Development of indices to assess the potential impact of drought to private wells in Nova Scotia

G. W. Kennedy and J. Drage
Nova Scotia Department of Natural Resources, Halifax, Nova Scotia, Canada
G. Check
Nova Scotia Environment, Halifax, Nova Scotia, Canada

ABSTRACT
In the summer and fall of 2016, southwestern Nova Scotia (NS) experienced moderate to severe drought conditions, with rainfall deficits persisting into the winter months. Available provincial observation wells in southwestern NS showed historical lows or below normal water levels. It is estimated that over 1000 private well users in southwestern NS experienced water shortages because of the drought, especially well users relying on dug wells for domestic water supply. The NS Department of Natural Resources developed an index map to show areas of the province where private well owners are more likely to experience water shortages and published the map as a web application for planning and risk communication purposes. A groundwater level index was also developed to characterize water levels recorded by the observation well network and published on the map.

RÉSUMÉ
En été et en automne de 2016, le sud-ouest de la Nouvelle-Écosse (N.-É.) a connu des conditions de sécheresse modérées à sévères et des déficits de précipitation persistant dans les mois d'hiver. Les puits d'observation provinciaux disponibles dans le sud-ouest de la N.-É. ont indiqué leurs plus bas niveaux d'eaux souterraines, ou des niveaux inférieurs à la normale, pour la période d'observation. On estime que dans le sud-ouest de la N.-É., les pénuries d'eau à cause de la sécheresse ont affecté plus de 1000 utilisateurs de puits privés, en particulier les utilisateurs de puits creusés. Le ministère des ressources naturelles de N.-É. a développé une carte d'indice pour indiquer les régions de la province où les propriétaires de puits privés sont plus susceptibles de connaître des pénuries d'eau et a publié la carte sous forme d'application Web pour la planification et la communication des risques. Un indice de niveau d'eaux souterraines a aussi été développé pour caractériser les niveaux d'eau enregistrés par le réseau de puits d'observation et publiés sur la carte.

1 INTRODUCTION

In the summer and fall of 2016, southwestern Nova Scotia (NS) experienced abnormally dry to severe drought conditions, with rainfall deficits persisting into the winter months. The impacts of the drought were concentrated in Yarmouth, Shelburne, Queens, Lunenburg, Hants and Halifax counties (Figure 1). Based on climate data from 1880 to 2016 (n=137) for the Yarmouth meteorological station (Environment Canada 2017), the summer of 2016 ranked as the driest and fourth warmest recorded in this part of the province. Severely dry conditions occur infrequently in southwestern Nova Scotia, and the 2016 drought event highlighted the region's vulnerability to drought given that a higher percentage of private well users rely on shallow wells (e.g. dug wells) in Shelburne and Yarmouth counties relative to the rest of the province (Nova Scotia Environment 2016). Although climate change models predict small precipitation increases for the region, they also project more extreme weather events and a 36% increase in summer water deficits (e.g. actual – potential evapotranspiration) from the 1980s to the 2050s (Richards and Daigle 2011). These types of seasonal droughts are therefore expected to become more common over the next several decades.

Impacts of the drought included sustained water supply shortages related to private well household water supply, crop irrigation, livestock watering, and fire protection. At the peak of the drought it was estimated that over 1000 households experienced private well water shortages, which in some municipalities represented as much as 25% of the jurisdiction's households. Areas with a higher proportion of residents relying on unconfined shallow aquifers for water supply (e.g. dug and shallow drilled wells) were especially affected by the drought. In southwestern NS, groundwater is obtained mainly from dug wells constructed in thin, low to moderate permeability tills, or from drilled wells in fractured slate,

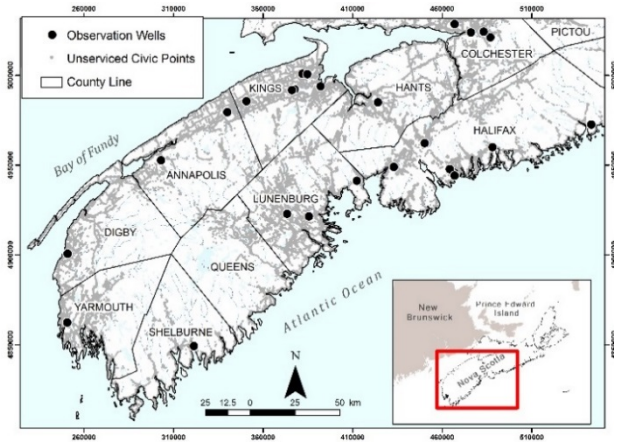

Figure 1. Southwestern Nova Scotia.

quartzite or granite aquifers (Porter 1982). Observation wells located in southwestern NS indicate that water levels in bedrock aquifers respond relatively quickly to rainfall (i.e. 1-3 days) (Nova Scotia Environment 2015). Other impacts of the 2016 drought included increased occurrence of wildfires, a loss of Christmas tree seedlings, smaller crop sizes (e.g. blueberries) and yields, and a loss of suitable fish habitat, stressing federally endangered species such as the Atlantic salmon.

