subdivision development. However, the shape of the Milford GMA is not that simple.

In an attempt to satisfy the intent of the NSE (2011) method, while also maintaining a somewhat realistic (but still hypothetical) well spacing for existing properties versus possible future land development (based roughly on the East Hants (2016) Planning Strategy and related (East Hants, 2020) Generalized Future Land Use Map 2), this review of possible well interference in the community, which assumes an (eventual) full development build-out, was carried out under three scenarios (see Figure 28 for an example of one of them), as follows:

Scenario 1. 118 lots (wells, existing and possible future) with an approximate 55 m well spacing in a 650 m by 500 m area to roughly represent the properties from Hwy. 14 to the northern boundary of the Milford GMA west of Hwy. 2.

Scenario 2. 300 lots (wells, existing and possible future) with an approximate 50 m well spacing in a 1,300 m by 650 m area to represent the part of the Milford GMA east of Hwy. 2 between the two schools.

Scenario 3. 156 lots (wells, existing and possible future) with an approximate 40 m well spacing in a 1,300 m by 200 m area to roughly represent properties on both sides of Hwy. 2 south of Riverside Drive.

The planned Walkable Comprehensive Development District (now zoned Rural Use)

---

[20] **Disclaimer regarding any use of data produced by the Groundwater Assessments for Subdivition Developments Toolkit spreadsheet provided by Nova Scotia Environment (NSE):** The NSE spreadsheet is supplied on an as-is basis. NSE and NS Department of Natural Resources offers no warranty, expressed or implied, as to its accuracy or completeness and are not obligated to provide the user with any support, consulting, training or assistance of any kind with regard to its use, operation, and performance nor to provide the user with any updates, revisions, new versions or "bug fixes". The user assumes all risk for any damages whatsoever resulting from loss of use, data, or profits arising in connection with the access, use, quality, or performance of this software. Likewise, earth-water Concepts inc. serves notice to anyone reviewing or making use of any data generated by the proprietary and access-protected software that the data is supplied on an as-is basis. earth-water Concepts inc. offers no warranty, expressed or implied, as to the accuracy or completeness of any data generated by the software. The end-user of the data assumes all risk for any damages whatsoever resulting from loss of use, data, or profits arising in connection with the access and use of any data generated by the software as provided by Nova Scotia Environment.

in the southwest corner of the Milford GMA and possible development within the open space north of that could be represented using either scenario 1 or scenario 2.

The well interference calculations were done using the recharge depth noted earlier, a value for T of 26.5 m^2/d (mean of the values from Table 3), and a value for Storativity S of 0.000405 (mean of the values obtained from the pumping tests on the LaFarge wells in Brookfield). Table 5 summarizes the data input into the NSE (2011) spreadsheet, and its results.

The drawdown estimates for pumping 118, 300 and 156 wells at a rate of 1,350 L/day for 365 days are 3.57 m, 8.03 m, and 4.33 m, respectively, for scenarios 1, 2 and 3.

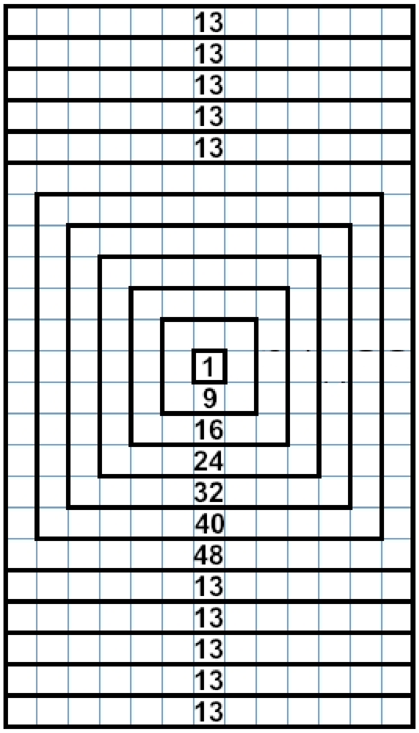


Figure 28. Well spacing scheme used for the hypothetical review of well interference in the east part of the Milford GMA.

NSE (2011) recommends that total predicted drawdown for any subdivision not exceed 50% of the available drawdown in each well. Therefore, any well within the scenario 1 and 3 areas of the Milford GMA with greater than about 8 m available drawdown should meet the NSE (2011) criteria, while any well located within the scenario 2 area of the community with greater than about 16 m available drawdown should meet the criteria.

Although this analysis is quite hypothetical in nature, it’s important to note that of the 100 wells with known UTM locations, 10% do not meet the 8 m criteria and 32% do not meet the 16 m criteria. Of the 374 wells in the Milford GMA, 15.5% and 39% do not meet the respective 8 m and 16 m criteria.

A review of static water levels and well TD (available drawdown) versus driller blow test yield rates suggests that the areas with the least available drawdown are predominantly where driller blow test yield rates are also highest (see Figure 26) – namely, the area from the Rennie Lane and Bayberry Drive subdivision southwest to include all of Riverside Drive and the northwest half of the area south of Riverside Drive. It would appear that the higher yields encountered while drilling may have encouraged drillers to advance shallower wells in those areas. But those higher yields may not be enough to compensate for possible general lowering of the water table with continued pumping at the existing wells over the years, or their vulnerability to well interference from additional wells drilled for new development.

Table 5. Data input and NSE spreadsheet results for well interference calculations.

	r (m)	No. of wells	Drawdown per well (m)	Drawdown for all wells at distance r
Scenario 1	0	1	0.093	0.093
	55	9	0.040	0.360
	110	16	0.034	0.544
	165	24	0.031	0.744
	220	32	0.028	0.896
	275	18	0.027	0.486
	330	18	0.025	0.450
	Sum	**118**		**3.573**
Scenario 2	0	1	0.093	0.093
	50	9	0.040	0.360
	100	16	0.035	0.560
	150	24	0.032	0.768
	200	32	0.029	0.928
	250	40	0.027	1.080
	300	48	0.026	1.248
	350	26	0.025	0.650
	400	26	0.024	0.624
	450	26	0.023	0.598
	500	26	0.022	0.572
	550	26	0.021	0.546
	Sum	**300**		**8.027**
Scenario 3	0	1	0.093	0.093
	40	9	0.042	0.378
	80	16	0.037	0.592
	120	10	0.033	0.330
	160	10	0.031	0.310
	200	10	0.029	0.290
	240	10	0.028	0.280
	280	10	0.026	0.260
	320	10	0.025	0.250
	360	10	0.024	0.240
	400	10	0.024	0.240
	440	10	0.023	0.230
	480	10	0.022	0.220
	520	10	0.021	0.210
	560	10	0.021	0.210
	600	10	0.020	0.200
	Sum	**156**		**4.333**

Also, there appears to be lesser amounts of available drawdown generally within the undeveloped northern parts of the community on both sides of Hwy. 2, generally north of Lisa Drive (an area with lower welly yields, actually). Those areas are also likely to be more vulnerable to well interference from wells drilled for new development.

This said, it must be noted in reference to the current well interference analysis that:

- the wells with lower available drawdown in the community may not be exactly situated per the analysis scenarios, or
- well yields at existing wells are in general greater on average than is assumed by the NSE (2011) spreadsheet generally, or
- the amounts of recharge and/or aquifer storage may be greater can be accounted for by the spreadsheet formulas, and
- the Milford GMA is not at this time fully built out.

However, this analysis should serve to raise the necessary red flags that well interference is likely to be a real concern with new development within the Milford GMA.

7. Milford GMA well water quality

Well water quality results from residential, business, school, or other public wells are normally kept private. Therefore, the only water quality data that is generally available may come from the occasional pumping test and from publicly funded research projects.

For this study, water quality data (Kennedy, 2020b) is available for 139 wells in the 70 km E-W by 50 km N-S area mapped by Giles and Boehner (1982). Of these, 26 are in surficial deposits, 113 were drilled into and completed in bedrock. Eleven of the bedrock wells are within the Milford GMA limits.

7.1 Natural well water quality

Table 6 summarizes the water quality results available for the 11 wells drilled into bedrock within the boundaries of the Milford GMA. Figure 29 shows their locations; all appear to have been drilled into the Green Oaks Formation HU.

The Piper Diagram in Figure 30 shows plots for data from the water quality database (Kennedy, 2020b) for samples from wells drilled into bedrock (not all data is plotted, some records do not include data on all necessary cations/anions, but where bicarbonate of carbonate values were missing, alkalinity values were used instead), which have been colour-coded roughly per

Table 6. Groundwater chemistry for wells in the Green Oaks Formation HU at the Milford GMA. See Figure 29 for well locations (Kennedy, 2020b).

