Community Based Monitoring: Applicability to the Low Water Response Program

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1. Introduction*

Freshwater is a natural resource that is critical to the health of both the environment and economy of Ontario. Exceedingly dry conditions that were once occurring every decade or so have become more frequent, putting pressure on both surface and groundwater resources, especially when combined with the increasing human demand (OMAFRA, 2016). The Ontario Low Water Response program assesses low water conditions based on the state of stream flow or rainfall accumulation, progressing through three stages as the conditions become more severe (e.g., Level I, II, and III; OMAFRA, 2016). It is likely that current extreme low water conditions are expected to become the new average condition under future climate change scenarios (Matrix Solutions Inc. & Blumetric Environmental Inc., 2017).

Rain gauges can accurately measure precipitation events, however, the high spatiotemporal variability of these events mean that the associated measurements have limited spatial representativeness (Villarini, et al., 2008). Hubbard (1994) found that one station every 60 km in relatively simple terrain was adequate to capture 90% of the spatial variability in daily maximum temperature. Minimum temperature and evapotranspiration variability would require network resolution of 30 km; soil temperature, 20 km; and daily precipitation 5 km (or 25 km^2 per station). Higher density networks, however, do not always provide better spatial representation of meteorological variables, so a balance between representative data and cost of installations must be obtained (Ren & Ren, 2012; Vinnikov, et al., 1999).

The large spatial scale of established meteorological networks is often inadequate to represent smaller-scale controls (e.g., terrain or proximity to large bodies of water) or summer convective storms (Doesken & Weaver, 2000). The sparse distribution of established monitoring networks (e.g., Environment and Climate Change Canada [ECCC] or Conservation Authority) therefore does not fully characterize precipitation events. The position of monitoring stations relative to the location of storm events, particularly smaller convective storms, may under- or over-represent the spatial amount of precipitation accumulation. For example, Doesken and Weaver (2000) document a storm event that brought as much as 267 mm of precipitation to parts of Fort Collins, Colorado, yet 6.5 km away, only ~ 50 mm were reported. The detailed review of this storm was made possible by residents who were maintaining reliable and well-sited rain gauges.

Meteorologically-focused citizen science or community-based monitoring (CBM) can be used to complement established gauged networks to infill data gaps with volunteers reporting actual observed conditions such as precipitation type which may

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not be discernable through instrumental observations alone (Chen, et al., 2016). Advances in the internet and geographic information system (GIS)-enabled web applications allow large volumes of location-based data to be submitted electronically to databases through simple online data-entry (Dickinson, et al., 2012). Participation in citizen science programs also empowers individuals with respect to resource management so that management decisions and the data that drive them are more likely to be in the hands of those who will be most affected by the outcomes (Dickinson, et al., 2012).

The Nottawasaga Valley Conservation Authority (NVCA) manages a network of 14 rain gauges, 12 of which are within the watershed to cover 3300 km^2 (with the additional sites located within the area monitored primarily by the Severn Sound Environmental Association; see Figure 1), for an average spatial coverage of 263 km^2 per station, which far exceeds the recommendations of Hubbard (1994). There are spatial gaps in this network, particularly in the north and west, indicating that the network may not be sufficiently capturing precipitation data to monitor the state of the watershed. CBM programs can engage residents while also strengthening the spatial resolution of precipitation data within the watershed. Focusing on meteorological data collection, the objectives of this review are to:

1) Evaluate CBM benefits and challenges,
2) Complete an overview of existing CBM programs presently active in Ontario, and
3) Review the current spatial availability of established networks and CBM data within the NVCA watershed in support of the Ontario Low Water Response (OLWR) and flood forecasting programs.

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2. CBM Benefits and Challenges

Monitoring weather data through citizen science initiatives dates back to at least the mid-1800s with the Smithsonian weather observing network (Doesken & Reges, 2010). Networks such as the Cooperative Network (in the USA), have become more organized with thousands of volunteers reporting daily maximum and minimum temperature and precipitation data (Doesken & Reges, 2010). Community-based monitoring is defined as a process where concerned citizens, government agencies, industry, academia, community groups and local institutions collaborate to monitor, track, and respond to issues of common community concern (Fleener, et al., 2004). It provides the means to work together to gather and deliver information and to adapt to change, not as isolated communities, but as a network that learns from each other and shares resources. It can also provide decision makers with early warnings of environmental issues. Benefits of CBM include:

- Allowing communities to increase knowledge about their environment by generating locally relevant monitoring information. CBM brings to monitoring a unique understanding of the local situation and the needs of individual communities.
- Using standardized monitoring methods will allow for the comparison and integration of information within landscapes and among communities.
- Giving local decision makers the information and tools they need to make informed policy choices and management plans which are adaptive and responsive.
- Contributing toward building "social capital" in participating communities. Increased social capital improves the community capacity to deal with the many complex issues and choices associated with sustainability (Ecological Monitoring and Assessment Network Coordinating Office & Canadian Nature Federation, 2003).