Emergency response measures were activated by the province in coordination with various affected municipal units to mitigate the impacts of the drought. These measures included the provision of bottled water and bulk water deliveries. Fill stations were designated where residents could obtain bulk water, and various facilities were identified where residents could utilize water services (e.g. laundry, showers, etc.), such as schools, community centres, and provincial parks. The Nova Scotia Department of Natural Resources (DNR) reported over 2000 visits to provincial parks in September and October for water or shower use, and extended the provincial park season by several weeks to provide potable water access to affected residents. A ban on open air burning and water use restrictions on municipal water users were implemented throughout much of southwestern and central NS during the drought event, and during the driest conditions, the province restricted access to Crown land for the first time in 15 years. Some municipalities collected information from affected residents through online surveys to help determine the distribution and severity of water shortages.

Residents were encouraged to conserve water and a 'water shortage webpage' (Nova Scotia Environment 2017a) was developed by the province to provide advice to affected well owners. Adaptations by private well owners included the routine collection of water from the nearest available source (e.g. neighbour, fire station, etc.), the arrangement of bulk water deliveries to their existing dug well or to a temporary storage container (e.g. fish boxes) for domestic use, and a surge in construction of new drilled wells or rainwater cisterns to replace or supplement dug wells.

To provide water managers, emergency response officials, and affected water well users a better understanding of the scope of the problem, and to indicate areas where issues may develop requiring the deployment of resources, precipitation patterns and water level trends from provincial observation wells were assessed by the departments of Natural Resources and Environment (NSE) using a groundwater level index method, and an index map was developed to show areas of Nova Scotia where private well owners are more likely to experience water shortages (especially owners of shallow wells).

2 METHODS

2.1 Analysis of Precipitation and Groundwater Level Trends

Monthly precipitation records were obtained from Environment Canada (2017) for the Yarmouth climate station and compared to monthly normals. Groundwater level data were obtained from the Nova Scotia provincial observation well network (Figure 1), which is maintained by NSE (Nova Scotia Environment 2017b). To provide a simple, rapid method of characterizing and reporting observation well water levels, a groundwater level index was calculated using the percentile method, similar to the approach used by the United States Geological Survey (USGS) (United States Geological Survey 2016).

The groundwater index calculations are based on available groundwater level data on a daily basis and are divided into five categories: Above Historical High (water level exceeds the maximum observed level on record for that day); Above Normal (water level exceeds the 75th percentile level on record for that day); Normal (water level is between the 25th and 75th percentile level on record for that day); Below Normal (water level is below the 25th percentile level on record for that day); and Below Historical Low (water level is below the lowest observed level on record for that day). These percentile classes are the same ones used in the USGS percentile method, although the USGS approach includes two additional categories for historical low and high levels. The index was calculated using all available historical water level data from the water well from previous years for the day of interest, excluding the current year's data. The number of years of available historic data is different for each observation well. As of 2017, the period of record available for the observation wells ranges from 3 to 50 years, although observation wells with less than 5 years of data were excluded from the present analysis.

2.2 Development of Potential Relative Impact of Drought to Private Wells Index

An index map was developed to show the relative potential impact of drought to private well users based on a simple treatment of factors known to influence well water shortages, such as drought severity, water use, aquifer type (i.e. well type) and available drawdown (i.e. well depth). Spatial analyses were conducted using ArcGIS™10 (Esri, Inc.), and designed so that the index could be readily updated using a geoprocessing model as input layers change over time. The index was calculated across Nova Scotia for each National Topographic System (NTS) 1:10 000 sheet. The coarse resolution of the index map ensured that there were sufficient data in each area to provide a representative trend. Rankings were assigned to each NTS map sheet based on five key criteria and the rankings were then weighted and summed to produce an overall relative index of the potential impact of drought to private wells. The ranking system for each of the five input criteria is qualitative, and is based on a five-category defined-interval classification. Weightings were applied to the criteria so that the index map captured observed spatial trends with respect to water shortages.