Jan	Unit	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Sample ID		Reg 5265	Reg 5027	Reg 5026	GSC 2492	Reg 5024	Reg 5025	Reg 5023	Reg 5022	Reg 5021	Reg 5289	Reg 5020
Sample data		2017-06-16	1977-12-01	1977-12-01	1975-07-15	1977-12-01	1977-12-01	1977-12-01	1977-12-01	1977-12-01	2017-08-28	1977-12-01
Alkalinity (as Ca)	mg/L	190	193	230	171	230	204	174	169	200	100	234
Bicarbonate	mg/L	190	--	--	--	--	--	--	--	--	99	--
Carbonate	mg/L	0.5	--	--	--	--	--	--	--	--	0.5	--
Sodium	mg/L	55	9.4	11	--	14	30	9.9	22	37	10	37
Potassium	mg/L	1.2	1.7	1.3	--	2.1	2	1.6	2.6	3.4	1.2	2.1
Calcium	mg/L	80	56	90	--	65	54	64	92	52	32	92
Magnesium	mg/L	9.2	17	17	--	15	9	10	16	11	3.2	16
Fluoride	mg/L	0.05	0.05	0.05	0.05	0.05	0.2	0.2	0.05	0.3	0.12	0.2
Sulphate	mg/L	25	16	50	--	28	2.7	39	180	52	4.9	47
Chloride	mg/L	110	39	21	--	4.8	4.8	3.9	5.7	5	12	57
Hardness (as Ca)	mg/L	240	209	293	--	225	173	202	298	174	93	298
Total dissolved solids	mg/L	410	264.0	336.9	0.0	274.1	233.7	241.6	427.7	289.1	140.0	402.1
pH	na	7.63	7.6	7.4	7.32	7.2	7.6	7.7	7.5	7.7	8	7.5
Nitrate/nitrite	mg/L	0.025	0.05	0.4	--	0.05	0.05	0.05	0.05	0.05	0.064	0.05
Arsenic	µg/L	0.5	2.5	2.5	--	2.5	2.5	2.5	2.5	2.5	1.1	2.5
Uranium	µg/L	0.82	--	--	0.9	--	--	--	--	--	0.05	--
Iron	µg/L	25	300	50	3,394	50	50	500	600	50	25	50
Manganese	µg/L	18	25	25	20	25	25	60	25	25	2.2	25

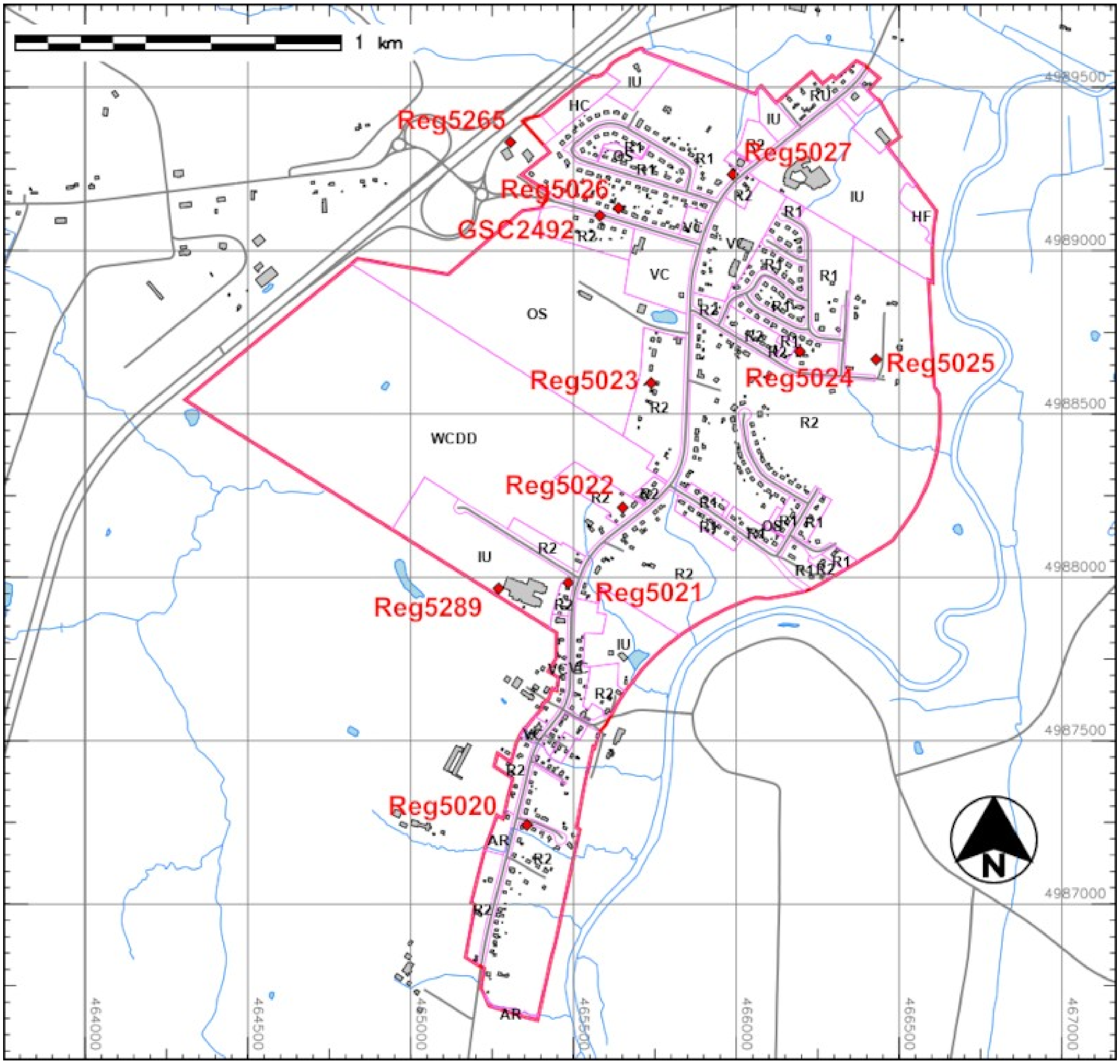


Figure 29. Water sample well locations. Purple lines are municipal zoning boundaries. Base maps from Geonova (2020) and East Hants (2021b).

the colours used for stratigraphy in Figures 10 and 12, based on the bedrock formation they appear to have been drilled into (based on where they plot on the geology data layer). However, it is unclear from the water quality database whether any of the wells may have been drilled through the formations they plot on into other formations below.

7.1.1 Piper Diagrams – explained

The use of Piper (1944) Diagrams is a graphic procedure to segregate relevant data to understand the sources of the dissolved constituents in water. It is based on the premise that most natural waters contain cations (positively charged ions) and anions

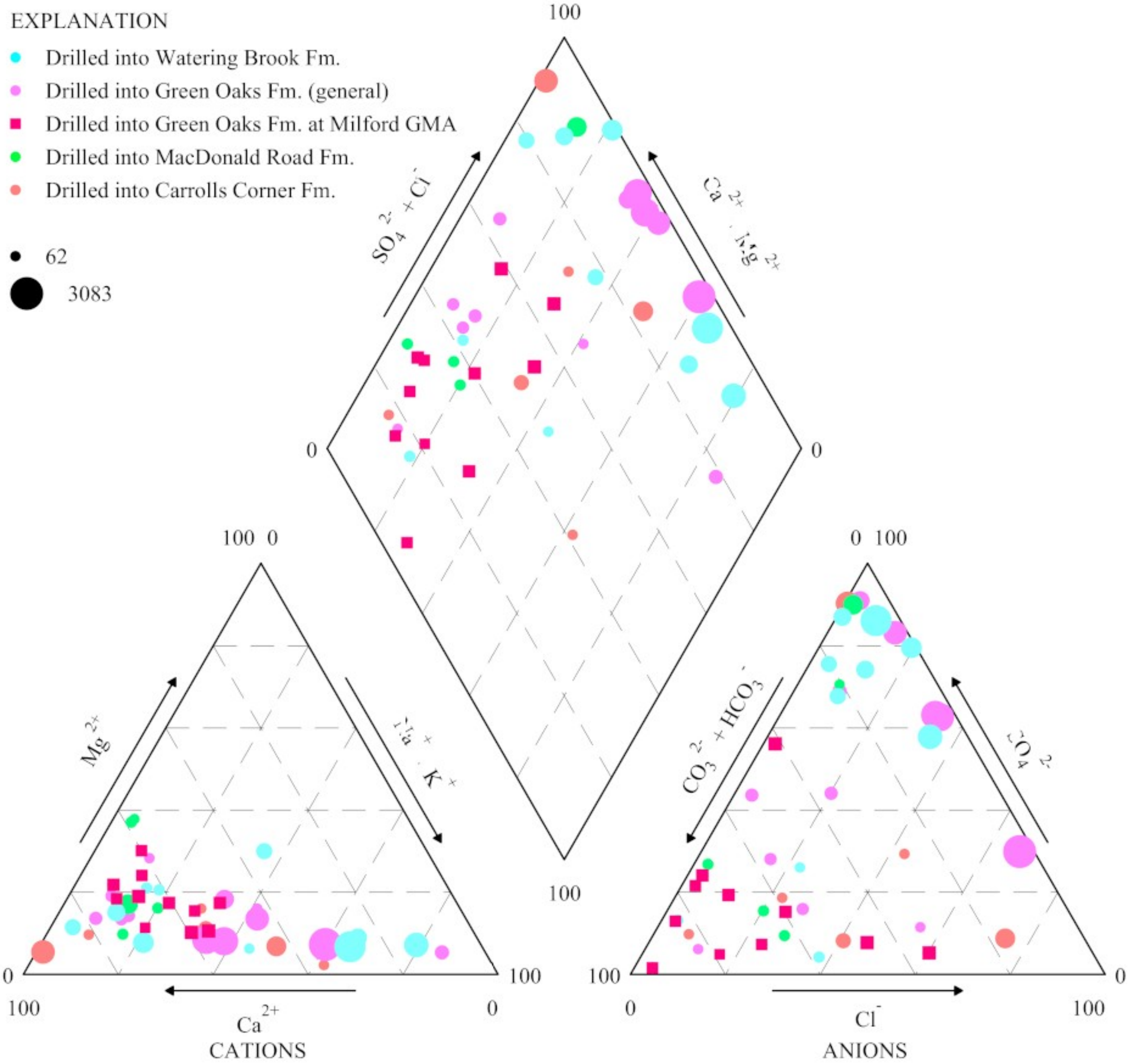


Figure 30. Piper Diagram for 113 water samples (Kennedy, 2020b) collected from water wells drilled into the Carboniferous bedrock units as mapped by Giles and Boehner, 1982.

