Groundwater

Issue Paper/

Community-Based Groundwater Monitoring Network Using a Citizen-Science Approach

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Abstract

Water level monitoring provides essential information about the condition of aquifers and their responses to water extraction, land-use change, and climatic variability. It is important to have a spatially distributed, long-term monitoring well network for sustainable groundwater resource management. Community-based monitoring involving citizen scientists provides an approach to complement existing government-run monitoring programs. This article demonstrates the feasibility of establishing a large-scale water level monitoring network of private water supply wells using an example from Rocky View County (3900 km^2) in Alberta, Canada. In this network, community volunteers measure the water level in their wells, and enter these data through a web-based data portal, which allows the public to view and download these data. The close collaboration among the university researchers, county staff members, and community volunteers enabled the successful implementation and operation of the network for a 5-year pilot period, which generated valuable data sets. The monitoring program was accompanied by education and outreach programs, in which the educational materials on groundwater were developed in collaboration with science teachers from local schools. The methodology used in this study can be easily adopted by other municipalities and watershed stewardship groups interested in groundwater monitoring. As governments are starting to rely increasingly on local municipalities and conservation authorities for watershed management and planning, community-based groundwater monitoring provides an effective and affordable tool for sustainable water resources management.

Introduction

Water level in aquifers fluctuates in response to the water balance (Bredehoeft 2002; Devlin and Sophocleous 2005). Seasonal and interannual variability of water level provides useful information regarding groundwater recharge and discharge processes, and long-term trends in water level may indicate the effects of water extraction (e.g., Sophocleous 2000), land-use change (e.g., Scanlon et al. 2005), and climatic variability (e.g., Chen et al. 2004). Therefore, the long-term monitoring of aquifer water level is essential for the sustainable management and development of groundwater. Owing to geological heterogeneity, individual sections or units of an aquifer system may respond differently to external factors, requiring a distributed network of monitoring wells within an area of interest, for example, a watershed or municipal district. This is in contrast to the monitoring of surface water quantity, whereby an integrated response of surface water system can be monitored by a relatively small number of stream gauging stations. For this reason, the information on groundwater status is relatively scarce compared with the information on surface water.

For example, in the southern portion (<54°N) of the Province of Alberta (2.6×10^5 km^2) in Canada, surface water flow in all watersheds is monitored by 259 gauging stations operated by the Water Survey of Canada (WSC) and Alberta Environment and Sustainable Resources

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Development (AESRD) (Environment Canada 2014). The same area has 154 groundwater observation wells operated by AESRD (2014), but most of which have been installed for specific purposes (e.g., groundwater monitoring near dams, industrial sites, or municipal water supply wells) and not strategically placed for regional-scale monitoring. A substantially larger number of observation wells are required for spatially distributed monitoring of aquifer water levels, but the capacity of the government to install and operate new observation wells is limited by financial and human resources. At the same time, the government has facilitated the creation of nongovernmental Watershed Planning and Advisory Councils (WPACs) for all major watersheds in the province, whose responsibility is *to assess the conditions of their watershed and develop plans and activities to address watershed issues* (Alberta WPAC 2014). However, WPACs generally lack the network of wells to monitor groundwater conditions at a sufficient spatial and temporal resolution.

Similar situations regarding the lack of or inadequate coverage of government-run environmental monitoring (e.g., Savan et al. 2003) has prompted the use of community-based monitoring involving citizen scientists as an effective approach to provide complementary function to government-run monitoring programs (Whitelaw et al. 2003; Conrad and Daoust 2008). Citizen science is a form of research that engages the public in gathering scientific information or data (Bhattacharjee 2005). The use of citizen science provides a cost-effective method for collecting large amounts of data over a geographic area or over long time spans (Bonney et al. 2009). It also offers extra benefits of having community volunteers contribute the local information and insights that are typically missed by external researchers, as well as opportunities to educate participants through their engagement in data collection (e.g., Thornton and Leahy 2012). Recent development of communication technology has provided effective tools for direct and rapid data upload and viewing on web-based database (e.g., Lowry and Fienen 2012).