2.2.1 Current Drought Conditions

The most important component of the relative drought impact index is the current level of drought severity. Agriculture and Agri-Food Canada (AAFC) produces

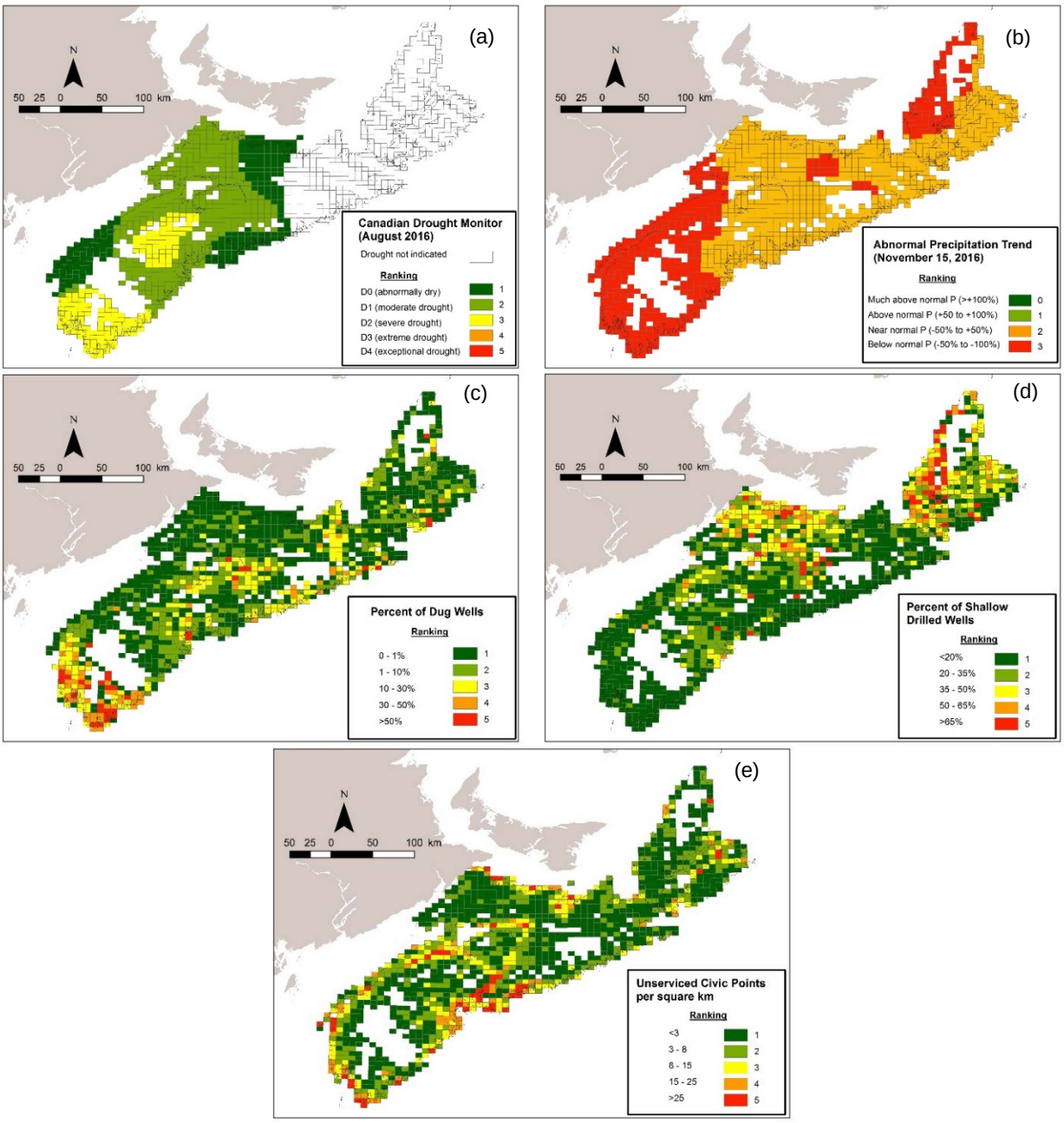

Figure 2. (a) Canadian drought monitor, (b) abnormal precipitation trend, (c) percent of dug wells, (d) percent of shallow drilled wells, and (e) unserviced civic point density.