Further, studies have shown that the experience of collecting data for use by professional scientists is highly motivating, fosters scientific knowledge, and provides opportunities for interacting with members of like-minded communities within local environments (Dickinson, et al., 2012). Citizens can be highly motivated to participate when research is closely aligned with their needs and interests (Hecker, et al., 2018).

However, challenges with CBM are recognized and consist of:

Ensuring Credible Data - the legitimacy of CBM data is dependent on the quality of the information produced so it is important that data is collected and analyzed in ways that can be trusted and that respect and benefit the communities involved. Since the public contributes data collected for citizen science programs rather than professionals, data reliability can be of concern (Kanu, et al., 2016).

Engaging and Motivating Citizens - an effective CBM program depends on the active engagement of motivated citizen volunteers. Catalyzing and maintaining this level of engagement is no easy task and there are many challenges to overcome in the process of recruiting, engaging and training citizens properly, as well as ensuring program succession to support long term data requirements (Kanu, et al., 2016).

Informing Decision Makers - the connection between CBM and decision making continues to present challenges. CBM programs that seek to inform decision making must be designed to ensure that data is produced and translated in a way that can address key threats and support the needs and questions of decision makers at different scales, including within the community (Kanu, et al., 2016).

Data Accessibility and Aggregation - much data that is collected continues to be inaccessible or stored in formats that make it difficult to use. If data is not made available and accessible in a usable format, its usefulness for informing decisions and even local actions will be limited. Making decisions on a broader scale, such as an entire watershed or region, requires multiple sources of information to be aggregated and translated to have a complete picture of the health of a watershed or region (Kanu, et al., 2016).

Site Location and Maintenance - one of the greatest challenges to data reliability at CBM stations is the installation of the station itself. Poor siting, exposure, ventilation, calibration, and maintenance are key factors that lead to measurement error (Bell, et al., 2013). CBM stations are often more densely situated in population centres; these sites may be situated in closer proximity to obstacles (e.g., trees and structures) that can impact readings. Temporal data gaps can have a significant impact on analysis results of precipitation data since it is summed over intervals of time (e.g., daily, monthly, and annual).

3. Existing Community-Based Monitoring Programs

The primary weather-based citizen science programs established in Ontario are the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) and the Weather Underground. Participants in both programs collect data using established standardized methods with data uploaded to the existing databases where it can be viewed quickly and easily. Both programs provide high quality precipitation data to observers, decision makers, and other end-users on a timely basis; act as an umbrella for one-stop precipitation information nationwide; increase community awareness about weather by inspiring citizens to participate; and provide enrichment activities to educators and the community. Data from both networks are publicly available and used by the wider scientific community for enhanced forecasting abilities through higher resolution networks (Bell, et al., 2013; The Weather Company, 2019).

CoCoRaHS:

CoCoRaHS (https://www.cocorahs.org/Canada.aspx) was established in 1998 in Colorado, after the aforementioned Fort Collins storm (Doesken & Weaver, 2000), with eventually all 50 States and the District of Columbia, Puerto Rico, U.S. Virgin Islands, The Bahamas, and Canada joining the network (Colorado Climate Center, 2018). The goals of CoCoRaHS include:

1) Providing accurate high-quality precipitation data for the many end users on a timely basis;

2) Increasing the density of precipitation data available by encouraging volunteer weather observing;
3) Encouraging citizens to have fun participating in meteorological science and heightening their awareness about weather; and
4) Providing enrichment activities in water and weather resources for teachers, educators and the community at large to name a few.

Sponsored principally by the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF), CoCoRaHS measures and maps precipitation (rain, hail and snow). There are currently 23,872 active stations participating in this network (Colorado Climate Center, 2018).