Many of the existing community-based water monitoring programs are focused on the observation of surface water quality using the measurement of chemical parameters and biological indicators (e.g., Savan et al. 2003; Conrad and Hilchey 2011). The application of community-based approaches to groundwater monitoring appears to be rare in the peer-reviewed literature and focused on water sampling and chemical analysis (e.g., Thornton and Leahy 2012), however, some community groups are starting to monitor groundwater levels (e.g., Ecology Action Centre 2014). Regular or semiregular monitoring over a long time can provide the baseline information on the natural variability of aquifer water levels in response to meteorological fluctuations (e.g., wet-dry cycles), which is critically needed for the detection of changes in aquifer conditions caused by increased water extraction, land-use changes, and other human-induced stresses.

The objective of this article is to describe the implementation of a community-based program for monitoring groundwater levels, point out the challenges and mitigation measures, and demonstrate the usefulness of the collected data using an example of Rocky View County in Alberta (see Study area for location). In this program, the unique collaboration among university researchers, county staff members, and community volunteers have enabled the implementation of a high-density monitoring network over a relatively large area using private water supply wells. The monitoring network is accompanied by a web-based data portal and an educational website for school teachers and the general public with the detailed information on how to build a similar network. It is hoped that the information presented in this article will enable other communities and watershed stewardship groups to start groundwater monitoring programs.

Study Area and Goals

Rocky View County is located in southern Alberta, surrounding the City of Calgary as well as a number of small urban centers (Figure 1). The region is characterized by a cold and semi-arid climate, typical of the Canadian prairies (Hayashi and Farrow 2014). The primary land use in the county is agriculture with a mixture of croplands (wheat, barley, and oil seeds) and grass pasture for cattle grazing. Much of the county, except along river channels, is covered by a few to 20 m thick glacial till (Barker et al. 2011), which is underlain by the Paleocene Paskapoo Formation, described as mudstone- and siltstone-dominated fluvial system with a series of sand channels that can form isolated aquifer units (Hamblin 2004; Burns et al. 2010). Much of the county relies on groundwater pumped from the Paskapoo Formation and other aquifers for domestic and livestock water supplies. Recent increase in water demands from residential developments and industrial use have the potential to affect groundwater resources in the region (Barker et al. 2011), meaning that the long-term monitoring of groundwater is critical for sustainable water resource management. However, when a pilot study for this project started in 2005, there was only one observation well operated by AESRD in the 3900 km^2 county.

The concept of community-based monitoring came about after a graduate student used a network of domestic water wells to monitor groundwater levels within the small (250 km^2) watershed of West Nose Creek located within Rocky View County (Figure 1). Local volunteers provided access to their private wells for the student to measure water level at a biweekly to monthly interval, which produced a valuable data set for understanding groundwater dynamics in the watershed (Grieef and Hayashi 2007). The support from the county staff, who served as the liaison between university researchers and community members was essential for the success of the West Nose Creek study. Encouraged by the successful implementation of the small-scale monitoring network, the county became interested in expanding the network to the entire county.

As it was not feasible for a single individual to monitor water levels in all participating wells in the large area, a decision was made to recruit and train community