monthly assessments of drought for Canada as part of the North American Drought Monitor, a cooperative effort between drought experts in Canada, Mexico and the United States. A comprehensive assessment of drought is best achieved through a variety of indices, and therefore the Canadian Drought Monitor (CDM) is developed from sources such as precipitation and temperature indicators, Normalized Difference Vegetation Index satellite imagery, streamflow values, the Palmer Drought Index, the Standardized Precipitation Index; as well as drought indicators used by the agriculture, forestry, and water management sectors (Agriculture and Agri-Food Canada 2016). The assessment is conducted by federal, provincial, and academic scientists, in coordination with international drought experts. A monthly map is produced by AAFC to assess the current drought risk to agriculture using a five-category system ranging from D0 (abnormally dry) to D4 (exceptional drought) based on the percentile probability of those conditions occurring.

The monthly drought monitor risk zone polygons were obtained from Agriculture and Agri-Food Canada and a rank was assigned to the provincial NTS map sheets intersecting the zones based on the criteria shown in Figure 2a. The current drought conditions component of the private wells drought impact index was assigned a weighting of 35% in the index calculation.

2.2.2 Abnormal Precipitation Trends

To improve the temporal resolution of the private well drought impact index compared to the monthly CDM map, and to incorporate a predictive component to the index, the Environment Canada 'Vigilance' map product was also used. The 'Vigilance' map compares precipitation totals from the previous nine days and forecasted precipitation for the next nine days with precipitation normals over the 18-day period to show abnormal precipitation trends (Environment Canada unpub. data). Precipitation estimates relative to normals were classified according to the criteria shown in Figure 2b based on the intersection of map sheets with zones showing abnormal trends. This layer was assigned a weighting of 15% in the index calculation.

2.2.3 Dug and Shallow Drilled Well Reliance

To consider the demographics of the aquifer type and available drawdown, the percent of dug wells compared to all wells recorded in the NS Well Logs Database (Nova Scotia Environment 2016) for each map sheet was estimated and classified according to the criteria shown in Figure 2c. It should be noted that dug well construction is under-reported in the well logs database compared to drilled wells, and these percentages do not accurately reflect the demographics of well type, but are indicative of the regional prevalence of well type. The dug well reliance component of the index was assigned a weighting of 25% in the index calculation. Similarly, the percent of drilled wells less than 30 m deep relative to the total number of wells in each map sheet was estimated and classified according to the criteria shown in Figure 2d. This component was weighted at 10% in the index calculation.

2.2.4 Density of Private Well Water Use

To consider the density of private well users, a map of civic address points from the Nova Scotia Civic Addressing File (GeoNOVA 2015) was clipped to exclude municipal servicing boundaries and the resulting layer of unserviced civic address points was used as a surrogate for the distribution of private wells. The number of unserviced civic points within each NTS map sheet was counted and divided by the map sheet area to estimate the density of groundwater use by private well users. Along the coast, map sheets were clipped to the coastline boundary for the density calculation. The resulting density values were classified according to the criteria shown in Figure 2e. This component of the index was assigned a weighting of 15%.

2.2.5 Potential Relative Impact of Drought to Private Wells

The index of the relative potential impact of drought to private wells was calculated as the sum of all five criteria, producing an overall rank. The overall rank was then assigned to the centroid of the NTS map sheet and interpolated across Nova Scotia using the inverse distance weighted technique in ArcGIS™10 (Esri Inc.). NTS map sheets that had or no private well users within the map sheet boundaries, or where the land mass covered less than 10% of the map sheet area (i.e. mostly ocean), were excluded from the interpolation and were blanked out in the drought index map. The index map was then compared to the available provincial observation well water level data as well as the reported distribution of water shortages to evaluate the reliability of the approach.

3 RESULTS

3.1 Precipitation and Water Level Trends

Over the summer of 2016, there were few weather fronts that stalled or became stationary over southwestern Nova Scotia, partly due to the dynamics of the jet stream, which

