Establishing a Rural Groundwater Monitoring Network Using Existing Wells: West Nose Creek Pilot Study, Alberta

Lisa A. Grieef and Masaki Hayashi

Abstract: Sustainable groundwater management requires long-term monitoring of aquifer water level, water quality, and water use with adequate spatial and temporal resolution in order to evaluate the response of the aquifer to changes in pumping rates and meteorological conditions. Since existing federal and provincial monitoring programs do not have sufficient spatial resolution, an alternative is to establish locally-based monitoring programs coordinated by municipalities or watershed groups. A network of more than 20 monitoring wells was implemented in the West Nose Creek watershed near Calgary, Alberta using existing water supply wells. The network effectively captured the pattern of seasonal and inter-annual fluctuations of aquifer water level. Understanding of the natural fluctuation will help the community detect any undesirable effects of increasing water extraction in the future. Biannual newsletters were distributed to the well owners and a wider community within the watershed to communicate the results and background knowledge. The methodology established in this pilot study may provide a cost-effective tool for rural groundwater monitoring in the Canadian prairies and elsewhere.

Résumé : La gestion viable des eaux souterraines requière une surveillance à long terme du niveau d'eau de l'aquifère, sa qualité, et son utilisation tout en conservant une résolution spatiale et temporelle adéquate afin d'évaluer la réaction de l'aquifère aux changements des taux de pompage et des conditions météorologiques. Puisque les programmes de surveillance fédéraux et provinciaux déjà en existence n'ont pas une résolution spatiale convenable, des programmes de surveillance locaux peuvent être établis et coordonnés par les municipalités ou des groupes de citoyens intéressés dans la conservation de l'eau dans leur bassin versant. Un réseau de plus de 20 puits de surveillance a été conçu et mis en place dans le bassin versant de West Nose Creek près de la ville de Calgary, Alberta, en utilisant des puits d'approvisionnement en eau existants. Le modèle des fluctuations saisonnières et interannuelles du niveau d'eau de l'aquifère a été capté par le réseau des puits de surveillance. Ainsi, la communauté pourra détecter les effets indésirables d'une augmentation de l'extraction des eaux souterraines. Des bulletins biannuels ont été distribués aux propriétaires des puits et à travers la communauté du bassin versant afin de communiquer une connaissance de base du projet ainsi que les résultats. La méthodologie qui a été établie dans cette étude préliminaire peut être un outil rentable pour la surveillance des eaux souterraines rurales dans les prairies canadiennes et ailleurs.

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Introduction

In rural farming areas of the Canadian prairies, groundwater is the primary source of water supply for municipal, domestic, agricultural and industrial use. In light of increasing demands from various sectors ranging from rural residential developments to industrial activities, it is important to develop and manage groundwater resources in a sustainable manner that minimizes negative impacts, such as excessive drawdown of aquifer water level and reduction in groundwater baseflow to streams (Sophocleous, 2000).

Regulatory agencies recognize the need to set the sustainable rate of groundwater withdrawal in a manner similar to the allocation of surface water resources. The current emphasis is placed on mapping aquifers to estimate the existing volume of groundwater, based on the same principles used to map hydrocarbon reservoirs. Such an approach, by itself, does not answer the critical question of sustainable pumping rate because groundwater is replenished by recharge processes, unlike hydrocarbons, and long-term sustainability depends on its dynamic response to pumping rather than the static reservoir volume. Well yield is commonly used as an indicator of aquifer productivity, but is normally based on short-term (hours to weeks) pumping tests at the time of well installation and, as such, has little use in predicting long-term aquifer responses to cumulative pumping from a large number of wells (Maathuis and van der Kamp, 2006).

Another approach is to view groundwater as a river-like system having recharge at one end and discharge at another end, with an idea that a sustainable pumping rate can be determined by considering the balance between recharge and discharge. However, recharge rates are highly heterogeneous and uncertain, and may be affected by pumping itself (Bredehoeft, 2002). In addition, groundwater discharge occurs in many places, not just in streams and creeks, meaning that it is impossible to quantify discharge rate with confidence.