This **manual** network requires all participants to be trained, use the same standardized low cost measurement tools, and upload daily observations (around 07:00 standard time preferred) to an interactive website where data is available in map and tabular form within minutes (Colorado Climate Center, 2018). Training materials are provided on the CoCoRaHS website and supplemented with videos available on YouTube. Conservation Authority staff should also be familiar with the content to assist with participant questions. The official CoCoRaHS rain and snow gauge is inexpensive ($30 for registered participants) and simple to use with a mobile app to upload data. This would only require several minutes daily and can be flexible and report multi-day totals when daily records cannot be reported. Though snow and hail can be monitored through this network, they are not mandatory.

Weather Underground:

The Weather Underground program (https://www.wunderground.com/) is a network of **automated** personal weather stations. This network, managed by the Weather Company and the Weather Channel, was initiated in 1993. It has now more than 250,000 weather stations worldwide collecting a variety of measurements including rainfall, air temperature, atmospheric pressure, and wind speed, reporting this data in real-time (The Weather Company, 2019). These stations typically involve an outdoor sensor suite with an indoor electronic console that stores data and uploads automatically to the online database (Bell, et al., 2013). This data is then incorporated into Weather Underground's localized forecasting system with higher spatial resolution and more frequent updating than those created by other weather models that do not incorporate personal weather stations (The Weather Company, 2019).

The Weather Underground network collects data using automated personal weather stations which cost roughly $300 and up, and requires the participant to supply the station with power and broadband internet. The base station would use approximately 2.5 W and the outdoor sensors require two to four AA lithium batteries which can last for more than 3 years. These stations require annual maintenance (cleaning) and can be expected to function for multiple years.

4. Application of Meteorological CBM at the NVCA

Current NVCA weather monitoring network:

The NVCA currently has a monitoring network of 12 precipitation gauges within the watershed, some of which are paired with Water Survey of Canada and NVCA stream gauges (Figure 1). There are considerable spatial gaps in Mulmur, Melancthon, Grey Highlands, Clearview and Springwater Townships, located particularly in the headwaters of the Pine and Mad Rivers above the Niagara Escarpment and in the Lower Nottawasaga River subwatershed. CBM is presently not integrated into the NVCA weather monitoring network.