(negatively charged ions) in chemical (electric charge) equilibrium. In water, the major cations are two "alkaline earths", calcium (Ca^{2+}) and magnesium (Mg^{2+}), and one "Alkali", sodium (Na^+). The common anions are one "weak acid", bicarbonate (HCO_3^-), and two "strong acids", sulphate (SO_4^{2-}) and chloride (Cl^-).

In a Piper Diagram, cations are plotted in the left triangle and anions in the right one, with the bases of the triangles representing each of their respective cations and anions. Since lab values are normally reported as mg/L and ions of same charge may have different atomic/molecular weight, lab values need to be normalized based on atomic weight, and

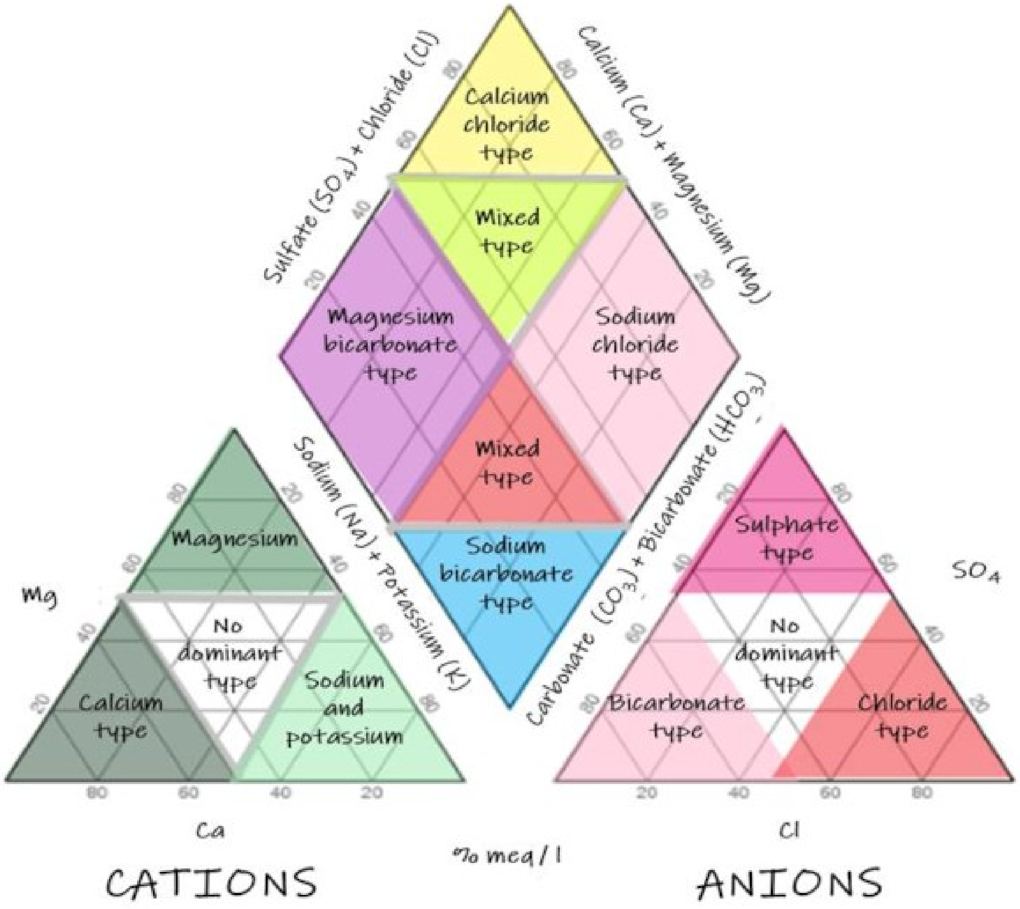


Figure 31. Water hydrochemical facies defined by Piper (1944) Diagrams.

the calculated milliequivalent per litre (meq/L) values are plotted as their relative percentage among the cations, and the anions, in each their respective triangles. Thus, each pair of plots shows the ionic proportion of the main cations and anions for each water sample. Those cation and anion plots are then projected into the diamond, and according to the location of the sample plot in the triangles and diamond, hydrochemical facies can be identified. These facies are the diagnostic chemical characteristic of water solutions occurring in hydrologic systems, and are explained in Figure 31.

Piper Diagrams can thus help define spatial differences in waters from various sources and provide diagnostic evidence for water mixing from those sources, and help describe temporal changes as groundwater travels through aquifers.

7.1.2 What the data tells us about well water within the Milford GMA

From Table 6 and Figure 30 (the red square plot symbols), the groundwater samples from wells drilled into the Green Oak Formation that's present under most of the Milford GMA are calcium-bicarbonate type waters, with slight mixing toward the calcium-chloride facies for some water samples.

The water samples in Table 6 are all hard to very hard[21], with moderate alkalinity, slightly above neutral pH, and moderate to high total dissolved solids (TDS). Values for sodium, sulphate and chloride in Table 6 are all safely below their respective Health Canada (2020) aesthetic guideline values of 200 mg/L, 500 mg/L and 250 mg/L. The samples are also all low in fluoride (health guideline is 1.5 mg/L) and nitrate/nitrite (health guideline 10 mg/L).

Regarding the metals of generally greatest concern in Nova Scotia, in Table 6 the values for arsenic and uranium are all below their respective health guidelines values of 10 µg/L and 20 µg/L[22]. The iron concentrations for 4 of the 11 water samples are above their aesthetic guideline value of 300 µg/L. The values for manganese are at or only just above its new aesthetic guideline value of 20 µg/L in 9 of the 11 water samples in Table 6, and all are below the new manganese health-based guideline value of 120 µg/L.

The value for iron of 3,394 µg/L in sample GSC2492 in Table 6 is quite anomalous and may be due to sampling method used in a not fully developed well (iron-rich sediment may have been included in that sample). However, the database gives no NSE well number for that sampling location, so more details on that well are not available.

There is no water quality data available for any wells drilled into the Watering Brook Formation within the Milford GMA borders. However, based on Figure 20, wells drilled into that bedrock HU should be expected to produce water that is very hard to perhaps extremely hard (some values as high as 810 and 880 mg/L are reported in the Shubenacadie Basin), with high TDS (values from 240 to 2769 mg/L are reported). Some wells report values for sodium up to 490 mg/L, and sulphate values in the 400 to 500 mg/L appear frequently, with one of 1,440 mg/L reported. Also, values for manganese and iron are typically high, with some exceeding 3 to 4 times their guideline values.

7.1.3 Comparing Milford GMA well water to well water elsewhere

The plots in Figure 30, discussed below from oldest to youngest Carboniferous bedrock unit for all water samples from Kennedy (2020b) collected from wells in the Shubenacadie-Musquodoboit Basin, yields the following observations.

---

[21] The simple definition of water hardness is the amount of dissolved calcium and magnesium in the water. Hardness values of 0 to 60 mg/L as calcium carbonate is classified as soft; 61 to 120 mg/L as moderately hard; 121 to 180 mg/L as hard; and more than 180 mg/L as very hard.

In hard water, soap reacts with calcium (which can be relatively high in hard water) to form "soap scum". When using hard water, more soap or detergent is needed to get things clean, be it hands, hair, or laundry, and it will often make hands feel like there is a film of residue on them after washing them. Hard water will often leave spots or a film on dishes in dishwashers, or films on shower tiles. Although the effects of hard water may be unsightly, drinking-water may be a contributor of calcium and magnesium in the diet, and the calcium and magnesium that make water hard are present in a form that can be used and is useful to good health.

[22] For readers unfamiliar with analytic units for water, mg/L is milligram per Litre (approximates parts per million when measuring solids), and a µg/L, or microgram per Litre, is 1,000 times smaller, or approximately equivalent to one part per billion.

Water samples from wells completed in the Carrolls Corner Formation plot generally as calcium-bicarbonate to calcium-chloride type waters, some with elevated TDS. As such, they plot within a facies similar to water form the Green Oaks Formation inside the Milford GMA, but with a greater tendency towards calcium-sulphate (gypsum) type waters.