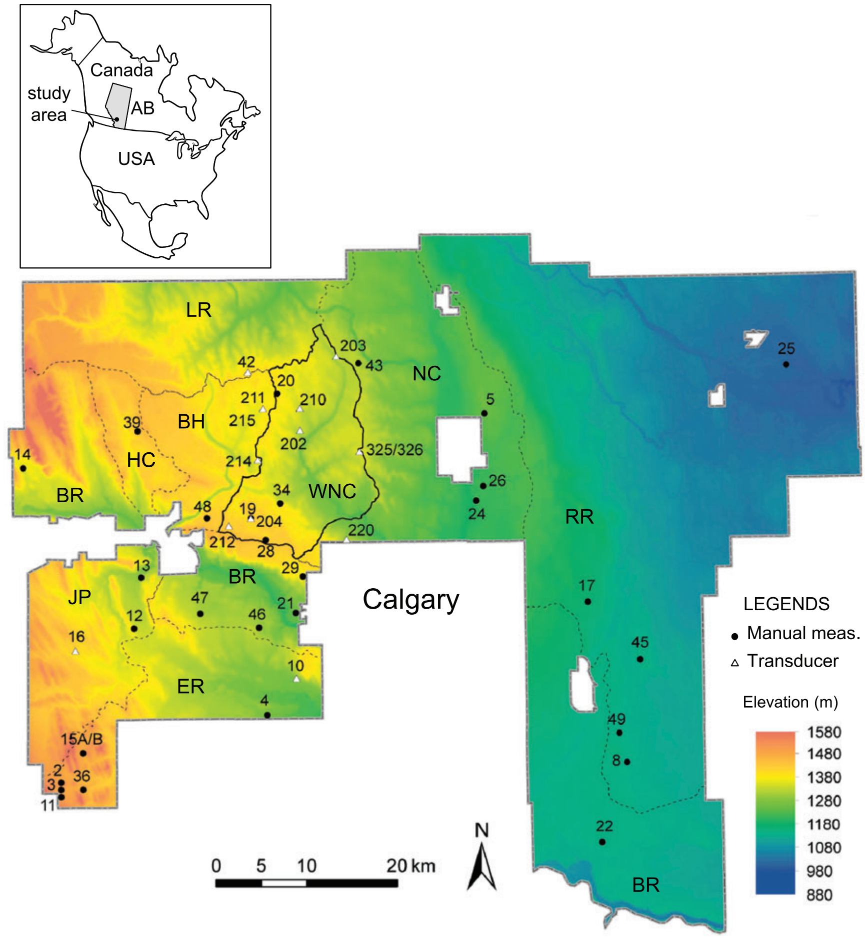

Figure 1. Elevation map of Rocky View County showing the location of active monitoring wells at the end of 2011, measured manually or using pressure transducers. Dashed lines indicate watershed boundaries, and the solid line indicates the West Nose Creek watershed. The insert shows the location of Alberta (AB) and the study area in North America. Nine watersheds in the county are: Bow River (BR), Rosebud River (RR), Nose Creek (NC), West Nose Creek (WNC), Little Red Deer River (LR), Big Hill Creek (BH), Horse Creek (HC), Jumping Pound Creek (JP), and Elbow River (ER).

volunteers as citizen scientists. A government grant was used to purchase water level sounders, and the countywide project started in the summer of 2007. The long-term goal of this project was to establish a network of private wells to monitor water levels to assist with long-term planning and future policy development concerning groundwater resource allocation. The specific target was to have 50 monitoring wells distributed over the county with at least one well in each of the nine watersheds within the county. It was intended as an experiment to develop a cost-effective new approach to studying groundwater resources in Alberta using a university-municipality partnership involving community members.

Methodology

Recruitment of Volunteers and Selection of Wells

The citizen-science approach involves recruiting local residents who can commit their time to measuring the water level in their wells for more than a few years. Therefore, recruitment and retention of volunteers is the key element of a successful community-based monitoring program. As academic researchers typically have little direct connection with community members, it is essential to have a strong partnership with a locally based organization. In this study, volunteers were recruited by Rocky View County through an advertisement in the weekly newspaper distributed to county residents.

After an initial contact, volunteers were asked to submit information regarding the condition of their wells in order to screen them for their suitability using the following criteria developed in the West Nose Creek pilot study: (1) the well screen is less than 7 m in length, (2) the well has the driller's report on lithology, (3) the well has a fast response so that the water level recovers quickly after pumping, and (4) the well is easily and safely accessible. In addition, efforts were made to select at least one well from each of the nine watersheds in the county, which resulted in 39 new wells distributed over a large area (Figure 1).

Initial Site Visit and Information Gathering

After wells were selected, the program coordinator from the county visited the volunteer well owners to explain the objective of the monitoring program and train them on site for the standard protocol for water level measurement using a sterilized probe (Wilde 2004). The coordinator also collected site-specific information including well specification (depth, age, casing diameter, etc.), design of water distribution system, water use frequency and purpose, the number of water users (both people and animals), well history, and land use around the well. This information is important for understanding the characteristics of water level fluctuations. Volunteers were asked to fill out an information sheet and sign a consent form allowing the county to disseminate data without disclosing the identity of well owners. The consent form was required by the University of Calgary as part of the standard protocol for conducting studies using human subjects. Examples of the information sheet and consent form are in Supporting Information accompanying this article, and also available from Groundwater Connections website (http://groundwaterconnections.weebly.com), which was developed in conjunction with this study.