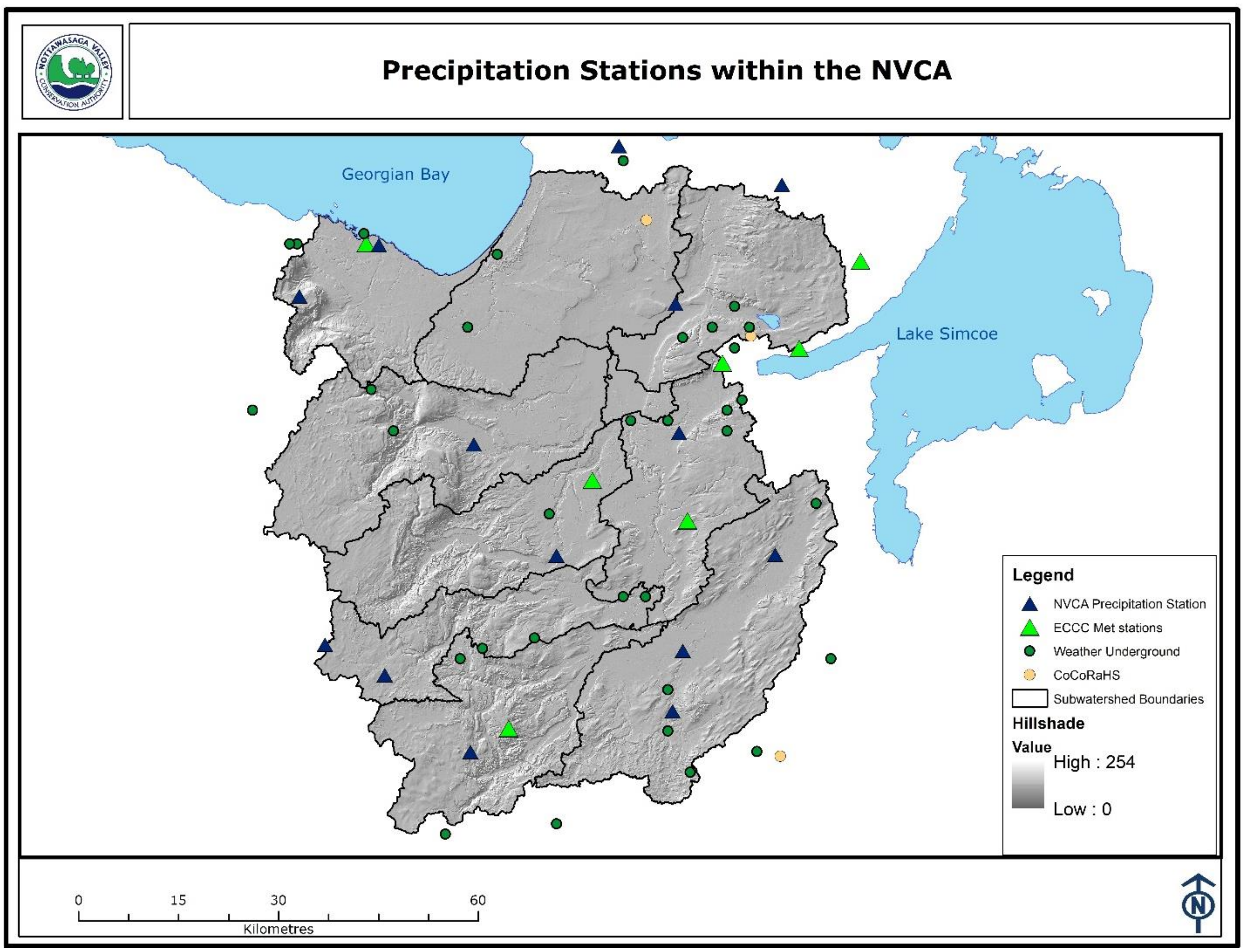

Figure 1: Map of the existing NVCA precipitation stations, ECCC meteorological stations, personal weather stations in the Weather Underground network, and manual rain gauges in the CoCoRaHS network.

The data from the NVCA-operated network primarily informs flood forecasting and low water response programs and is used to compare present conditions to past events. This data is automatically transmitted, or manually retrieved if transmissions fail, to the SQL server, where this raw data is available online and can also be downloaded through a login which anyone can obtain. Though there is a list of created logins, details of user activity are not tracked, and it is unknown how many of these users remain active. The overall community interest from viewing data (login not required) is also unknown, though this web page has not been widely advertised. There are occasional temporal data gaps from this network and there have not been any quality assurance nor did quality control measures apply to these precipitation data sets.