The water samples collected from the MacDonald Road Formation plot primarily as calcium-bicarbonate type water, but with one plotting very strongly as calcium sulphate (gypsum) type water. It supports the advice in section 5.2 of this report to not drill deeper than 140 m in the Green Oaks Formation in fear of possibly drilling into the MacDonald Road Formation below it.

The well water samples collected from the Green Oaks Formation that are from outside the Milford GMA boundaries plot overall as calcium-bicarbonate type waters. But those with higher TDS all trend toward the sodium-chloride and calcium-sulphate facies, which suggests that a fair amount of both, halite and gypsum, can be dissolved from the Green Oaks Formation. This is a situation that may exist also at the Milford GMA, but which may not have been picked up in the small number of samples available for this study.

As noted earlier, some of the well water samples collected from the Watering Brook Formation plot within the calcium-bicarbonate hydrochemical facies (only two are similar to Green Oaks Formation type water at the Milford GMA), but most plot very strongly as sodium-sulphate to calcium-sulphate (gypsum) type waters.

7.2 Other water quality issues

Not included in any of the data available, but of equal concern to natural water quality, are the human effects possible on groundwater quality in both rural and urban settings. These may include:

- Winter maintenance road salt – while roads inside the community and the secondary highways near wells may be sanded only during winter, Highway 102 will always continue to be salted.
- Heating oil tank and related fuel line failures – poorly installed heating oil storage tanks can be subject to early failures, and fuel transfer lines under concrete basement floors may leak for months before getting noticed. And while the tight tills present at the community may help to provide some protection to groundwater against heating oil tanks or line leaks, their cumulative effects may nonetheless prove difficult to mitigate.
- Vehicular service stations – underground storage tank leaks and spills at filling islands always pose a threat to groundwater supplies.
- Fluid spills resulting from vehicular accidents – although these may in general involve smaller volumes and are easy to spot and deal with, accidents involving bulk fuel transfer vehicles can cause much more harm to groundwater and be much more difficult to deal with.
- Fertilizer and pesticide use within and around the community can impact the community groundwater supply quality.

7.3 Water quality issues, treatment options, and costs

The more common water quality issues that may be expected from wells drilled into the Green Oaks Formation at the Milford GMA may include:

- **Hardness:** Can cause soap efficiency to decrease (i.e. needing more soap for laundry), spotting of dishes in dishwashers, development of calcium films on bathroom tiles, and buildup in piping, hot water tanks, and boilers.

- **Elevated iron and/or manganese:** Can cause staining of plumbing fixtures, staining of laundry if bleach (a strong oxidizer) is used, or staining in dishwashers (many dishwater soaps contain bleach). Can also cause bad taste in drinking water when present in higher concentrations.

- **Sodium and/or sulphate:** May be an issue if the aquifer contains halite or gypsum at the well location. Elevated sodium is a concern for people with hypertension. Elevated sulphate can cause diarrhea in people who are not acclimated to sulphate, and cause dehydration.

- **Elevated TDS:** A result of the cumulative concentration of other elements present in the water. Typically a problem in waters high in sodium, chloride, and sulphate.

- **Taste, colour, odour issues:** A byproduct of either elevated sulphate, or iron, or the presence of petroliferous material in the bedrock aquifer.

Besides causing taste and odour problems directly, the presence of petroliferous materials in aquifers can create chemically reducing (low redox) conditions in the subsurface. These low redox conditions may cause iron and manganese to be dissolved from the aquifer matrix, cause the breakdown of other organic materials to form methane (with possible explosive consequences), and the reduction of sulphate to hydrogen sulphide (H_2S), which in the concentrations typically present in water wells, gives water a rotten egg smell. This may be more noticeable in hot water (i.e. in the shower).

The presence of hydrogen sulphide in well water may also cause well casings to corrode at the air/water interface in wells where water levels do not change much, where upon becoming oxidized, the H_2S produces sulphuric acid (H_2SO_4, the same as in car batteries) at the water surface The acid can dissolve the steel of the well casing through to the outside. This type of casing failure can allow surface contaminants into the well.

Although there are no detailed data from which to define water quality issues for wells that may be drilled into the Watering Brook Formation at the Milford GMA, the water quality problems that may be expected from wells drilled into it would be similar to those for wells drilled into the the Green Oaks Formation, only worse. The values for hardness and iron and manganese values and sodium and sulphate concentrations in water from the Watering Brook Formation may be expected to be several times higher than those from the Green Oaks Formation.

The matrix in Table 7 lists the more common home water treatment units available along side the Milford GMA groundwater quality issues that may need to be addressed.

Table 8 describes the treatment technologies listed in Table 7 and gives ball-park cost estimates for each. The cost estimates are based on quotes obtained in 2017 and 2021 and research in 2018, adjusted to 2021 in Canadian dollars; actual costs may vary. In general, the low-end cost is for a treatment unit homeowners may be able to install; the high-end cost is for treatment systems installed by water treatment professionals. Except for under-counter point-of-use units, water treatment systems should be installed by professionals.

Table 7. Common types of home water treatment units available and the water quality issues at the Milford GMA.

	Adsorptive media filtration[1]	Aeration and filtration	Anion exchange[1]	Carbon filter[1]	Continuous chlorination and filtration	Distillation	Oxidizing media filtration	Ozonation and filtration	Reverse osmosis	Ultraviolet (UV) disinfection	Water softening (cation exchange)
Colour, taste, odour issues		●		●	●	●	●	●	●		
Bacteria[2]					●	●		●	●	●	
Calcium (hardness)						●			●		●
Chloride						●			●		
Hydrogen sulphide		●		●	●		●	●			
Iron	●	●		●	●	●	●	●	●		●
Magnesium (hardness)						●			●		●
Manganese	●	●		●	●	●	●	●	●		●
Methane		●									
Sodium						●			●		
Sulphate	●		●			●			●		
Viruses[2]					●	●		●	●	●	

1. The substances these technologies reduce or remove depends on the filter media or resin.
2. If using a filter, it must have the pore size needed for the bacteria or virus being removed.

Table 8. Summary of home water treatment options.

Treatment option	Description	Pros and cons	Point-of-use cost estimate	Point-of-entry cost estimate	Designed to fully or partially remove
Adsorptive media filtration	A charged media bed causes ions of the opposite charge to be pulled out of the water and attach to the media.	**Pros:** Produces very little wastewater. Does not require adding chemicals to the water. **Cons:** Treatment effectiveness may depend on the pH of the water.	Initial: $300 to $700 Maintenance: $300 to $500 every 6 to 12 months	Initial: $3,400 to $6,500 Maintenance: $1,000 to $1,300 per year	Depends on the type of media. The two most common are activated alumina and iron-based. Activated alumina media removes arsenic, fluoride, selenium, sulphate, uranium. Iron-based media removes arsenic. It may not be as effective at removing arsenic if there is also phosphate in the water.
Aeration and filtration	An aerator brings oxygen into the water. The oxygen helps change dissolved contaminants into solid particles large enough to be filtered out of the water. Some types of aeration cause VOCs and dissolved gases to evaporate out of the water.	**Pros:** Does not require adding chemicals to the water. **Cons:** Water with too much oxygen can be corrosive and corrode pipes; this may be a health concern if there are copper or lead pipes.	N/A	Initial: $1,100 to $6,400 Maintenance: Extra water to backwash; replacement of the filter media.	Color, taste, or odor issues Ammonia, chlorine, hydrogen sulfide, iron, manganese, methane, other dissolved gases, radon, TCE, THMs, vinyl chloride, VOCs May partially remove: arsenic (only if there is also high iron), nitrite, radium.

Also, to avoid scams, proper, complete lab analysis (general chemistry and metals scan) should be done of well water samples before deciding on what type of treatment system to install and/or making any system purchases.

In light of the our assessment of the limited water quality results available for this study, a water softener may be adequate to meet most household needs for wells that produce moderately to very hard water with some iron or manganese. However, for maintenance, some form of acid (citric-based) may be needed occasionally during system backwash to remove iron/manganese coatings that may form on resin beads should oxidizing

Table 8. Summary of home water treatment options (continued).