Since there is a large degree of uncertainty in estimating the existing volume of groundwater and its recharge and discharge rates, the most realistic approach to sustainable groundwater management is through monitoring of aquifer water level and stream baseflow so that any undesirable effects of groundwater extraction can be detected at an early stage. Such an approach can enable the user community to implement adaptive management strategies. Groundwater monitoring in Canada is generally the responsibility of provincial governments (Maathuis, 2005); for example, Alberta Environment currently monitors approximately 200 observation wells in the province. With such a small number of provincial monitoring wells, however, the density of wells is too low to be useful for monitoring the complex behaviour of groundwater in heterogeneous prairie aquifers. The user communities, such as municipalities, need a sufficient density of water level measurements to understand the local groundwater system and its dynamics. Since it is unreasonable to expect the government to install a large number of new monitoring wells, an alternative monitoring approach is needed. Considering the high cost of drilling new wells, the most practical and cost-effective approach is to use existing water supply wells that meet certain criteria for water level monitoring. This locally-based approach requires cooperation of well owners and watershed groups, which may present a challenge, but nevertheless offers an opportunity for education and active participation of water users in monitoring programs. In some water-scarce regions of the world, user participation is becoming an essential part of groundwater management (Chebaane *et al.,* 2004).

Locally-based groundwater monitoring can provide the community with accurate information of groundwater in a timely manner. This will help the community understand the groundwater flow system and its response to increased extraction by new users and to natural stresses such as drought. Such an understanding can eventually be incorporated into numerical watershed models (e.g., Sophocleous and Perkins, 2000) for effective planning and management of surface and groundwater resources (Sandoval, 2004).

Despite the potential usefulness of locally-based groundwater monitoring networks, an effective methodology for implementing such networks has not been established. Since the monitoring network needs to be implemented by local groundwater users in a grass-roots manner, it is necessary to develop scientifically sound methods and make them available to a large community of water resource professionals. To this end, a pilot study was conducted in the West Nose Creek watershed near Calgary, Alberta to develop and test methods for implementing a monitoring network. The objective of this paper is to introduce a concept of locally-based groundwater monitoring, describe the methods of implementation, and document difficulties and challenges encountered during the study. It is hoped that the paper will serve as a guide for other communities in need of implementing similar groundwater monitoring programs in the Canadian prairies and elsewhere.

Study Site

West Nose Creek (WNC) watershed is located directly north of Calgary, Alberta (Figure 1), within the 4,049 km^2 Municipal District (MD) of Rocky View. The watershed itself has a gross drainage area of 250 km^2. The 1971-2000 normal annual precipitation is 413 mm and monthly mean temperature ranges from -8.9°C in January to 16.2°C in July at the Calgary International Airport located 14 km east of the gauging station (Environment Canada, 2006).

The watershed outlet in this study is defined by the former stream gauging station operated by the Water Survey of Canada (WSC) from 1982 to 1995 during ice-free periods. Since it is essential to monitor stream baseflow for sustainable groundwater management, the gauging station was re-activated in 2003 as part of this study. Average discharge of West Nose Creek in ice-free season (April-October) during 1982-1995 was 0.061 $m^3\ s^{-1}$ (Johnson, 2002), whereas winter flow (November-March), estimated from late-October discharge values, was 0.04 $m^3\ s^{-1}$ during the same period. Using these values and the gross drainage area, mean annual runoff is estimated to be six mm.

Much of the watershed is covered by glacial till and generally has hummocky or undulating topography with numerous depressions that are internally drained. Therefore, the effective drainage area of the watershed is likely considerably smaller than the gross drainage area. Hence, the mean annual runoff (calculated above) underestimates the actual runoff from the effective drainage area. West Nose Creek occurs in a valley floor incised 30-50 m below the surrounding area (Figure 1),