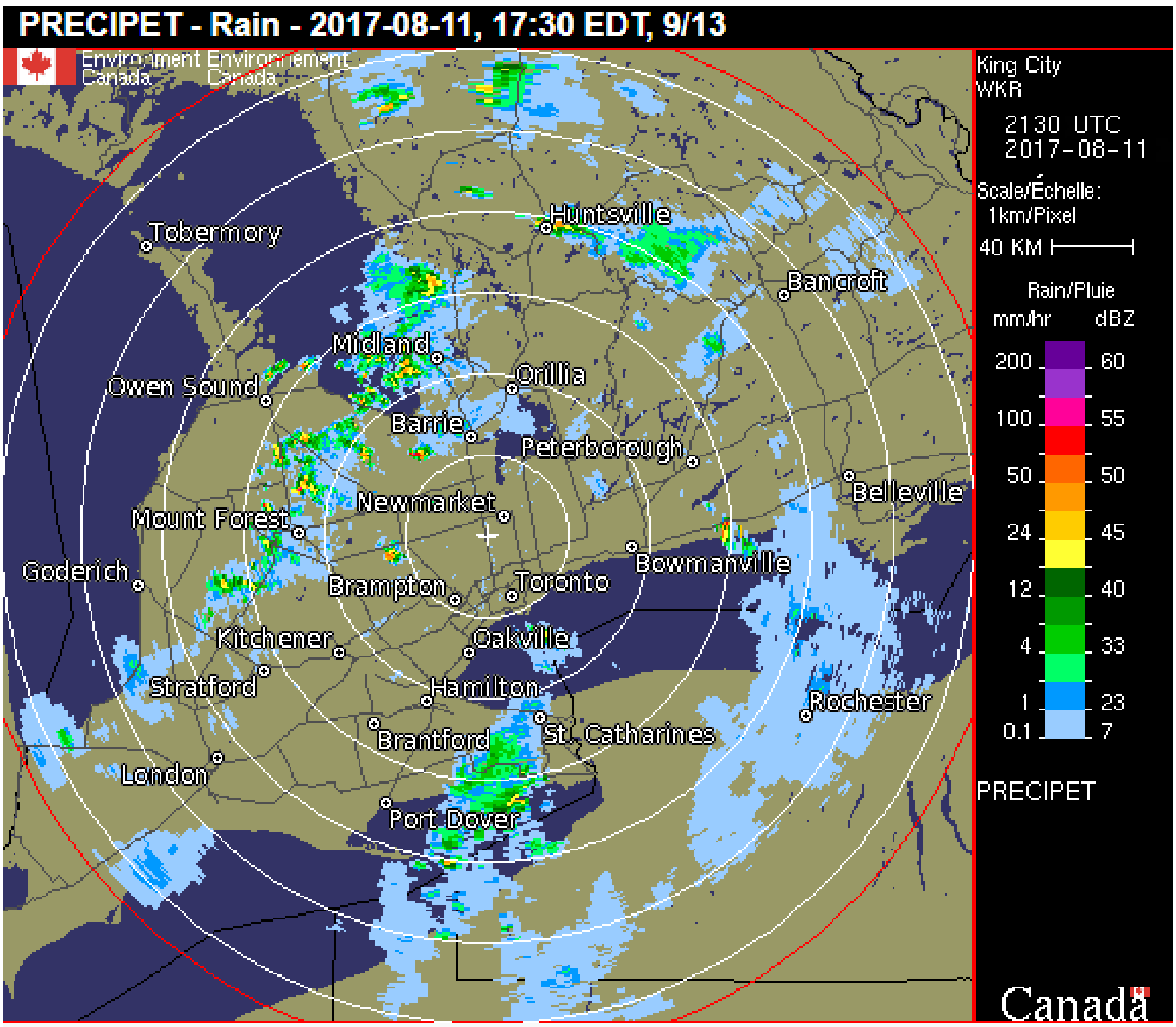

Figure 2: Radar map from August 11, 2017, highlighting small storm events with intense rainfall west of Barrie and Orangeville (ECCC, 2018).

The distribution of the NVCA precipitation monitoring network is quite coarse, with a spatially averaged coverage of 263 km^2 per gauge. Summer precipitation events are important impacting Low Water status, but these events are often highly localized, as illustrated by the historical radar image in Figure 2, with isolated high intensity pockets west of Barrie and northwest of Brampton. The NVCA network alone is insufficient to adequately characterize local-scale precipitation events.

Though not currently being used by the NVCA, there are three other established networks of rain gauges operating in the area. There are 4 meteorological stations operated by Environment and Climate Change Canada, 2 CoCoRaHS sites, and 26 Weather Underground stations (though one is currently not reporting) located within the watershed. The spatial distribution of these networks is illustrated in Figure 1 and detailed in Appendix A. When these networks are combined, there remain considerable spatial gaps in the headwaters of the Mad and Pine Rivers subwatersheds above the Niagara Escarpment and in the lower reaches of the Mad River and Lower Nottawasaga River Subwatersheds. However there is an improvement on the overall network density. Table 1 outlines the number of stations and their average spatial coverage per station, however, these sites are not evenly distributed across the watershed (e.g., there are 3 Weather Underground stations – appearing as one icon in Figure 1, an ECCC station, and NVCA station in the Collingwood area). The bottom row of Table 1 accounts for clusters of gauges (frequently found in more urbanized areas such as Collingwood, Alliston, and Barrie) and counts them once to provide a better estimate of the spatial coverage of the existing networks.

Table 1: Existing rain gauge coverage within the NVCA watershed.

Network	Number of Stations	Mean Spatial Coverage (km^2) per Station	Equivalent Mean Distance Between Stations (km)
NVCA	12	263	16
ECCC	4	788	28
CoCoRaHS	2	1, 575	40
Weather Underground	26	121	11
NVCA & ECCC	16	197	14
All networks combined	44	72	8
Gauge clusters (all)	27	117	11

Conservation Authorities' use of metrological CBM:

Conservation Authorities that appeared to have stations within the CoCoRaHS network (either through the CoCoRaHS station listing or a web search of reference to CoCoRaHS on Conservation Authority websites) were contacted for further information about their use of the program. The Grey Sauble Conservation Authority (GSCA) incorporates data from both CoCoRaHS and Weather Underground into their monitoring programs (J. Bittorf, personal communication). Kettle Creek Conservation Authority also uses data from both networks to supplement their monitoring network, with several CoCoRaHS stations operated by the KCCA, however, there has not been any external interest from the public to add CoCoRaHS stations (J. Dow, personal communication). Mississippi Valley Conservation Authority occasionally uses data from CoCoRaHS to validate the automated gauge network, but it is not incorporated into their official programs (C. McGuire, personal communication).