Treatment option	Description	Pros and cons	Point-of-use cost estimate	Point-of-entry cost estimate	Designed to fully or partially remove
Anion exchange	Anion exchange removes dissolved minerals in the water. Sodium chloride or potassium chloride (salt) added to the system replaces negatively charged minerals in the water.	**Pros:** Sodium chloride and potassium chloride are safe to handle and easy to buy. **Cons:** Anion exchange may affect how corrosive water is to pipes; this may be a health concern if there are copper or lead pipes. If treatment is not maintained properly, high concentrations of the contaminant can be dumped back into the water. Salt use can negatively affect the environment.	N/A	Initial: $2,100 to $3,600 Maintenance: $100 to $450 per year for salt	Depends on the resin. Resins may be certified to remove arsenic, fluoride, nitrate, nitrite, selenium, sulphate, uranium.
Carbon filter (Includes granular activated carbon filters – GAC)	Contaminants accumulate on the filter while water passes through.	**Pros:** Point-of-use carbon filters are inexpensive and easy to find and use. **Cons:** Harmful bacteria can grow if not regularly maintained and filters are not replaced according to instructions. If filter is not replaced according to the instructions it can become saturated and begin to release contaminants into the water.	Initial: $300 to $600 Maintenance: $20 to $150 every few months to replace the filter.	Initial: $800 to $4,300 Maintenance: Extra water to backwash or adding a disinfectant to kill bacterial growth. Replacement of the filter.	Color, taste, or odor issues Contaminant removal depends on the filter's pore size. Some filters are certified to remove chlorine, fluoride, hydrogen sulfide (H_2S), iron, lead, manganese, radon, TCE, THMs and other disinfection by-products, VOCs. Studies have shown that GAC filters are effective at removing PFAS. POE units may also treat pesticides and other SOCs.

conditions prevail at the well or water treatment system. There are water softener systems available recently that employ an innert material inside the resin beads that allow for more complete media regeneration and thus, reduced salt use when compared to systems using conventional resin media.

Table 8. Summary of home water treatment options (continued).

Treatment option	Description	Pros and cons	Point-of-use cost estimate	Point-of-entry cost estimate	Designed to fully or partially remove
Continuous chlorination and filtration	Chlorine bleach (a disinfectant that kills bacteria and viruses) is added to a holding tank. A pump feeds chlorine into the water, which oxidises and helps change dissolved contaminants into solid particles large enough to be filtered out of the water.	**Pros:** Use of chlorination helps prevent microbial growth throughout the plumbing system. **Cons:** Chlorination systems are complex, may take up a lot of space, and require frequent maintenance and monitoring. May create chemicals (by-products) in the drinking water. If the levels are high enough, by-products can cause long-term health issues. An additional carbon filter may be needed to remove chlorine taste from drinking water.	N/A	Initial: $800 to $3,500 Maintenance: Cost of bleach; extra water to backwash; replacement of the filter media.	Color, taste, or odor issues Arsenic (only if there is also high iron), bacteria, hydrogen sulfide (H_2S), iron, manganese, nitrite, viruses May partially remove: ammonia, radium.
Distillation	Distillers boil water, which makes steam. The steam rises and leaves contaminants behind. The steam hits a cooling section, where it condenses back to liquid water.	**Pros:** Removes a wider variety and greater amount of contaminants than many other treatment options. Kills 100% of bacteria, viruses, and pathogens, water can still be consumed during boil water advisories or if the well becomes contaminated. **Cons:** Heating the water to create steam can be expensive. Water may taste ‘flat’ because oxygen and minerals are reduced.	Initial: $450 to $1,800 Cost consideration: Energy cost to boil water.	N/A	Color, taste, or odor issues Arsenic, bacteria, calcium, chloride, copper, fluoride, iron, lead, magnesium, manganese, nitrate, nitrite, ODS, some pesticides and other SOCs, radium, selenium, sodium, sulphate, uranium, viruses

Table 8. Summary of home water treatment options (continued).

Treatment option	Description	Pros and cons	Point-of-use cost estimate	Point-of-entry cost estimate	Designed to fully or partially remove
Oxidizing media filtration	A media bed changes dissolved contaminants into solid particles large enough to be filtered out of the water.	**Pros:** More effective than other oxidation and filtration methods at removing iron, manganese, arsenic, and radium. Does not require a continuous chemical feed. **Cons:** Requires periodic regeneration of the media (backwashing or soaking with a chemical solution to make the media work again). Regeneration can be messy, and the chemicals can be harmful, so they must be handled and stored carefully.	N/A	Initial: $2,100 to $4,300 Maintenance: Extra water to backwash; cost for chemicals; replacement of the filter media.	Color, taste, or odor issues Arsenic (only if there is also high iron), hydrogen sulfide (H_2S), iron, manganese, radium
Ozonation and filtration	Ozone (kills bacteria and viruses) is generated using electricity and then injected into the water. The ozone changes dissolved contaminants into solid particles large enough to be filtered out of the water.	**Pros:** Does not require handling of chemicals. Ozone rapidly degrades, so no ozone reaches the consumer through the drinking water. **Cons:** Uses a lot of energy.	N/A	Most are custom designed, must call water treatment professional to get a quote.	Color, taste, or odor issues Arsenic (only if there is also high iron), bacteria, hydrogen sulfide (H_2S), iron, manganese, nitrite, viruses

For wells that produce lower amounts of sulphate, an anion exchange treatment system may be used. However, sulphate is likely to occur also with hardness, in which case a cation-based water softener may also be required. In those situations, the cation exchange unit should be installed before the anion exchange unit. Care should also be exercised during system maintenance (see cons in Table 8).

Table 8. Summary of home water treatment options (continued).

Treatment option	Description	Pros and cons	Point-of-use cost estimate	Point-of-entry cost estimate	Designed to fully or partially remove
Reverse osmosis (RO)	RO uses energy to push water through a membrane with tiny pores. The membrane stops many contaminants while allowing water to pass through.	**Pros:** Removes a wider variety and greater amount of contaminants than many other treatment options. **Cons:** Can create a lot of wastewater. May require pretreatment to prevent the membrane from getting clogged. Systems may require storage tanks and booster pumps, which require space.	Initial: $400 to $2,100 Maintenance: $200 to $300 every 1 to 2 years	Initial: $7,700 to $17,000 Maintenance: $350 to $800 every 1 to 2 years	Color, taste, or odor issues Arsenic, bacteria, calcium, chloride, copper, fluoride, iron, lead, magnesium, manganese, nitrate, nitrite, other dissolved solids, pesticides and other SOCs, PFAS, radium, selenium, sodium, sulphate, other metals, TCE, THMs, uranium, vinyl chloride, viruses, VOCs
Ultraviolet (UV) disinfection	A UV lamp shines UV rays through the water to kill bacteria, viruses, and other pathogens.	**Pros:** Does not require adding chemicals to the water. UV disinfection can be more effective than chlorination. **Cons:** May require pre-filtration if water has cloudiness (turbidity > 1 NTU).	Initial: $250 to $450 Maintenance: $80 to $150 per year	Initial: $350 to $1,200 Maintenance: about $150 per year	Bacteria, viruses

Finally, in light of the estimated initial installation and nearly doubled maintenance cost for a combined cation-exchange based softener and anion exchange treatment system for dealing with hard water with sulphate, or in situations where sulphate concentrations are more extreme and/or halite (salt) effects are also present, then notwithstanding a possibly slightly higher initial installation cost, since they can treat greater number of things and their long-term maintenance costs are generally less, it may make sense to install a whole house reverse osmosis (RO) system at the point of water entry into homes.

Table 8. Summary of home water treatment options (continued).

Treatment option	Description	Pros and cons	Point-of-use cost estimate	Point-of-entry cost estimate	Designed to fully or partially remove
Water softening (cation exchange)	Water softeners remove dissolved minerals in the water. Sodium chloride or potassium chloride (salt) are added to system to replace positively charged minerals in the water. This makes the water softer. Water softeners are sometimes installed to treat only some water in the home. The water softener may not be connected to cold water plumbing or kitchen faucet plumbing.	**Pros:** Sodium chloride and potassium chloride are safe to handle and easy to buy. Water softening is the cheapest option for removing hardness (calcium and magnesium). **Cons:** Water softening with sodium chloride adds sodium to the water, which may be a health issue for some people. Water softening may affect how corrosive your water is and can corrode pipes; this may be a health concern if there are copper or lead pipes. Salt use can negatively affect the environment.	N/A	Initial: $2,100 to $3,600 Maintenance: $100 to $450 per year for salt	Calcium, copper, iron, magnesium, manganese, radium

8. Conclusions

The geology at and around the Milford GMA is complex – a result of a long (over 400 Ma), continent-building history of tectonic activity accompanied by rapid, significant shallow marine deposition in a geographically and topologically dynamic tropical environment, along with periods of significant erosion.

Besides the proto-continental Meguma metasedimentary basement rocks, two sets of pre-glacial deposits are preserved in the Milford Station area. Those include an extensive, cyclical 800 m thick sequence of Early Carboniferous age shallow marine evaporites (gypsum, anhydrite, and halite) and carbonates, with terrestrial deposits above and below them. Then following a 180 Ma gap in the geologic record, a series of Early Cretaceous Age terrestrial/fluvial sediments, of which up to 130 m of poorly indurated fluvial deposits have been locally preserved within structural, karst and eroded valleys within the Carboniferous deposits.

A complex sequence of structural activities have occurred during the Acadian tectonic collision and subsequent continental breakup throughout the 400 Ma of sedimentary and volcanic deposition, but that complicated structural geology has been poorly mapped within the Shubenacadie Basin, and is poorly understood around the Milford GMA.

The aquifers units present at the Milford GMA and available to community well owners include the bedrock of the Green Oaks Formation, which is present directly under most of the community, and the overlapping Watering Brook Formation, which is located in the southern-most part of the Milford GMA. The MacDonald Road Formation, which may also serve as a viable bedrock aquifer unit, appears to underlie the the shallower two bedrock formations under all of the community.