Each volunteer was given a monitoring kit consisting of a water level sounder, spray bottles for bleach solution and clean water for sterilizing a probe, and latex gloves. A manual sounder consisting of a graduated tape and an electric-contact probe (Water Tape, Heron Instruments, Ontario, Canada) was chosen because of its relatively low cost compared with acoustic sounders or pressure transducer systems. Among several similar models available on the market, this particular sounder was chosen due to a slightly lower cost compared with others. The total cost of a kit was 700 Canadian Dollars, and the kits are still in a good working condition after 7 years of use by the volunteers. To minimize the influence of pumping, volunteers took readings when the pump was turned off, as easily detected by the sound, and took three water level readings over a period of several minutes to ensure that the readings were stable.

Even though the primary objective of the program was water level monitoring, it was important to ensure that water level measurements did not cause an accidental contamination of the wells. Therefore, a water sample was collected from each well for chemical and bacteriological analysis before the first measurement of water level. This also gave an opportunity to inform the volunteers about the water quality.

Data Entry, Quality Control, and Dissemination

During the first 4 years of the program volunteers reported water level data to the county by telephone, fax, or e-mail, which were forwarded to the university project coordinator for quality control before being added to the database. The quality control consisted of comparing the current data point with the previous data series to check for any inconsistency resulting from reading errors (e.g., reading 12.51 m, where the actual value should be 11.51 m) or transcription errors. If an inconsistent data point was found, the volunteer was contacted to resolve the error.

To improve the efficiency of data entry and dissemination, a web-based data portal called Rocky View Well Watch (http://rockyview.geocens.ca/) was implemented in January 2012 to allow the volunteers to upload their data, the project coordinator to perform quality control, and the public to view the data. Rocky View Well Watch uses the GeoCENS technology developed by the University of Calgary researchers, which facilitated a close collaboration between the hydrogeologists and the software engineers involved in the project. GeoCENS is unique in that it is compliant to the international standards of Open Geospatial Consortium's (OGC) Sensor Web Enablement (see Supporting Information for details). This is in contrast to most of the existing web-based environmental data portals that use proprietary technologies and encode their environmental observations in ad hoc data models and formats. As such GeoCENS has the advantages of extensibility, interoperability, scalability, and longer life cycle. For example, being open standard-compatible has the advantage of easily accommodating new monitoring networks in any parts of the world (extensibility and scalability) and allowing multiple community-based monitoring systems to be integrated into a coherent system of systems (interoperability). In addition to the newly recruited volunteer wells, some wells from the West Nose Creek study were transferred to the new network (Figure 1). These wells have pressure transducers (Levelogger, Solinst, Georgetown, Canada) installed and maintained by the university researchers. The water level data were recorded at a 30-min interval and downloaded approximately every 3 months. After filtering out the data points affected by pumping-induced drawdown, daily average data were subjected to quality control and posted to Rocky View Well Watch site. This step is important, as a simple daily average of all points can be influenced by the drawdown.

Communication and Education

The retention of volunteers is critical for successful community-based monitoring projects (Evans et al. 2005; Cooper et al. 2007; Conrad and Hilchey 2011). To this end, it is important to keep the volunteers interested and engaged in the study's findings and their relevance to local water management. Rocky View Well Watch helps engage the volunteers as they can view their own data and compare them with data collected by other volunteers. In addition, a newsletter was prepared by the project coordinator once or twice a year and distributed to the volunteers to explain data trends and introduce background information. Groundwater Connections website was developed as part of the monitoring program to educate the residents in the county and surrounding regions about the fundamental concepts of sustainable groundwater management, and general and region-specific hydrology.

The same website provides lesson plans and local field trip guides for science teachers in junior and senior high schools, which can be used to supplement freshwater-science modules in their curricula. These materials were developed by four science teachers from local schools working with the university researchers in a series of curriculum design workshops at the University of Calgary over a 4-month period. The website also provides a detailed online manual for designing and implementing a community-based groundwater monitoring network. The manual is intended for community and watershed groups in other regions of Canada and elsewhere, who are interested in setting up a similar groundwater monitoring program.