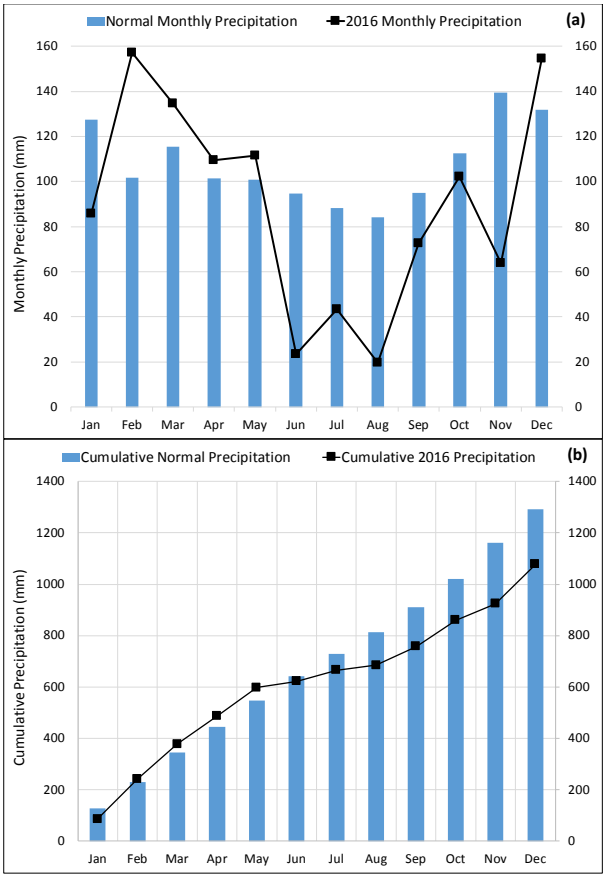

Figure 3. Precipitation in Yarmouth. (a) Normal monthly versus 2016 monthly precipitation, (b) cumulative normal monthly versus 2016 cumulative monthly precipitation.

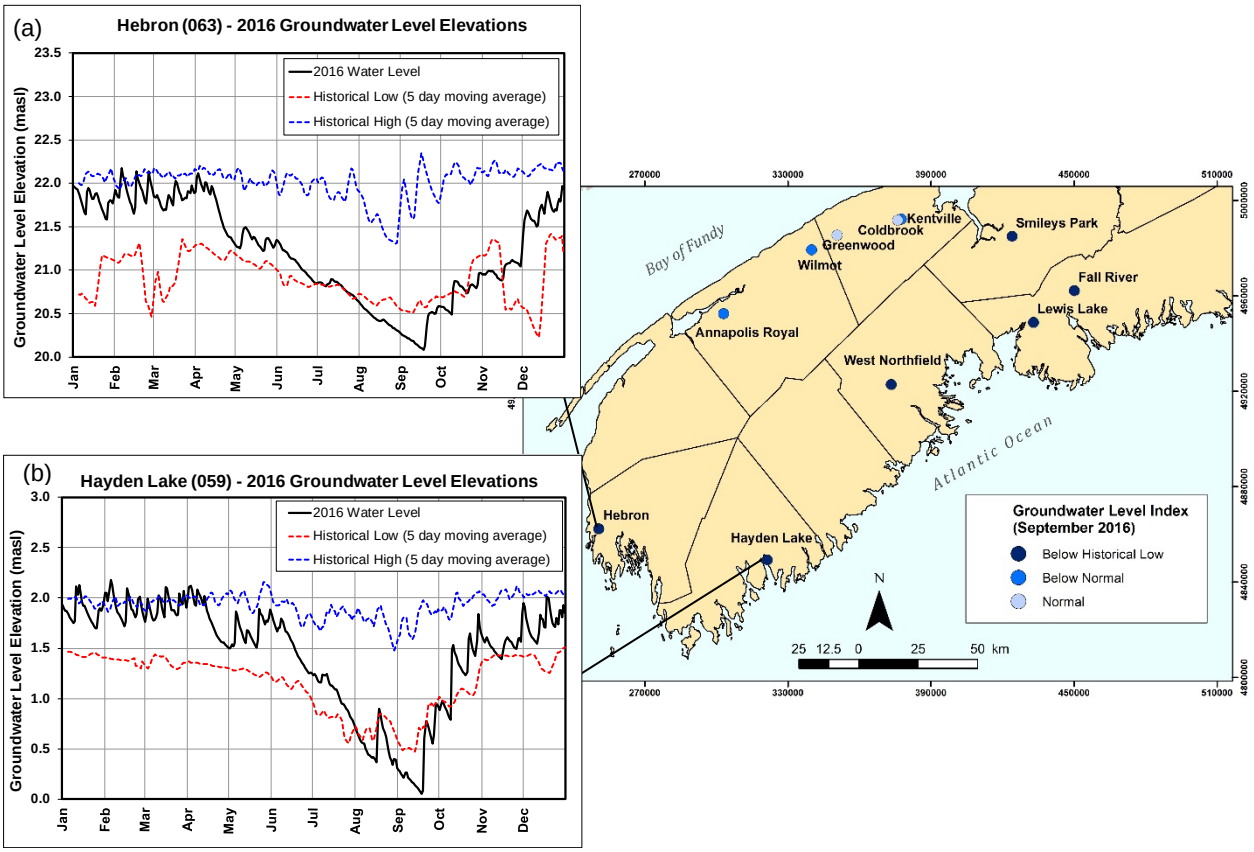

Figure 4. Groundwater level index for provincial observation wells in southwestern Nova Scotia and 2016 hydrographs from (a) Hebron observation well and (b) Hayden Lake observation well.