The Cretaceous Chaswood Formation, an important component of the Shubenacadie-Milford Aquifer Complex (SMAC) that serves the village of Shubenacadie, is unfortunately not present below the Milford GMA; the community is situated on a bedrock topographic high, on the very edge of the Cretaceous fluvial valley, so that these Cretaceous deposits appear to wrap just east of and around the community.

While the community is almost entirely underlain by Pleistocene tills, due to their too great depth, constructing productive dug wells in these surficial deposits appears viable at only a few locations within the community – specifically at the very north and within the open space zones lands at the northwest edge of the Milford GMA. However, the use of dug wells is not advised generally in denser urbanized areas due to their greater vulnerability to surface-source contamination and groundwater drainage effects of mostly gravel-filled central sewer collection system trenches.

There are 375 records in the NS database for wells that are said to be constructed within the Milford GMA. Of those, one is a dug, 374 have been drilled into bedrock, and of those drilled wells, detailed UTM coordinate locations are available for only 100 wells. Those 100 wells are the basis upon which much of this study was carried out.

Most of the wells within the community have been drilled to a relatively shallow average depth of only 33.5 m (range 4.6 m to 61.6 m), but due to the relatively thick overburden and apparent fracturing and/or weathering of the bedrock immediately beneath it, well casings depths average 20 m (6 to 12 m is typical in Nova Scotia), and range from 1.5 m (does not meet today's well construction standards) to 56 m. The distribution for casing and well total depths generally match the trends of the bedrock surface topography. Thus, except for some areas along the eastern edge of the Milford GMA, the costs to drill wells in the community should be expected to be roughly at par with the average cost to drill wells elsewhere in Nova Scotia.

The driller blow test yield rates reported for wells drilled in the Milford GMA are in general quite high, averaging 92 L/min for the 100 wells with known locations, and average 66 L/min and range from 2.3 to 455 L/min for all wells in the community. To put this into perspective, a blow test yield rate of 2.25 L/min is generally considered enough to meet most domestic needs, providing there is sufficient cold-water storage (available drawdown) to meet peak water demands.

Static (non-pumping) water levels in drilled wells, which follow the ground surface and bedrock surface, but in a subdued fashion, are relatively deep in the community, ranging from zero (flowing conditions) to 39.6 m (averaging 17.9 m in all wells). And since wells are generally quite shallow, this makes for relatively short water columns and very small amounts of available drawdown (cold water storage) in the Milford GMA wells. While perhaps not an issue when wells were first drilled, aquifer stresses from continued pumping over time may have lowered the water table generally in areas of existing wells, which may explain complaints about water quantity. This is a situation that may worsen with time, and which could certainly be exacerbated by well interference from new wells drilled for new development.

There are only three pumping tests on record for wells drilled in the Green Oaks Formation within the Milford GMA; those test results are commensurate with the driller blow test yield rates reported in the community with a 0.5 to 0.75 adjustment factor applied.

Estimates made during a groundwater recharge and aquifer water storage analysis of the immediate Milford GMA region suggest that there should be sufficient source water replenishment from recharge to sustainably support around 560 homes (or equivalent) assuming very conservatively (unreasonably so) that recharge occurs strictly within the boundaries of the community. However, the availability groundwater recharge for wells drilled within the community is expected to extend a short distance outside Milford GMA boundaries such that conservatively, upwards to 1,900 homes (or equivalent) may be supported sustainably in the community.

Calculations suggest that there is sufficient water stored in the local surficial and bedrock hydrostratigraphic units to support several decades of droughts. However, where water quantity issues may arise and complaints based on is due to the shallow wells, of well interference among existing wells and from pumping at new wells drilled to meed the needs of new residential and business/institutional growth within the Milford GMA. The assessment in this study of possible well interference under three assumed scenarios, albeit extremely hypothetical at this time, suggests that the amounts of available drawdown that may be experienced in existing wells may not meet the NSE well interference acceptance criteria for up to 15.5% of existing wells under two scenarios, and up to 39% for the other.

The potential for well interference should be carefully considered and evaluated for any new development in the Milford GMA.

The Green Oaks Formation, which serves as the main aquifer unit beneath nearly all the Milford GMA, is comprised mostly of carbonate deposits and only minor gypsum and halite. So based on this and a limited amount of available water quality data within the Milford GMA, this aquifer unit should be expected to produce moderately to very hard water calcium-bicarbonate type water with moderate TDS and iron and manganese concentrations that are near or slightly above their aesthetic guideline values.

Since the Green Oaks Formation is only about 140 m thick below the Milford GMA, when seeking larger well yields or available drawdown (i.e. for commercial use), caution should be exercised to avoid drilling through it and into the MacDonald Road Formation below, which is reported to possibly contain more gypsum and/or halite.

Water softeners should be able to adequately treat those waters. However, some wells drilled into the Green Oaks Formation may encounter gypsum and/or halite, which if not shut out using well casing, could produce water with elevated concentrations of sulphate and/or sodium. Water treatment by reverse osmosis (RO) may be better suited to those wells.

The Watering Brook Formation, which directly underlies only the very southern part of the Milford GMA, is reported to contain much more gypsum and/or halite than the Green Oaks Formation. As such, wells drilled into this bedrock unit may be expected to produce very hard to extremely hard calcium-sulphate type water, possibly with higher TDS and concentrations for iron and manganese that may be 3 to 4 times their guideline values.

While water softeners may be able to treat water from some wells drilled into the Watering Brook Formation, the use of RO treatment systems may be much better suited to wells drilled within the southern-most parts of the Milford GMA. Alternatively, it may be possible in some of that area to drill through the Watering Brook Formation into the Green Oaks Formation below it and to advance well casings to seal off any gypsum and halite zone in shallower parts of the hole.

As with any community with on-site domestic wells, care must be exercised to mitigate against possible urban sources of groundwater contamination. These may include road salt, petroleum product spills, fertilizers and pesticides, and leaking central sewage collection systems. If one is not already in place, consideration should maybe be given to developing some form of source water protection plan for the Milford GMA.

9. Recommended future work

The SMAC may be able to serve the Milford GMA should development of a central water supply ever be considered for the community, whether that purpose and goal is to improve water quality (which based on the data available for review for this study may involve only a few homes), or to mitigate unacceptable well interference caused over time by continued pumping at existing wells or from pumping at additional wells drilled for new development.

But first, greater detailed and more extensive mapping than was done by Matheson (1999) of the SMAC should be done to better define its sub-aerial extent within the borders East Hants (for well control), its long-term sustainable yield capability to meet the demands for more users, and its protection.

There is a shortage of pumping test data at the Milford GMA in terms of properly understanding the nature of the bedrock aquifer unit fracture flow, and to better assess possible effects of well interference before allowing more land development within the community, in particular near existing densely populated areas.

While these pumping tests may be requested to be done by developers, this can become a detriment to development investment, and can result in a haphazard distribution of aquifer information in terms of the aquifer the East Hants planning strategy. Thus, East Hants may wish to implement a well defined, science-based and planned well pumping test program for wells located at key locations.

Such a pumping test program may be done using either existing wells, or new wells drilled for that purpose on Municipal land (wells could then be used for municipal buildings or parks). These tests should be done with a sufficient number of strategically located observation wells (existing domestic wells may be used if homes are supplied with water during tests) to yield the data needed.

If one is not already in place, a source water protection plan should be developed for the community. Where land-use related issues cannot be avoided, proper information and educational programs for well owners may go a long way to giving home owners the insight to protect their water supplies and those of their neighbours. A well designed and implemented source water protection plan may also to extend the time before a central water supply is needed.

10. References cited

Boehner, R.C., 1977: The Lower Carboniferous stratigraphy of the Musquodoboit Valley, central Nova Scotia; M.Sc. Thesis, Acadia University, 204 p., 14 maps.

Boehner, R.C., 1981: Stratigraphy and Depositional History of Marine Evaporites in the Lower Carboniferous Windsor Group, Shubenacadie and Musquodoboit Structural Basins, Nova Scotia, Canada; NS Natural Resources Mines and Energy Branch Open File Report 468, 31 p.

Dalrymple, R.W. 1992: Tidal depositional systems. In: Facies models: response to sea level change. Edited by R.G. Walker and N.P. James, Geological Association of Canada, p. 195-218.

Davis, D.S., 1998: Natural History of Nova Scotia: Volume 1, Topics and habitats; editors Davis, D.S., and Browne, S., Nova Scotia Museum, Nimbus Publishing, Rev. ed. (Jan. 12 1998), 514 p.

Dickie, G.G., 1986: Cretaceous Deposits of Nova Scotia; NS Dept of Mines and Energy Paper 86-1, 65 p.

Drage, J., 2017: Nova Scotia Well Log Database, unpublished spreadsheet.

Driscoll, F.G., 1986: Groundwater and Wells; pub. by Johnson Division, St. Paul, Minnesota, 1089 p.

East Hants, 2016: Municipal Planning Strategy, East Hants Official Community Plan, Bylaw P-400, July 2016, 139 p.

East Hants, 2020: Municipality of East Hants Official Community Plan, Appendix C, Generalized Future Land Use Map 2 – Milford Growth Management Area, Approved 27 July 2016, Amended 26 February 2020.