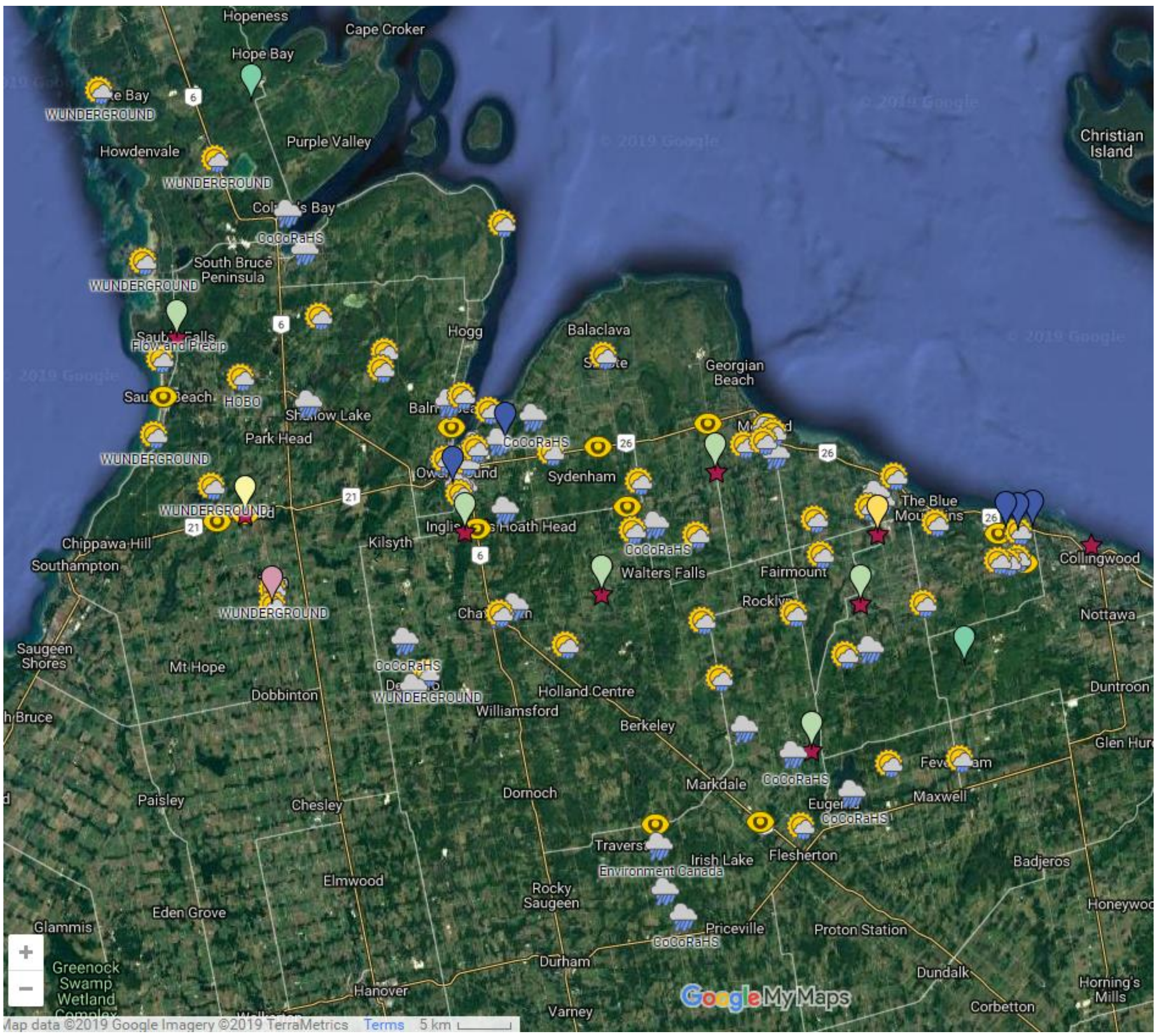

Figure 3: Stream flow, precipitation and weather gauges, and weather cameras used by the GSCA (2019). Weather icons denote network type (rainy icon is either CoCoRaHS or ECCC; partial sun icon is Weather Underground, WeatherLink, or HOBO stations). Yellow eye icons denote weather cameras. Red star icons denote Water Survey of Canada flow gauges and the coloured map pins summarize the type of data available from flow gauges.