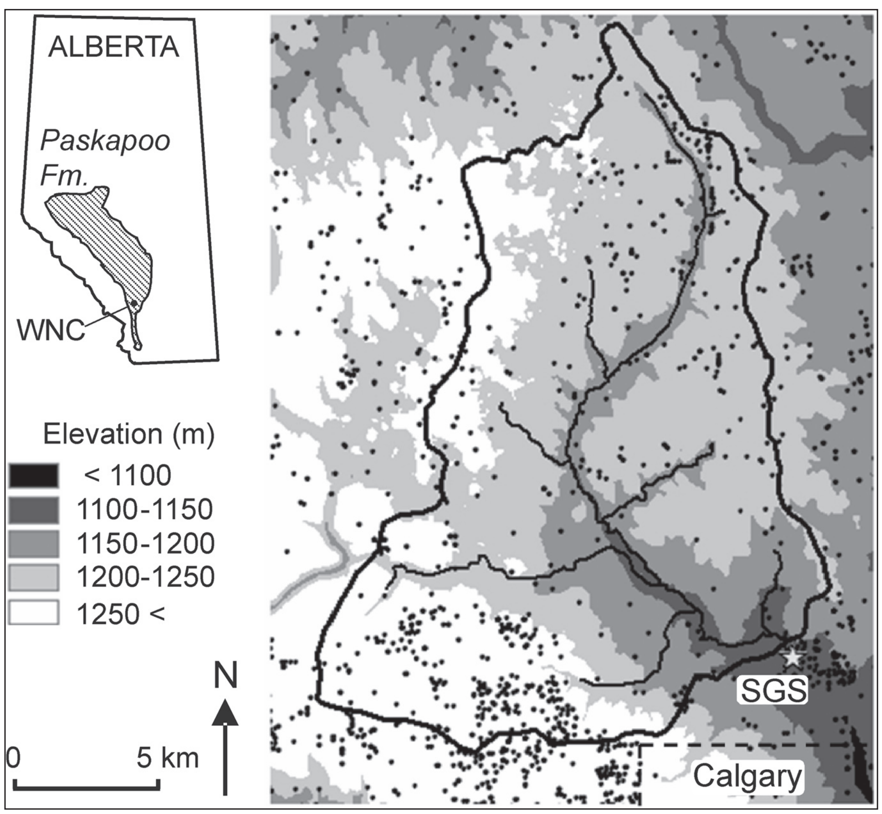

Figure 1. Elevation map of the West Nose Creek (WNC) watershed showing the location of existing wells (dots) in Alberta Environment Water Well Drilling Reports, stream gauging station (SGS), and the Calgary city limit (dashed line). The insert shows the location of WNC in Alberta and the extent of subcropping Paskapoo Formation.

which is believed to have formed as a melt-water channel at the end of the last glaciation (Hills, 2007). The northwestern part of the watershed is particularly hummocky and has numerous permanent and semi-permanent wetlands. The till is generally a few metres to 30 metres thick (HCL, 2002) and underlain by inter-bedded mudstone, siltstone and sandstone of the Paleocene Paskapoo Formation (Hamblin, 2004). Up to 15 m thick sand and gravel deposits occur between the till and the Paskapoo Formation in southwestern parts of the watershed (HCL, 2002); these deposits are associated with partially buried valleys incised to bedrock (Hills, 2007).

Alberta Environment Water Well Drilling Reports (WWDR) list 760 wells in the watershed and the surrounding area (Figure 1). Depths of the wells vary between five and 150 m, with 80% of wells shallower than 80 m. Most of the wells are screened in the sandstone units of the Paskapoo Formation, which were deposited in fluvial environments (Hamblin, 2004). The Paskapoo is the subcropping bedrock unit underlying approximately 10,000 km^2 of densely populated area (see insert in Figure 1). The occurrence of sandstone units within the Paskapoo is highly irregular and unpredictable; hence, the Paskapoo is regarded as a complex system of numerous isolated or interconnected aquifers, rather than a single aquifer of large spatial extent. Therefore, groundwater monitoring in the Paskapoo aquifer system requires a relatively dense network of wells to capture its complexity.

The majority of landuse in the watershed is agricultural, with approximately half used as pasture for cattle grazing and half as crops, including barley, canola, wheat and oat. Towards the south end of the watershed, particularly in the southwest, numerous residential subdivisions have sprung up over the last decade or so. Many of these areas have large homes that are dependent on groundwater. Due to its close proximity to Calgary, residential development in the watershed is expected to continue and may lead to increased groundwater extraction rates from the Paskapoo aquifer system. Some traditional groundwater users are expressing concerns regarding the cumulative effects of increased extraction, but the information currently available does not allow for reliable prediction of such effects. The nearest existing monitoring well is located in Irricana, 40 km east of the watershed, which is too far to provide meaningful information on local groundwater conditions in the watershed. To restore and maintain the quality of water and aquatic habitat in West Nose Creek and Nose Creek, the MD of Rocky View and other stakeholders formed the Nose Creek Watershed Partnership in 1998. Groundwater is seen as an important element of the watershed as it provides baseflow to the creeks and sustains riparian vegetation.