East Hants, 2021a: Shubenacadie Aquifer travel time zones GIS data layer; https://newdata-easthants.opendata.arcgis.com/datasets/shubenacadie-aquifer?geometry=-63.528%2C45.048%2C-63.301%2C45.090&selectedAttribute=Zone_Yr

East Hants, 2021b: Various planning/development GIS data layers, East Hants Open Data; https://newdata-easthants.opendata.arcgis.com/

Eisnor, K., 2002: Palynology of the Lower Cretaceous Chaswood Formation, Elsmvale Basin and Shubenacadie Ourlier, Nova Scotia; BSc. Honours Thesis, Dalhousie University, 149 p.

Environment Canada, 2020: Canadian Climate Normals 1981-2010 Station Data, Halifax Stanfield International Airport A, date modified 2020-12-10.

Falcon-Lang, H.J., Fensome, R.A., Gibling, M.R., Malcolm, J, Fletcher, K.R., and Holleman, M., 2007: Karst-related outliers of the Cretaceous Chaswood Formation of Maritime Canada; Can. J. Earth Sci., v. 44, p. 619-642).

Farvolden, R.N., 1959. Groundwater supply in Alberta. Alberta Research Council, unpublished report, 12 p.

Fletcher, K.R., 2004: Cretaceous Deposits of the Windsor Area, Nova Scotia: Another Glimpse of the Chaswood Formation; BSc. Honours Thesis, Dalhousie University, 108 p.

Freeze, R.A. and Cherry, J.A., 1979: Groundwater; Prentice-Hall Inc., NJ, 604 p.

Geonova, 2020: Basemap GIS data layers for streets, hydrology, designated land use, and others; https://geonova.novascotia.ca/

Geonova, 2020: LiDAR Digital Elevation Model data (1 m resolution) flown in 2019 (vertical datum GCVD-2013); https://geonova.novascotia.ca/

Gibling, M.R., Culshaw, N., Rygel, M.C., and Pascucci, V., 2008: The Maritimes Basin of Atlantic Canada: Basin Creation and Destruction in the Collisional Zone of Pangea; Chapter 6 of Sedimentary Basins of the World, Volume 5, Elsevier B.V. Press, ISSN 1874-5997, DOI 10.1016/S1874-5997(08)00006-3, p. 35 p. 212-237.

Giles, P.S., 1981: Major Transgressive-Regressive Cycles in Middle to Late Visean Rocks of Nova Scotia; NS Dept of Mines and Energy Paper 81-2, 27 p., 1 map.

Giles, P.S., 2009: Orbital forcing and Mississippian sea level change: time series analysis of marine flooding events in the Vesean Windsor Group of eastern Canada and implications for Gondwana glaciation; Bulletin of Canadian Petroleum Geology, v. 57, p. 449-471.

Giles, P.S. and Boehner, R.C., 1982: Geological Mpa of the Shubenacadie and Musquodoboit Basins, Central Nova Scotia; NS Dept Natural Resources, Mines Branch Map 1982-004, scale 1:50,000.

Gillis, M.X., 1997: A Report on the Shubenacadie Area Diamond Drilling Program for Kaoclay Resources Inc.; NS Dept. Natural Resources, Mines and Energy Branch, Assessment Report AR97-129., 38 p.

Gillis, M.X., 1998: A Report on the 1998 Exploration Program for Kaolin Clays in the Musquidoboit, Stewiacke and Shubenacadie Regions of Nova Scotia; Assessment Report for Kaolin Resources Ind., NS Dept Natural Resources, Mines and Energy Branch, Assessment Report AR98-128., 583 p.

Gobeil, J.-P., 2002. Stratigraphy, sedimentology, and provenance of the Chaswood Formation, West Indian Road pit, Shubenacadie, Nova Scotia. M.Sc. thesis, Dalhousie University.

Gobeil, J.-P., Pe-Piper, G., and Piper, D.J.W., 2006. The Early Cretaceous Chaswood Formation in the West Indian Road pit, central Nova Scotia. Canadian Journal of Earth Sciences, 43,
391-403.

GRASS GIS Development Team, 2020. Geographic Resources Analysis Support System (GRASS) Software, Version 7.8.3 Open Source Geospatial Foundation. https://grass.osgeo.org

Hacquebard, P.A. 1984: Composition, rank and depth of burial of two Nova Scotia lignite deposits: Geol. Survey of Canada, Current Research, Part A, Paper 84-1a.

Hantush, M.S., 1964: Advances in Hydroscience, chapter Hydraulics of Wells, p 281–442, Academic Press.

Health Canada, 2020: Guidelines for Canadian Drinking Water Quality, Summary Table released September 2020; prepared by Health Canada in collaboration with the Federal-Provincial-Territorial Committee on Drinking Water of the Federal-Provincial-Territorial Committee on Health and the Environment, 28 p.

HRM, 2018: LiDAR Digital Elevation Model data (1 m resolution), vertical datum GCVD-

2013: http://www.halifax.ca/opendata/files/HRM_LiDAR_DEM/HRM_LiDAR_DEM_2018_1m_wgs84.zip

Hundert, T., Piper, D.J.W., and Pe-Piper, G., 2006. Genetic model and exploration guidelines for kaolin beneath unconformities in the Lower Cretaceous fluvial Chaswood Formation, Nova Scotia; Exploration and Mining Geology, v. 15, p. 9-26.

Jacob, C.E., 1947: Drawdown test to determine effective radius of artesian well; in Transactions, American Society of Civil Engineers, 112(2312), p. 1047-1070.

Javaid, K.M., 2011: Development and Structure of the kennetcook-Windsor Basin, Nova Scotia, Atlantic Canada; MSc Thesis, Dept. of Earth and Atmospheric Sciences, University of Alberta, 152 p.

Jutras, P, Ryan, R.J., and Fitzgerald, R., 2006): Gradual encroachment of a rocky shoreline by an invasive sea during the Mississippian at the southeastern margin of the Maritimes Basin, Nova Scotia, Canada; Can. J. Earth Sci, v. 43, p 1183-1204.

Kennedy, G.W., Garroway, K/G., and Finlayson-Bourque, D.S., 2010: Estimation of Regional Groundwater Budgets in Nova Scotia; NS Natural Resources, Mines Branch Open File Illustration ME 2010-2.

Kennedy, G.W., 2014: Identification and Preliminay Mapping of Surficial Aquifers in Nova Scotia; in NS Dept. of Natural Resources, Mineral Resources Branch, Report of Activities 2013, Report ME 2014-001, p. 33-43.

Kennedy, G.W., 2020a: Nova Scotia Pumping Test Database; partially complete database available from NS Dept. of Energy and Mines; ditigal product ME 489, 2020, https://novascotia.ca/natr/meb/download/dp498.asp

Kennedy, G.W., 2020b: Nova Scotia Well Water Quality Database; mined from the NS Dept. of Energy and Mines Groundwater Interactive Map; https://fletcher.novascotia.ca/DNRViewer/?viewer=Groundwater

Keppie, J.D., Sr., 2000: Legend for the Geological Map of the Province of Nova Scotia; NS Dept. of Nat. Res., Minerals and Energy Branch Map ME 2000-1.

Keppie, J.D., Sr., (undated): Fracking in the Windsor-Kennetcook subbasin of Nova Scotia: is there a viable potential?; unpublished report, Instituto de Geologia, Universidad macional Autonoma de Mexico, 04510 Mexico, DF, Mexico, 44 p.

Keppie, J.D., Jr., 2013: New Insights for the Regional Geology of the Kennetcook Basin, Meguma Terrane, Nova Scotia; in NS Dept. Natural Resources, Mineral Resources Branch, Report of Activities, Report ME-2012-001, p. 19-25.

Lay, T., 1979: Groundwater survey – Field investigations, Shubanacadie-Stewiacke River Basin, Nova Scotia; Tech. Report #42, prepared for the Shubenacadie-Stewiacke River Basin Board, March 1979, 88 p.

MacMulin, S., Doane, K, Keppie, F.D., MacDonald, A., Dempsey, S., Dmytriw, R., Makrides, C., Smith, B., Brown, D., Kendell, K., Rhyno, S., Bianco, E., Luheshi, M., Cuilhe, L., Saint-Ange, F., Moccia, A., Prélat, A., Chrest, T., Carayon, V., Basuyau, C., Le Saos, A., Barres, E., Barrois, A., Thomas, D., Bimont, C., Quilbe, B., Ke-Kien, H., Chenet, P-Y., Fowler, M., Giles, P., Fensome, R., Alenandre, N., MacRae, A., Weston, J., and

Shaw, D., 2017: 2017: Sydney Basin Play Fairway Analysis, 2017 Call for bid area; BeicipFranlab, Offshore Energy Research Association, and NS Dept. of Energy, Nova Scotia; Chapter 1, 12 p.

Maréchal, J.C., Dewandel, B., Ahmed, S., Galeazzi, L., and Zaidi, F.K., 2006: Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture; Journal of Hydrology, 329, 1-2, p. 281-293.