Table 1. Summary of water level and groundwater index (September 2016) for selected observation wells with at least 5 years of available data.

Observation Well	Monitoring Period as of 2016 (years)	Aquifer Type	Well Depth (mbgs)	Historical Low Water Level (masl)	Historical High Water Level (masl)	Water Level (Sept. 2016, (masl)	Groundwater Level Index (Sept. 2016)
Greenwood	50	Glaciofluvial	7.6	20.96	21.98	21.31	Normal
Coldbrook	7	Sedimentary	70.7	8.59	9.79	9.04	Normal
Wilmot	50	Glaciofluvial	18.3	5.85	6.61	5.95	Below Normal
Kentville	36	Glaciofluvial	21.3	6.37	7.54	6.57	Below Normal
Annapolis Royal	26	Plutonic	62.5	108.71	109.47	108.80	Below Normal
Hayden Lake	28	Metamorphic	48.8	0.80	1.92	0.41	Below Historical Low
Hebron	26	Metamorphic	45.7	20.62	22.07	20.10	Below Historical Low
Fall River	8	Metamorphic	61.0	100.88	105.82	98.89	Below Historical Low
West Northfield	8	Metamorphic	48.8	49.22	50.10	48.80	Below Historical Low
Lewis Lake	8	Plutonic	76.2	68.91	69.36	68.63	Below Historical Low
Smileys Park	5	Glaciofluvial	9.8	31.50	32.64	31.34	Below Historical Low

mbgs: metres below groundwater surface, masl: metres above sea level

flowed almost directly west to east; a pattern associated with fast moving weather fronts and lower rainfall amounts. Below normal monthly rainfall totals were observed in Yarmouth from June to November, resulting in a growing cumulative rainfall deficit that began in June and persisted into December (Figure 3). The cumulative rainfall deficit recorded over the months of June to November was 214 mm.

Figure 4 shows the distribution of provincial observation wells in southwestern Nova Scotia and the groundwater level index based on water levels observed in September 2016, as well as two examples of groundwater level hydrographs.

The analysis of groundwater level trends over the summer and fall of 2016 showed that 9 of the 11 observation wells with at least 5 years of data had below normal water levels, and 6 of these wells had below historical low water levels (Table 1). The hydrographs indicate that groundwater levels are sensitive to below normal summer rainfall amounts, falling rapidly between June and September, but also rising rapidly when near normal rainfall amounts occur in late September and October (Figure 3a). The sensitivity of groundwater levels to precipitation can be attributed to the low water storage capacity and fast recharge rate of the region's fractured bedrock aquifers. Above normal precipitation was observed during December (Figure 3a), engendering improved drought conditions in southwestern NS and 'normal' groundwater levels according to the groundwater level index (Figure 4).

3.2 Potential Impact of Drought to Private Wells Index Map

Figures 5a-5c show the relative potential impact of drought to private wells generated for the months of September, October and November in 2016, with the greatest potential impact of the drought predicted in October. The greatest potential impact was predicted in October because the input CDM polygons (Agriculture and Agri-Food Canada 2016), reflecting conditions as of September 30, 2016, were associated with the largest area of severe drought conditions (e.g. D2, 10-20 year frequency) occurring in Nova Scotia in 2016. By the end of October, only moderate drought and abnormally dry conditions persisted in southwestern NS due to significant late September and October rainfall events.

Although a rigorous validation of the approach is difficult without a province-wide survey of water shortages, the index map shows good correspondence between areas of greatest potential impact and the location of observation wells with below normal water levels and dry wells recorded by some municipalities (n=713) (Figure 6). Municipalities with the highest average rank predicted by the drought impact index (e.g Argyle and Shelburne) also had the highest density (dry wells/km^2) and total number of dry wells, based on the available survey information. The survey information also confirmed that most water shortages, over 93% (n=494), were associated with dug wells (where well type was indicated in the survey response).