The GSCA has a well-established integrated network of professional and CBM stations. There is a series of three maps available on their Current Watershed Conditions webpage (http://www.greysauble.on.ca/water-management/current-watershed-conditions/; GSCA, 2019). These include streamflow, precipitation and weather stations and weather web cameras (e.g., Figure 3), summary monthly precipitation, and snow data, collected through snow surveys and modelled by NOAA for CoCoRaHS sites. Links to the raw data (i.e., to each respective station's network website) are easily accessible through these maps. Data from these stations can be automatically uploaded to their database and links to near-real time graphs for some parameters (i.e., streamflow) that are stored on Google Drive.

Proposed NVCA CBM model for consideration:

Low cost opportunities exist to enhance the current NVCA meteorological monitoring network in order to reduce the spatial gaps in the monitoring sites. It is envisioned that the meteorological network would integrate existing Weather Underground and CoCoRaHS sites into the internal information management platform to enhance data used for forecasting delivery. This includes both Low Water Response and the Flood Forecasting programs. A hierarchical approach will be used for QAQC purposes with the Environment Canada-NVCA gauges forming the keystone monitoring sites. This would be complimented by the Weather Underground automated stations and lastly supported by the manual measurements provided through the CoCoRaHS platform. There are only 2 current participants of the CoCoRaHS network located within the NVCA watershed, whereas there are already 26 stations participating in the Weather Underground network. Additional infill locations are encouraged, particularly in more rural sites, to further enhance the network density and distribution.

Limitations with CoCoRaHS network includes relying on participants to contribute data daily (even 0 mm must be reported) and the timing of the once-daily measurement (morning), making it subject to post-event evaporation and not temporally compatible with other datasets which provide daily total precipitation to midnight.

The Weather Underground network requires investing in a network of automated personal weather stations, but will result in less human measurement error and greater data reliability, provided they are installed following best practices guidelines. Event characteristics such as rainfall frequency, duration, and intensity determine rainfall effectiveness, which are not captured through the manual CoCoRaHS measurements, directly inform local drought and low water conditions (Wilhite, 2000). Datasets from the automated personal weather stations would also be more comparable with those of other established meteorological monitoring networks reporting hourly and daily total precipitation (e.g., Environment and Climate Change Canada). As this data is available in near real-time, the Weather Underground network can also supplement the established networks to inform flood forecasting programs.

If pursued, the NVCA would need to champion this endeavor and solicit new and additional participants to the two platforms. Also, participants need to be distributed across the watershed. To attain Hubbard's (1994) recommended rain gauge every 5 km (coverage of 25 km^2), 126 station locations would be required, distributed evenly across the watershed. More realistically, a network of 50 stations would be distributed across the watershed. This equates a rain gauge every ~8 km with coverage of 63 km^2. This would require an additional 23 monitoring locations strategically located to infill spatial gaps. In support of this, the NVCA could aid in the identification of potential suitors however once established let the respective programs manage these sites and the NVCA scrapping the data for internal uses.

One sector that could assist in the infilling of the spatial monitoring gaps is the agricultural community. A participant benefit is the access to real-time, and locally-accurate data that can inform optimal irrigation decision making. Additionally, members of the agricultural community may already have manual or automated precipitation monitoring systems in place that could be connected to either of these broader networks. An open source google earth map/platform that spatially integrates the three platforms would beneficially be for participant buy in. This is in line with Tredick et al. (2017) who proposed a system to evaluate citizen science programs, covering elements of: stakeholder collaboration and program resources; goals and objectives; design and implementation of monitoring methods; data entry, storage, analysis and synthesis; reporting and dissemination; and outcome assessment and program review.

Internally, staff need to be able to easily integrate, manage, analyze, and interpret the incoming data. For the data to be included as a low water indicator, complete temporal records at the monthly scale are required. Pairing a manual rain gauge with an automated station (whether at the same site or in close proximity at neighbouring properties) would provide quality assurance and quality control to ensure the real-time data is representative, and fill gaps in the event an automated station malfunctions. Lessons learned from the Grey Sauble Conservation Authority could be used if the NVCA decides to implement this endeavor.