Matheson, T.R., 1999: A Hydrogeological Evaluation of the Shubenacadie-Milford Aquifer Complex, with Emphasis on Program Development through Existing Database Study; Master of Applied Science Thesis, Dalhousie University – Daltech, Halifax, NS., 333 p.

Neilsen, M.G., 2002: Estimated quantity of water in fractured bedrock units on Mt. Desert Island, and estimated groundwater use, recharge, and dilution of nitrogen in septic waste in the Bar Harbor area, Maine; USGS Open-File Report 01-435, 53 p.

NGWA, 2007: Groundwater Fundamentals, educational web site series by the National Ground Water Association, Westerville, OH, USA; https://www.ngwa.org/what-is-groundwater/About-groundwater, accessed February 2021.

NSDEM, 2020: Nova Scotia Well Log Database, partially complete database available from NS Dept. of Energy and Mines; digital product DP ME 430 2020, https://novascotia.ca/natr/meb/download/dp430.asp

NSE, 2011: Guide to Groundwater Assessments for Subdivisions Serviced by Private Wells" July 2011, 33 p. incl. appendices.

NSE, 2016, 2018: Nova Scotia Well Log Database, raw complete database available from Nova Scotia Environment; https://novascotia.ca/nse/groundwater/welldatabase.asp

NSEM, 2021: Nova Scotia Groundwater Atlas, NS Dept. Energy and Mines, https://fletcher.novascotia.ca/DNRViewer/?viewer=Groundwater, accessed February 2021.

O'Neill, M., and Poole, J., 2016: Nova Scotia Drillhole Database; NS Dept. of Energy and Mines digital product DP ME 3, Version 5, 2016; https://novascotia.ca/natr/meb/download/dp003.asp

Pe-Piper, G., Piper, D.J.W., Stea, R.R., Gobeil, J.-P., Hundert, T., Dolansky, L., and Douglas, E., 2004: The geology of the Chaswood Formation of Nova Scotia and New Brunswick; Final report for ExxonMobil Sable Project, May 2004 under contract between ExxonMobil and Saint Mary's university, 118 p.

Pe-Piper, G., Piper, D.J.W., 2010: Volcanic ash in the Lower Cretaceous Chaswood Formation of Nova Scotia: source and implications; Can. J. Earch Sci., v. 47, p. 1427-1443.

Pe-Piper, G., Piper, D.J.W., 2018: Field Trip 2, Onshore equivalents of the Cretaceous reservoir rocks of the Scotian Basin: Detrital petrology, tectonics and diagenesis; Conjugate Margins Conference, Halifax 2018, ISBN: 0-9810595-10, 72 p.

Pe-Piper, G., Stea, R.R., Ingram, S., and Piper, D.J.W., 2004a. Heavy minerals and sedimentary petrology of the Cretaceous sands from the Shubenacadie outlier, Nova Scotia. NS Dept. of Natural Resources, Open File Report ME 2004-5, 78p.

Pe-Piper, G., Traintafyllidis, S., and Piper, D.J.W., 2008: Geochemical identification of clastic sediment provenance from known sources of similar geology: the Cretaceous Scotian Basin, Canada; J. Sedimentary Research, v. 78, p 595-607.

Piper, A.M., 1944: A graphic procedure in the geochemical interpretation of water analyses; Transactions - American Geophysical Union, vol. 25, p. 914-928.

Piper, D.J.W., Pe-Piper, G., and Ernest, V.D., 2005: Tectonic deformation and its sedimentary consequences during deposition of the Lower Cretaceous Chaswood Formation, Elmsvale basin, Nova Scotia; Bulletin of Canadian Petroleum Geololgy, v. 53, No. 2, p. 189-199.

Piper, D.J.W., Pe-Piper, G, Hundert, T, and Venugopal, D.V., 2007: The Lower Cretaceous Chaswood Formation in southern New Brunswick: provenance and tectonics; Can. J. Earth Sci., v. 44, p. 665-667.

Piper, D.J.W., Pe-Piper, G., and Ledger-Piercey, S., 2008: Geochemistry of the Lower Cretaceous Chaswood Formation, Nova Scotia, Canada: Provenance and diagenesis; Can. J. Earth Sci., v. 45, p. 1083-1094.

Price, J., 2000: Silica Sand Exploration in the Shubenacadie Basin 1999//2000; Shaw Resources – Technical Report 1, NS Dept. Natural Resources, Mines and Energy Branch, Assessment Report AR2000-036, 90 p. including maps.

Reynolds, P.H., Pe-Piper, G., and Piper, D.J.W., 2010: Sediment sources and dispersion as revealed by single-grain $^{40}Ar/^{39}Ar$ ages of detrital muscovite from Carboniferous and Cretaceous rocks in mainland Nova Scotia; Can. J. Earth Sci., v. 47, p. 957-970.

Scott, A.C., Collinson, M.E., Nichols, G.J., Cripps, J. and Calder, J.H. 1998: Fire ecology of Cretaceous vegetation in the Isle of Wight, England and Nova Scotia, Canada. Geol. Soc of America, Program with Abstracts, p. A36.

Stantec, 2010: Shubenacadie PW-11 Step 2 GUDI Hydrogeological Assessment; unpublished report prepared by Stantec Consulting Ltd. for Municipality of East Hants, 30 p.

Stea, R.R., Conley, H., and Brown, Y., 2006: Surficial Geology Map of the Province of Nova Scotia; DP ME 36, Version 2, 2006. Digital Version of Nova Scotia Department of Natural Resources Map ME 1992-3, Surficial Geology Map of the Province of Nova Scotia, Scale 1:500 000, by R. R. Stea, H. Conley and Y. Brown, 1992

Stea, R.R., Finck, P.W., Pullan, S.E., and Corey, M.C., 1996: Cretaceous deposits of kaolin and silica sand in the Shubenacadie and Musquodoboit valleys, Nova Scotia, Canada; NS Dept. of Natural Resources, Minerals and Energy Branch, Open File Report 93-003, 58 p. plus appendices.

Stea, R.R. and Kennedy, C.M., 1998: Surficial Geology, Shubenacadie Area, NTS Sheet 11E/03; NS Dept. Natural Resources, Minerals and Energy Branch, Open File Map 1998-003, scale 1:50,000.

Stea, R.R., and Mott, R.J., 1990: Quaternary Geology of Nova Scotia, Guidebook for Field Excursion; NS Dept. of Mines and Energy, Open File Report 90-008, 85 p.

Stea, R.R. and Pullan, S.E., 2001: Hidden Cretaceous basins in Nova Scotia; Can. J. Earth Sci., v. 38, p. 1335-1354.

Stea, R.R., Pe-Piper, G., and Piper, D.J.W., 2003: Early Cretaceous Outliers in Northern Nova Scotia: The Fault Connection; Mining Matters for Nova Scotia 2003, NS Natural Resources Mines and Energy Branch Report ME 2003-2, p. 15.

Stea, R.R., Pe-Piper, G. and Piper, D.J.W., 2004. Early Cretaceous outliers in northern Nova Scotia: the fault connection. Atlantic Geoscience Society Colloquium Program and Abstracts, 30, 29.

Theis, C.V., 1935: The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage; in Transactions, American Geophysical Union, vol. 16, No. 2, p. 519–524.

USGS, 2019: Aquifers and Groundwater; US Geologic Survey, Water Science School, https://www.usgs.gov/special-topic/water-science-school/science/aquifers-and-groundwater?qt-science_center_objects=0#qt-science_center_objects, accessed February 2021.

Utting, J., 1980: Palynology of the Windsor Group (Mississippian) in a borehole at Stewiacke, Shubenacadie Basin, Nova Scotia: Can J. Earth Sci., v. 17, P 1031-1045).

Vaughan Engineering, 2001: Municipality of East Hants Shubenacadie/Milford Infrastructure Study (Draft, April 2001); unpublished report to East Hants, 143 p.

Waldron, J.W.F., Roselli, C.G., Utting, J., and Johnston, S.K., 2010: Kennetcook thrust system: late Paleozoic transperssion near the southern margin of the Maritimes Basin, Nova Scotia; Can. J. Earth Sci., v. 47, p. 137-159.

Warringer, J.L. 1996: Cretaceous marginal marine and freshwater rhizopods from central Nova Scotia, Canada. Dalhousie University, Halifax, Nova Scotia, B.Sc. (Honours) thesis.

Wightman, J.F., 2012: AlGreen Minerals Inc. Report on Evaluaition of Kaolin Clay and Silica Sand Deposits, EL 09706, EL10196 & EL 10197, Shubenacadie, Hants/Halifax Co., N.S., Reference Map 11-E-3-B; NS Dept. Natural Resources, Mines and Energy Branch, Assessment Report AR2012-119, 336 p.

Williams, G.L., Fyffe, L.R., Wardle, R.J., Colman-Sadd, S.P., 2018: CSPG Lexicon of Canadian Stratigraphy, Volume 6, Atlantic Canada; Boehner, R.C. (editor)

Winter, T.C., Harvey, J.W., Franke, O.L, and Alley, W.M., 1998: Ground Water and Surface Water, A Single Resource; US Geological Survey Circular 1139, 87 p.