Methods

Selection of Wells

From the 760 wells listed in the Alberta Environment WWDR (Figure 1), about 100 wells in the Paskapoo Formation were selected that had screen lengths less than seven metres, and reasonable lithologic logs and well completion details described by the driller. A shorter screen was preferred to target particular units within the formation. Well screens are generally available in three-metre lengths and are commonly six metres or longer.

After selecting these wells, an attempt was made to identify current well owners, but this proved to be difficult, as the WWRD has records of original well owners and some properties have changed hands several times since the wells were installed. In addition, the locations of wells are given only to the center of the quarter section, which is an area of about 800 m by 800 m. To obtain more accurate well information, an attempt was made to contact well owners by knocking on doors and placing letters in mailboxes at residences thought to be associated with a particular well in question; however, this methodology was not efficient as a number of the people contacted were not the owners of the specific well. Consequently, the majority of wells were located by searching current telephone listings for the well owner's name that was listed on the well record. These wells often were still owned by the original owner, or had been handed down within the same family. The Agricultural Fieldman from the MD of Rocky View was also consulted to review the list of well owners and identify those well owners who might be interested in this study. Most well owners contacted this way were interested in the study and willing to participate. Through discussion, it was evident that farmers and ranchers view groundwater as a very important resource and are concerned about the sustainability of this resource under increased use.

Once a well owner was contacted, a visit to the well was made to confirm that it was accessible and in good condition. Wells in well pits were rejected for water level monitoring, as were wells that were in use and where a static water level could not be obtained at a given visit. The well owner was asked to fill out a questionnaire (Grieef, 2006) to collect relevant information, such as the surrounding land use, the use of the well, the location of any nearby wells, the method of water treatment used, the locations of taps and hydrants, and whether springs are present on the property.

In selecting candidate wells for the network, efforts were made to have good spatial coverage of wells across the watershed, including the potential recharge area on the highlands and discharge areas near the creek, and to include some wells close to one another, but installed at different depths, to investigate vertical flow. Efforts were also made to include some wells outside or at the watershed boundary to examine if the watershed received groundwater inputs from adjacent areas. The current monitoring network has 20 wells for water level and seven wells for water use metering (Figure 2); all of these wells are available for water quality monitoring.

Ethical Conduct and Risk Management

In this type of study there are risks that have to be managed to protect both the observers and the well owners. It is important to consider the liability associated with working on private property and with wells used by people for drinking water. A document for informed consent was prepared, which listed the purpose of the study, foreseeable benefits and risks involved, and the details of what the researchers would be doing at the well and with the data (Grieef, 2006). This document was approved by the University of Calgary Conjoint Faculties Research Ethics Board and was used to inform the well owners of the intent of the study and to obtain their signed consent.

A number of precautions were taken to avoid issues that could arise from this work such as introduction of contaminants to the well water systems, property damage, or injury to researchers. Background information, such as photos and water samples for chemical analyses, were collected prior to accessing the wells. For those wells that were metered for water use, a separate letter was drafted to inform the well owners of the intent of the study and to assure them