5. Conclusion

In order to enhance the understanding of state of the watershed, as relevant to OLWR and engage members of the agricultural community whose livelihoods depend on water resources, a network of CBM precipitation stations should be developed. These stations can infill spatial data gaps, informing low water advisories and aiding the agricultural community in making water management optimization decisions.

Ideally, this endeavor would aim to incorporate automated stations into the Weather Underground network paired with manual rain gauges of CoCoRaHS for greater data reliability and value for interpretation and analysis. The envisioned next steps are to incorporate the existing ECCC, Weather Underground, and CoCoRaHS datasets into the NVCA Monitoring site. There may additionally be data available from sources such as Municipal offices with rain gauges. All sites should then have data quality evaluated for reliability, as complete datasets are required for flood forecasting and Low Water Response. A spatial analysis of precipitation patterns can then be conducted to target areas that are high priority for a new rain gauge installation. Further, an internal data management system is encouraged to be explored to which the QA/QC'd data from the various platforms can be housed, analyzed, and integrated via a public facing, web-based platform.

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Appendix A – Rain Gauge Network Association and Start Date

Gauge name	Network	Location	Data Start Date
Bailey Creek at 10th Side Road New Tec	NVCA	Beeton	2007
Beeton Creek Near Tottenham	NVCA	Tottenham	2005
Innisfil Creek at 5 SD Inni	NVCA	Innisfil	2007
Mad River Below Avening	NVCA	Avening	2000
Melancthon Municipal Office	NVCA	Melancthon	2006
NVCA Admin Office	NVCA	East of Utopia	2006
Petun C.A.	NVCA	West of Nottawa	2007
Pine River Near Everett	NVCA	Everett	2007
Pretty River Near Collingwood	NVCA	Collingwood	2006
Shelburne WTP	NVCA	Shelburne	2015
Town of Mono Administration	NVCA	Mono	2007
Willow Creek Near Minesing	NVCA	East of Minesing	2006
Borden AWOS[2]	ECCC	Angus	2000
Collingwood[3]	ECCC	Collingwood	1994
Egbert CS[4]	ECCC	Egbert	2000
Mono Centre	ECCC	Mono	2013
CAN-ON-130	CoCoRaHS	Barrie	2014
CAN-ON-153	CoCoRaHS	Phelpston	2015
IADJALAT3	Weather Underground	Lisle	2017
IBARRIE5	Weather Underground	Barrie	2017
ICLEARVI4	Weather Underground	Glen Huron	2018
ICOLLING16	Weather Underground	Collingwood	2018
ICOLLING19	Weather Underground	Collingwood	2018
ICOLLING20	Weather Underground	Collingwood	2018
IESSA5	Weather Underground	Utopia	2018
IESSA7	Weather Underground	Angus	2018
IMONO6[5]	Weather Underground	Violet Hill	
INEWTECU2	Weather Underground	Alliston	2008
INEWTECU3	Weather Underground	Alliston	2017

[2] Former stations in the immediate vicinity have data for 1926-1945 (Camp Borden A); 1960-1966 (Camp Borden); 1966-1970 (Borden A); 1985-1992 (Borden STP); and 1996-2013 (Borden).
[3] Former stations in the immediate vicinity have data from 1869-1974 (Collingwood) and 1973-1997 (Collingwood WPCP)
[4] A former station has data for 1988-2007 (Egbert Care)
[5] Currently not reporting data

Gauge name	Network	Location	Data Start Date
INNISFI9	Weather Underground	Churchill	2019
IONALLIS2	Weather Underground	Alliston	2012
IONMIDHU2	Weather Underground	Snow Valley	2011
IONTARIO177	Weather Underground	Stayner	2006
IONTARIO220	Weather Underground	Violet Hill	2007
IONTARIO492	Weather Underground	Tottenham	2012
IONTARIO598	Weather Underground	Barrie	2013
IONTARIO631	Weather Underground	Beeton	2015
IONTARIO1146	Weather Underground	Midhurst	2016
IONTARIO1150	Weather Underground	Barrie	2016
IONTARIO1155	Weather Underground	Rosemont	2016
IONTARIO1181	Weather Underground	North of Barrie	2016
IONTARIO1316	Weather Underground	Devil's Glen	2016
IONTARIO1320	Weather Underground	Tottenham Airfield	2016
IWASAGAB2	Weather Underground	Wasaga Beach	2016