To receive comments and suggestions from the volunteers, a survey was conducted on the monitoring program in general and the user-friendliness of Rocky View Well Watch website shortly after its implementation. An anonymous survey form was mailed out with the newsletter to each participant. The survey form included questions on the program such as; how the volunteers felt about the value of their contribution to the program and the relevance of the data to local water resource management, what aspects of the program they liked and disliked, if the water level sounder was easy to use, and if the website needed changes and improvements. The complete survey form is in Supporting Information and also available from Groundwater Connection website. Approximately 40% of the participants returned the survey form.

Results

Recruitment and Retention of Volunteers

Forty-nine volunteers responded to the initial call by the county and 39 wells were selected for monitoring after the screening. In addition, 11 wells were transferred from the West Nose Creek study to meet the target of 50 wells. However, several volunteers stopped data collection (see the Discussions section for possible reasons), which reduced the number of actively monitored wells to 40 by the end of 2011(Figure 1). Figure 2 shows the monitoring frequency computed from the number of measurements taken during 2010 to 2011. The majority of wells were measured at least once every 2 months (frequency greater than 0.5 points/month).

The monitoring program was initially set up for a 5-year period starting in the fall of 2007. At the end of this period, a few volunteers wished to end their data collection, but others were interested in continuing with monitoring. This allowed the county to maintain 38 active wells for long-term monitoring beyond 2013, including the five wells that had been equipped with new pressure transducers (Figure 2). Three of these were a prototype of low-cost transducer (Well Minder, Nyquest Manufacturing, Hatchet Lake, Canada) installed for testing purposes in collaboration with Agriculture and Agri-Food Canada.

Long-Term Variability of Water Levels

The long-term data from network wells revealed valuable information regarding the seasonal pattern and baseline condition of local aquifers. For example, data from Well 20 and 39 (Figure 1 for location) show the

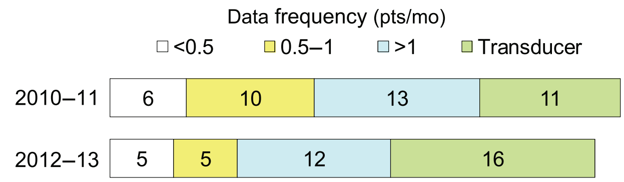

Figure 2. Average frequency of monitoring (points/month) during 2010 to 2011 and 2012 to 2013. The wells with pressure transducers have daily data. The numbers indicate the number of wells within the frequency range.

effects of snowmelt and summer precipitation on water level fluctuations (Figure 3a). These wells are screened in the sandstone units of the Paskapoo Formation at a screen-center depth of 33 m for Well 20 and 43 m for Well 39. Water level fluctuations in bedrock aquifers reflect the water table fluctuations in overburden sediments in the Canadian prairies region including the study area (Anochikwa et al. 2012). Therefore, the magnitude of water level rise in each year indicates the relative magnitude of groundwater recharge in the overburden. Interannual variability in the magnitude of recharge reflects the variability in meteorological factors such as precipitation and evapotranspiration. Figure 3b shows a clear correlation between water level rises to total precipitation in Calgary in the respective hydrological year defined as November to October (Mohammed et al. 2013). Figure 3a also shows a gradual upward trend in water levels, which is caused by a relatively wet condition during the study period as part of the decadal-scale wet-dry cycles (Hayashi and Farrow 2014).

As mentioned in the Introduction, WPACs are mandated by the Alberta government to assess the conditions of watersheds and preparing the "state of the watershed" reports, which should include the information on the natural variability of groundwater quantity. However, such information is not readily available due to the low density of government-run monitoring wells. The long-term data collected by the community-based monitoring network can provide the essential information for quantifying the variability. Figure 4 shows the range of water levels observed in all of the active monitoring wells that had at least 5 years of data and 60 data points. The variability in water level is generally higher in the wells with shallower water level and lower in the wells with deeper water level. There was no particular spatial pattern in the variability. These data are critical for scientific understanding of hydrological processes, which in turn provides the guidance for sustainable groundwater management in the county.