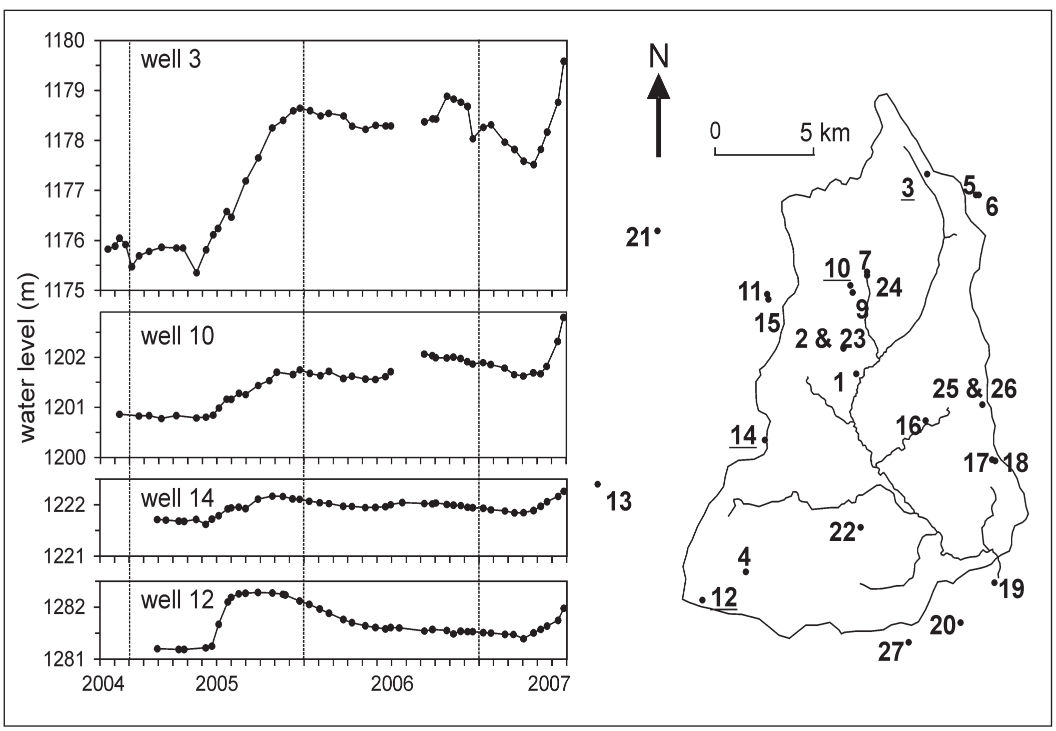

Figure 2. Map of the watershed showing the location of groundwater monitoring wells and identification numbers, and water level (m above mean sea level) measured in wells 3, 10, 12 and 14 (underlined in the map). Dotted lines in the graph indicate the beginning of year and tick marks indicate the beginning of month.

that, for their privacy, specific water use data would not be published in association with any location or name.

Since this study was intended to last for a number of years, it was important to maintain a positive public perception so that people would continue to welcome the research team into their community. For example, the researchers participated in a community open house organized by the Nose Creek Watershed Partnership. This type of study also offers an opportunity to increase awareness among community members about water issues. In addition to speaking to individual well owners during site visits, information packages and biannual newsletters were used to provide the results and background knowledge to the well owners.

Water Sample Collection and Analysis

Well water samples were collected from all wells for several purposes; first to examine the presence or absence of well contamination by bacteria prior to using the wells, second to survey the groundwater quality of the wells, and finally to characterize the spatial distribution of chemical and isotopic composition of groundwater in the watershed. Water quality monitoring was not an objective of the network, but the data can provide valuable background information if the network is used for water quality monitoring in the future. Samples were collected at indoor or outdoor taps and upstream of any water treatment system. Taps were run for about 15 minutes prior to sample collection. Samples were stored in a cooler during transport, and refrigerated until they were analyzed for major ions, nitrate and stable isotopes. The samples for microbiological analysis were collected in sterilized bottles provided by the Alberta Provincial Laboratory, Calgary Branch, where samples were analyzed. The tap itself was sterilized prior to sampling by immersing it in a cup of bleach and then rinsing it with tap water. The presence or absence of total coliforms and *E. coli* group organisms were determined by the defined enzyme substrate method. When these organisms were found in a sample, additional samples were collected to confirm the results. If previous results were confirmed, a public heath inspector advised the well owner how to proceed with mitigative measures, such as shock chlorination of the water system.

Water Level Measurement and Well Location Survey

Water levels were measured approximately every two weeks using a tape equipped with an electronic probe. A standard protocol was followed for sterilizing the probe prior to lowering it in each well, whereby, latex gloves were worn and the probe was rinsed with a 50 mg L^{-1} bleach solution, followed by rinsing with distilled water (Wilde, 2004). When measuring water levels in wells used for water supply, it was necessary to ensure that the level measured was not influenced by the short-term effects of pumping. If the pump was on when the observers arrived at a well, as easily detected by the sound, the observers waited until the pump was turned off. At each well, the water level was measured a number of times over a period of several minutes and, if the levels were changing, the observers waited for a stable reading.

To evaluate the response of wells to pumping, a sterilized pressure transducer (In-Situ, Mini-Troll) was installed in each well for a period of one week. Water level was recorded every ten minutes. The transducer had a slightly larger diameter than the manual water level probe, which made it difficult to navigate past some well pit-less adapters while lowering the probe down the well. Care was required to avoid getting the transducer caught by the adapter or accidentally disengaging it. The data collected by the transducer indicated that the water level in most wells recovered to pre-pumping values within ten to 30 minutes after pumping.