4 DISCUSSION

The two separate indices developed during this work provide a valuable tool for communicating the risk of water shortages to well users, and were published as a web map application during the drought (Nova Scotia

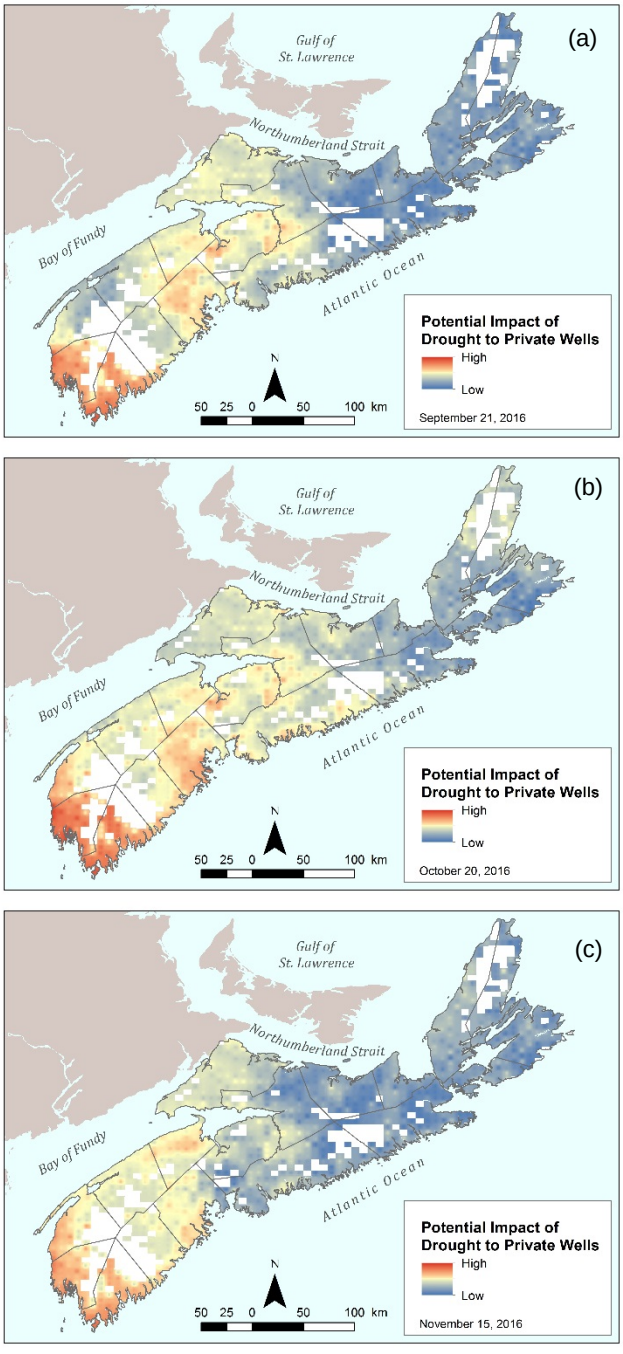

Figure 5. Index map of potential impact of drought to private wells for (a) September, (b) October and (c) November 2016.