Data Quality Control and Error Analysis

The water level data may be affected by several sources of errors including: (1) transcription or reporting error by observers, (2) accuracy of manual reading using a water level sounder, and (3) "spot measurements" not representing the true water level due to the influence of pumping even though a care was taken to measure

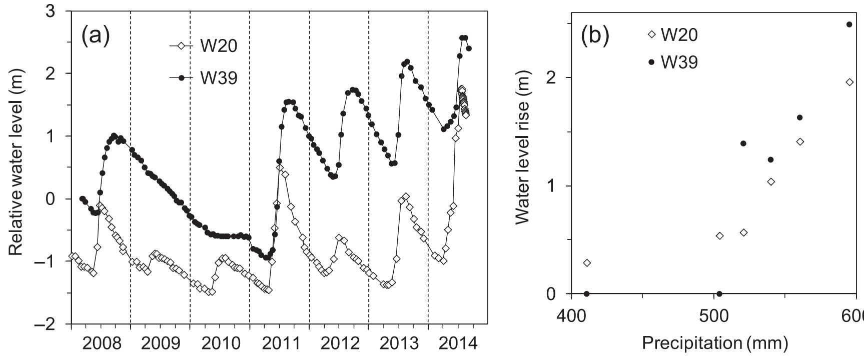

Figure 3. (a) Examples of water level data from Well 20 and Well 39, expressed as relative values with respect to arbitrary references. (b) Relation between the magnitude of water level rise in each year and total precipitation for the corresponding hydrological year (November to October) in Calgary for 2008 to 2013.

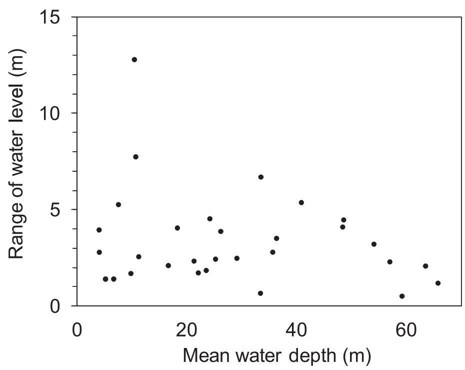

Figure 4. Relation between the mean water level, measured below the top of casing, and the range of water level observed during the monitoring period for those wells that have sufficiently high number (greater than 60) of data points.

the water level when it was stable over a few minute interval. Reporting errors were rare and relatively easy to detect by examining the consistency of the submitted data point with the graph of previous data of the well. The occurrence of reporting error was no more than once for each of the monitoring wells. The accuracy of manual reading was evaluated by comparing the values of three water level readings taken by volunteers for each measurement. The average range of three readings was calculated for 10 wells, for which the volunteers consistently reported three readings for each measurement. The range varied from 2 to 11 mm, indicating that the reading was reasonably accurate.

To evaluate the errors associated with spot measurements, the pressure transducer data were examined in the nine 200-series wells in the West Nose Creek watershed (Fig. 1). The daily average transducer data (see Methodology section for calculation procedure) were compared with the manual measurements taken by university researchers every 3 to 4 months. The mean absolute error between the daily average and manual spot measurement for individual wells ranged between 2 and 6 cm (average of 4.1 cm for nine wells), and the root-mean-squared error ranged between 3 and 11 cm (average of 7.4 cm). These results imply that the spot measurements taken by the volunteers for other wells likely have an uncertainty on the order of 10 cm or less.

Discussions

Challenges, Mitigation, and Suggestions for Improvement

After the initial implementation of the monitoring network, the major challenge was the retention of volunteers. A number of volunteers left the program for a variety of reasons including a loss of interest, moving, or a change in lifestyle. The wells used in this network were located outdoors, often some distance away from the volunteers' house, which made it difficult for the volunteers to take water level readings. This resulted in infrequent data collection (Figure 2) or a large data gap during winter months. To keep the volunteers motivated, project coordinators need to engage them and make them feel that their efforts are being incorporated into the study objectives (Evans et al. 2005; Cooper et al. 2007; Conrad and Hilchey 2011). Responses to the survey of volunteers indicated that they wanted more feedback from the project team about the use of the collected data and their interpretation, and the progress of the project. We reflected this result in our newsletter to report timely information, such as the response of groundwater to a major flood event in June 2013 that affected many citizens in the region. In return, we received valuable hydrological information, for example, a generally wet condition of the farms in the northwestern part of the county, which is consistent with the rising water levels in monitoring wells (Figure 3a).