The precise location and casing-top elevation of all wells were determined using a differential global positioning system (Trimble GPS Pathfinder Pro XR). The data points were post-processed through differential correction using the Trimble base station located at an Alberta Survey Control Marker. Estimated accuracy after the correction was less than one metre for horizontal coordinates and less than 1.4 m for elevation.

Water Meter Installation

Sustainable groundwater management requires information on water extraction rates, but such information is very difficult to obtain except for large users who are required to monitor and report pumping rates. Therefore, water extraction rates are commonly estimated from population and agricultural census data, as well as from approximate per-capita consumption rates found in the literature (de Loë, 2005; Kulshreshtha and Grant, 2007). To assess the accuracy of the census-based method, water meters were installed in selected wells to monitor pumping rates and compare them to a published table of water use calculations (Buchanan *et al.*, 2000).

Positive displacement meters (AMCO Water Metering Systems, C700 1") were installed by a certified plumber in water supply lines connected to six household water wells that were monitored for the water levels, and two additional wells used for livestock water supply. The flow data were read manually from the meters or at remote readers outside the house in conjunction with bi-weekly water level measurements. According to the manufacturer, the accuracy of the meters is within +/- 1.5% at a normal flow of 11 to 190 litres per minute, and -5 to + 1% at low flows of about three litres per minute.

Since water meters are installed within the household water supply systems, special care is required to ensure proper installation and operation of the meters. Experience points to the importance of contracting local water supply professionals who have experience in rural water wells, as opposed to urban water supply, and who are known to the residents. It is also important to identify any special needs of well owners, and the equipment and safety considerations required at each location prior to commencing work.

Preliminary Results

Water Level Monitoring

The purpose of monitoring is to establish the natural variability of water level so that the drawdown caused by excessive pumping can be clearly detected. The water levels were relatively low in most wells when the monitoring started in late 2004 or early 2005, presumably because levels were still recovering from the drawdown caused by a severe Prairie drought in 2000-2002 (Bonsal and Regier, 2007). Figure 2 shows examples of water levels in four wells representing different parts of the watershed. June 2005 was characterized by unusually heavy storm events, which caused flooding in central and southern Alberta. High precipitation was also recorded in August and September 2005. The 1971-2000 normal precipitation was 80 mm for June and 105 mm for August and September, while 2005 precipitation was 248 mm for June and 184 mm for August-September. As a result of these heavy rains, water levels started to rise in June 2005 and kept rising until late fall (Figure 2). Stable or declining water levels in early 2006 are likely the result of a lack of snowmelt recharge. A small rise in water level is recorded in June-July 2006 in some wells. Significant snowmelt recharge was observed in April-May 2007 (Figure 2). With a few more years of monitoring, the community will have a good understanding of seasonal and inter-annual water level fluctuations in the local aquifer system.

The range of measured water levels was compared against the non-pumping water levels recorded at the time of installation (as found in the Alberta Environment WWDR between 1975 and 2005) (Figure 3). The values in the WWDR were within approximately five metres of the observed range during 2004-2006 for all wells except one (Figure 3), and within three metres of the observed range for 80% of wells. Therefore, the WWDR data can be used as a reliable indicator of the spatial distribution of the water level in aquifers. This finding is important as it increases the confidence level of mapping groundwater levels in other areas of Alberta based on the information found in the WWDR.

Using the water levels measured in April 2005, a water-level contour map of the Paskapoo aquifer system is plotted in Figure 4. Groundwater tends to flow from the watershed boundary towards the creek, which is consistent with the occurrence of numerous springs on the creek bank (Grieef, 2006). However, it is not certain if the groundwater drainage divide coincides with the surface drainage divide. Preliminary analysis of the WWDR data in the area suggests that groundwater may flow into the watershed from the west (Grieef, 2006).