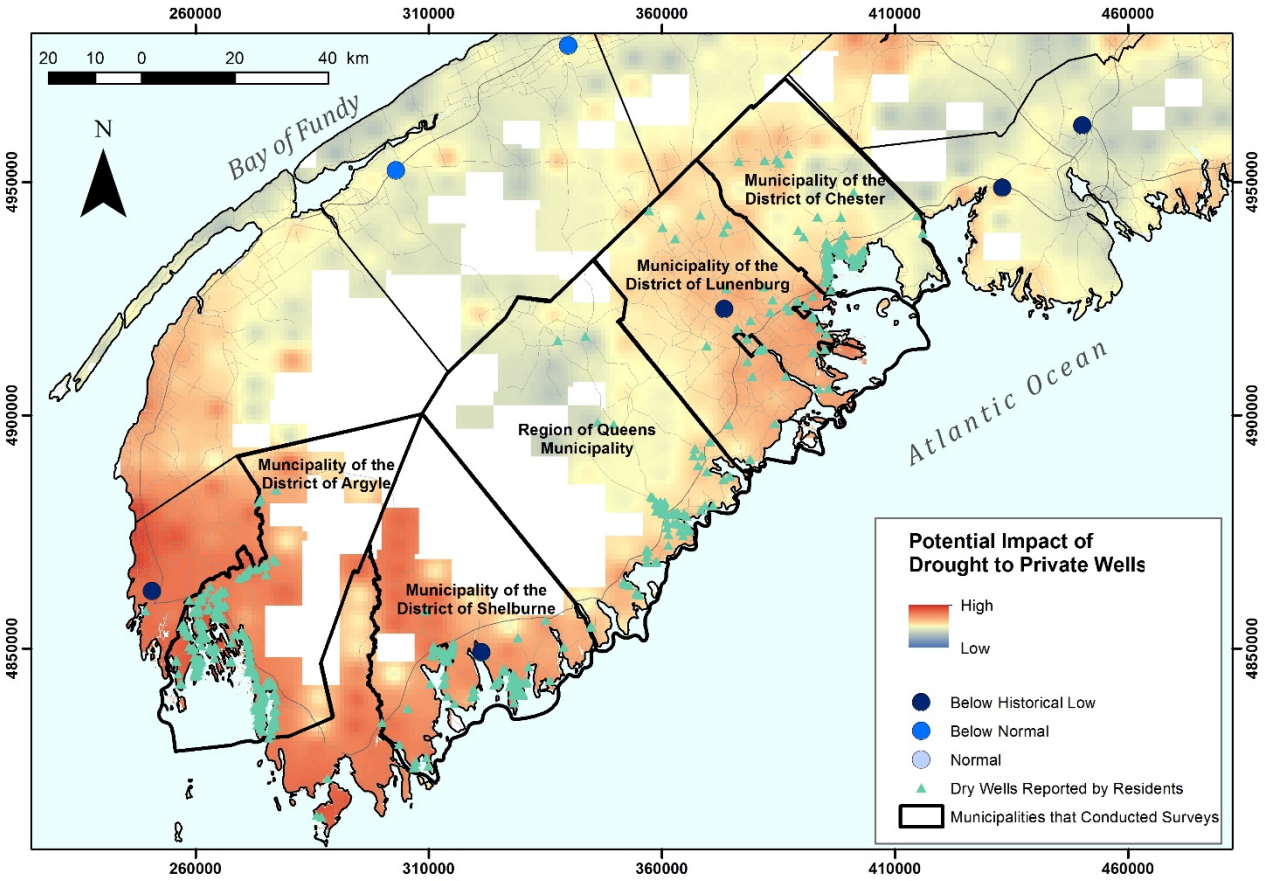

Figure 6. Potential impact of drought to private wells index compared to the location of dry wells and the groundwater level index for provincial observation wells. Blank areas indicate areas with no private well users.

Department of Natural Resources 2016). Numerous information requests were received by the province from the public and the media during the drought event, and these indices can provide a simple visual description of the scope and severity of drought impacts to private well users. The indices can also be used by water managers and emergency management officers.

For example, the map was used during the 2016 drought event to support decision-making on which provincial parks should remain open past the usual seasonal closure date to supply water to residents affected by the drought. The map was also used to identify areas that may have the greatest need for resources (e.g. bottled water) and public water supplies that may be at risk of water shortages. These public water supply owners were contacted during the 2016 drought so that emergency response officers could coordinate support services as needed. In future years, the water level drought index could be used by municipalities in the province as a warning system to identify the onset of drought conditions so that water conservation measures can be implemented before wells go dry and the impact of water shortages can be mitigated.

The relative impact of drought to private wells index highlighted the regional vulnerability of southwestern Nova Scotia to abnormally dry conditions due to the reliance of many of the region's residents on dug wells for water supply. This vulnerability may be exacerbated by climate change, since droughts and more extreme weather events are expected to become more common in Nova Scotia over the next several decades. To improve their resilience to drought, many residents of southwestern Nova Scotia have drilled, or plan to drill, deeper wells or make other water supply system improvements. In response, the province made legislative amendments in the fall of 2016 to allow municipalities to provide programs for financing water supply upgrades. Other municipalities, such as the Municipality of the District of Chester, have initiated studies to examine the feasibility of municipal water servicing to ensure a more secure water supply for the village's residents and businesses.

The work also highlighted the lack of suitable observation wells in shallow aquifers and DNR is exploring ways of using low-cost water level meters to augment the provincial observation well network, which consists mainly of drilled wells in bedrock aquifers, with more monitoring of shallow aquifers (e.g. dug wells). The drought vulnerability and groundwater level indices will be further evaluated during the summer of 2017 to assess

whether they are useful long-term tools for characterizing and communicating groundwater level conditions and the impacts of groundwater drought to Nova Scotians.

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