The close collaboration between the university researchers and the county staff allowed the successful implementation and operation of the monitoring network. However, the wells are unevenly distributed and the eastern part of the county has a low density of wells (Figure 1). In a retrospect, a more even distribution of wells could have been achieved by engaging a key community member in each area, who would recruit volunteers from the local community. This approach would have contributed to a stronger engagement of volunteers and more effective communication between the researchers and volunteers.

Cost and Benefit of Monitoring Network

It is not simple to estimate the cost of the community-based groundwater monitoring network; however, the cost can be divided into the initial set up and long-term operation. For the initial set up, the Rocky View County allocated approximately 200 h of staff time for the recruitment and training of 39 volunteers. The monitoring kit consisting of the water level sounder, spray bottles, and latex gloves was 700 Canadian Dollars, and the instruments are still in a good working condition after 7 years of use by the volunteers. After the initial set up, the program was maintained by the university project coordinator who spent approximately 6 d a month for data quality control and various other tasks that were directly related to the monitoring operation.

The manual measurements by volunteers using the water level sounder was adopted in this program because it was less expensive and deemed more reliable than pressure transducers or acoustic sounders available at the time. The price of self-logging pressure transducers have come down and are now available for less than 1000 Canadian Dollars depending on the specification (e.g., vented vs. nonvented, cable length). Therefore, a groundwater monitoring network using existing water supply wells can be set up for a reasonable cost using automated monitoring systems without involving community volunteers. The initial cost of the automated network would be similar to the current one because the well providers still need to be recruited and screened, and the equipment needs to be installed properly by a trained technician. The operation of the network will also require significant human resource to download and process data at a reasonable frequency (e.g., four times a year). This is necessary for detecting sensor malfunction, correcting data for long-term drift, and observing any changes in the condition of wells. It is estimated that the operation of 40 automated monitoring wells covering an area similar to Rocky View County will require 30 to 40 d per year of technician's time. Therefore, there would be relatively minor cost difference between the community-based and automated monitoring program.

While the automated approach has the benefit of regular and frequent (e.g., daily or hourly) measurements, the community-based approach has many other benefits that can offset the disadvantage of lower data frequency. First, it provides opportunities to engage the community volunteers and encourage them to become interested in the stewardship of local groundwater resources. Second, it allows the local municipality or watershed stewardship group to disseminate information on groundwater to the community. In addition, the volunteers can provide the important information on local hydrological conditions to the municipal staff and researchers.

In the future, water level measurements by volunteers can be made easier by using a permanent sensor installed in the well and connected to a remote readout device in a convenient location (e.g., inside the house), if these devices are reliable and available at a low cost. This will allow volunteers to take water level readings without having to go to the well, remove the well cap, and lower the water level sounder each time. The monitoring network provided a testing opportunity for the development of a new low-cost pressure transducer and readout device in collaboration with Agriculture and Agri-Food Canada, which helped the manufacturer to identify technical issues related to the use of the system in harsh environments. Replacing the manual water level sounder with a more convenient system of sensor and reading device will increase the participation of volunteers and sustainability of community-based monitoring programs.

Conclusions

This study has demonstrated that a community-based groundwater monitoring network can be implemented in a large municipal district using the citizen-science approach, whereby community volunteers measure water levels in their private water supply wells. The novel aspects of the monitoring program are the close collaboration among the university, Rocky View County, and community volunteers; and the integration of the monitoring program with education and outreach programs. The monitoring network has generated a rich data set regarding the seasonal and interannual water level dynamics and their spatial variability, as well as the long-term trend reflecting the decadal-scale meteorological fluctuations. These data will provide the essential information for understanding the groundwater flow system in the region, which will be used by the county for water resource and land-use planning and hence, provide opportunities for community volunteers to influence policy and management decision making.

The methodology used in this study can be easily adopted by other municipalities and watershed stewardship groups interested in groundwater monitoring. The web-based database can be shared by many of these groups and facilitate interaction among user groups. As governments are starting to rely increasingly on local municipalities and conservation authorities for watershed management and planning, community-based groundwater monitoring provides an effective and affordable tool for sustainable water resources management.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. GeoCENS Technology for Web-based Data Portal.

Appendix S2. Example of Questionnaire Form the Initial Site Visit.

Appendix S3. Example of Informed Consent Form.

Appendix S4. Example of Volunteer Feedback Survey Form.

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