Water Quality and Water Use

The initial water quality data for each well were summarized in a table and communicated to the well owners with some commentary to make the numbers meaningful to a non-technical person. Nitrate and bacteria are of particular concern. Out of 20 well

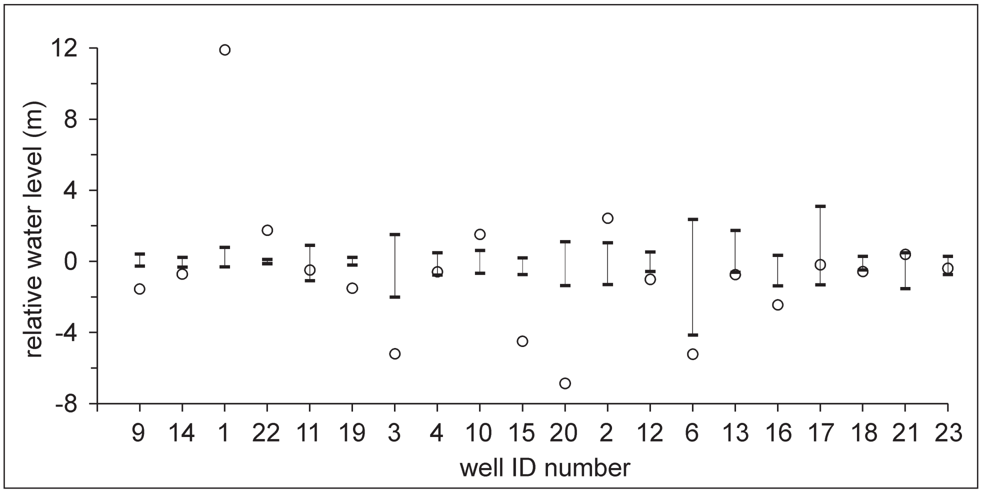

Figure 3. Variability of water level in the monitoring wells (see Figure 1 for location). Solid line indicates a range of observed maximum and minimum water level relative to the mean water level, and open circles indicate the water level found in Alberta Environment Water Well Drilling Reports. Wells are ordered from the oldest (1975) to the youngest (2005), from left to right.

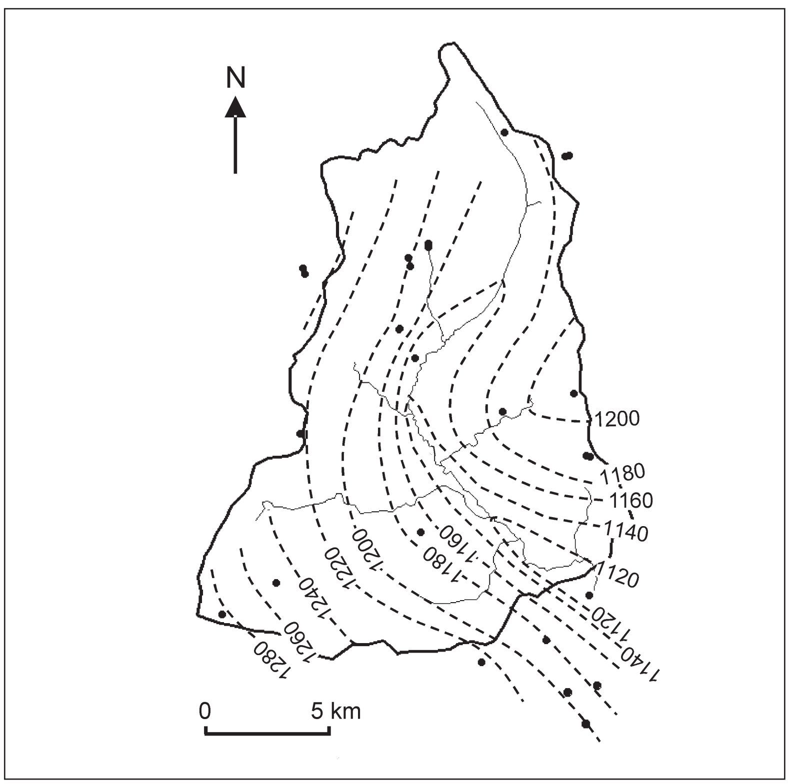

Figure 4. Spatial distribution of water level in the Paskapoo aquifer system based on the measurements in April 2005. The wells used to draw elevation contours (m) are indicated by solid circles.

water samples analyzed in this study, noticeably high concentrations (> 10 mg NO_3 L^{-1}) of nitrate were found in six samples, but only one well (used for livestock water supply) exceeded the Canadian drinking water guideline of 45 mg NO_3 L^{-1} (Health Canada, 2007). Of the 11 household water supply wells subjected to microbiological analysis, total coliforms were detected in three wells. There was no obvious correlation between nitrate and coliform. These data serve as useful background information regarding groundwater quality in the watershed.

Water meters were monitored at five household water supply wells for 12-16 months, at one household well for one month, at two livestock water supply wells for 16 months, and at one livestock well for one month. During the monitored period, average pumping rates from household wells ranged from 0.34 m^3 d^{-1} to 1.8 m^3 d^{-1}, depending on the number of people and animals using the wells. Pumping rates from each individual well were reasonably stable, with some seasonal variations. Rates of water use, based on the number of people and animals, were also estimated using a published "water-use calculation" table for Alberta farms (Buchanan *et al.,* 2000). Estimated rates of groundwater use (i.e., pumping rates) were 56 to 180% of actual pumping rates. However, when all six wells were averaged, the estimated rate was 95% of the actual rate, suggesting that the calculation based on the published tables and population data provides reasonably accurate estimates of rural household water use in small watersheds. However, it should be noted that this result is based on a relatively small number of samples.

Pumping rates from livestock wells, averaged over the monitoring period, ranged from 0.55 to 6.8 m^3 d^{-1}. Pumping rates for each individual well had large temporal variability due to livestock operations, which changed the number of animals using the well, and the availability of other water sources, such as surface water in dugouts and seasonal ponds. The rates of water use, estimated using the published tables (Buchanan *et al.,* 2000), were 20 to 380% of actual pumping rates. The estimated rate was 31% of the actual rate when the average of the three wells was used, indicating difficulties in obtaining accurate estimates of pumping rates from livestock wells.

Response of the Community

A biannual newsletter was distributed, which explained the purpose of the study and preliminary results. This newsletter also provided some basic information on the science of hydrology and sustainable water management. The newsletter was intended for the well owners who participated in the study, but it was subsequently distributed to other community groups, such as the Nose Creek Watershed Partnership. In response to interest by community groups in low-cost, high-density groundwater monitoring, the MD of Rocky View implemented a pilot program, similar to that in West Nose Creek, in six other watersheds within the MD. In this pilot program, which began in August 2007, the well owners themselves measure water levels. The data are reported to the watershed management specialist of the MD, who compiles the data. The data will be made available to the general public, in a timely manner, most likely in a web-based format. Once the program is implemented for long-term operation, the MD will have a capability to monitor the response of local groundwater in each watershed to natural variability, such as drought, and to detect early signs of unsustainable drawdown caused by increased pumping. Such capability is currently lacking in many parts of the Prairie Provinces, but is critical for sustainable groundwater management.

Conclusions

A pilot study was implemented in the West Nose Creek watershed to establish a groundwater monitoring network using existing water supply wells. Out of 760 wells listed in the provincial water well database, 20 wells in the Paskapoo aquifer system were selected, using the following criteria: 1) the well screen is less than seven metres in length; 2) the well has a reasonably good lithological description as reported by the driller; 3) the well has a fast response such that the water level recovers quickly after pumping; and 4) the well is easily and safely accessible. Though a number of challenges were encountered during the implementation, working with the municipality's agricultural field person, who assisted with locating and contacting well owners, and working with local water service professionals experienced in rural water supply systems proved to be important for successful implementation. It was also important to follow risk-management protocols regarding accidental contamination of wells, potential damage to water supply systems and injury to monitoring personnel, and for dealing with issues of privacy of information.

The data from the network captured the natural fluctuation of water level due to seasonal and inter-annual variability in precipitation inputs. This information will be useful for distinguishing potential future drawdown caused by pumping from natural variability. Comparison of the measured water levels and the non-pumping water levels reported in the provincial well drilling reports showed that the latter are a reliable indicator of aquifer water level. Water use monitoring confirmed that published water use calculation tables along with census data are representative of household water use within the watershed, but were perhaps not as representative for livestock wells. Water quality sampling provided a general understanding of aquifer water chemistry and local pollutants. Biannual newsletters, prepared for the well owners, have subsequently been distributed to a wider community within the watershed and the municipality. This has generated significant interest in the locally-based monitoring program, and has prompted the municipality to initiate similar programs for other watersheds in the region. It is anticipated that the methodology established in this study will provide a useful and cost-effective tool for sustainable rural groundwater management in the Canadian prairies and elsewhere.

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