Evaluating groundwater sustainability for fractured crystalline bedrock

Meredith J. Metcalf and Gary A. Robbins

ABSTRACT

Water sustainability is an important concern for communities that rely on groundwater in fractured rock; yet the complexity of the fracture system and the unknown rate of recharge make quantifying groundwater availability difficult, if not impossible, using conventional water balance calculations. This study provides a new approach for estimating groundwater sustainability in fractured rock that entails synthesis of pre-existing well data into a comprehensive database that permits defining bedrock groundwater drainage basins and flow for use in estimating recharge and usage. The method was tested in the Coventry Quadrangle, Connecticut and entailed the use of more than 2,500 wells. Groundwater recharge and usage were estimated for each drainage basin and the sustainability of each basin was determined by taking the difference between these estimates. Additionally, temporal analysis of well parameters indicated a decrease in well yield by approximately 20% and the depth to water declined. The method demonstrated here provides a means to allow the consideration of groundwater sustainability in land use planning and decision-making.

Key words | drainage basins, fractured bedrock, groundwater, recharge, sustainability

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INTRODUCTION

Rural communities in New England, as well as other regions across the world, principally rely on groundwater extracted from fractured crystalline and sedimentary bedrock. Despite the importance of and reliance on groundwater in the fractured rock, little is known about the water supply making it difficult to manage on a regional or town wide basis. Fundamental questions concerning current stewardship practices as they relate to usage of water remain unanswered. These questions include: what is the potential limit of a local water supply, and has the water supply been impacted by human development, and if so, how? The lack of knowledge on the supply of and demands on groundwater can result in poor decision-making in land use planning related to new development. For example, without proper knowledge of the sustainability of the supply, a new development can overtax the water supply in an area, which would impact nearby domestic wells, surface water bodies, wetlands, etc.

The sustainability of the groundwater resource is and will become more of a concern with population growth and perhaps changes in climate. The usual method for evaluating aquifer sustainability by conducting water balance calculations is generally not achievable when describing fractured bedrock conditions. A major constraint in conducting water balance analyses is the lack of information on bedrock recharge rates. Such data are not readily available owing to the high cost for data collection, the complexity of the fracture network, and a lack of studies directed at sustainability. Advances in technology have allowed scientists to use geographic information systems (GIS) and remote sensing as tools to conduct spatial analyses to better understand the effects of landscape change on groundwater and surface water (Prasad *et al.* 2007; Biswas 2009; Bhalla *et al.* 2010). Most recently, GIS has been used to determine groundwater zones influenced by development (Jaiswal *et al.* 2003), to delineate groundwater

doi: 10.2166/ws.2013.179

potential zones (Krishnamurthy *et al.* 1996; Murthy 2000; Obi Reddy *et al.* 2000; Pratap *et al.* 2000), and to conduct groundwater modeling (El-kadi *et al.* 1994; Shahid *et al.* 2000; Saraf *et al.* 2004). This research is directed at using GIS and a database developed using well completion reports (boring logs) to evaluate the sustainability of groundwater within fractured rock.

DESCRIPTION OF THE STUDY AREA

The Coventry Quadrangle exemplifies typical groundwater conditions for the State of Connecticut, as well as other New England states and mountainous regions, where the fractured crystalline bedrock is the main source of water supply. Additionally, this study area has undergone high-density development between 2002 and 2006 (CLEAR 2013) that is expected to continue in the foreseeable future (CtSDC 2013), which offers the opportunity to determine the impact of development on groundwater sustainability.

The Coventry Quadrangle is located in northeastern Connecticut and is intersected by the towns of Andover, Coventry, Mansfield, Tolland, and Willington (Figure 1). Although Connecticut has a highly variable lithology, the Coventry Quadrangle is dominantly composed of Paleozoic and Proterozoic gneiss and schist with small intrusions of dolerite and diorite scattered throughout. The surficial materials found within the Quadrangle are dominantly till and thick till, with areas of alluvium, sand, gravel, fines, or a combination thereof dispersed over the extent of the Quadrangle. The thickness of the overburden material ranges from 0 meters (outcrops are present) to approximately 49 meters (Meyer *et al.* 2008c). A medium-sized valley follows the meandering stream and cuts through the center of the Quadrangle in a north-south direction.

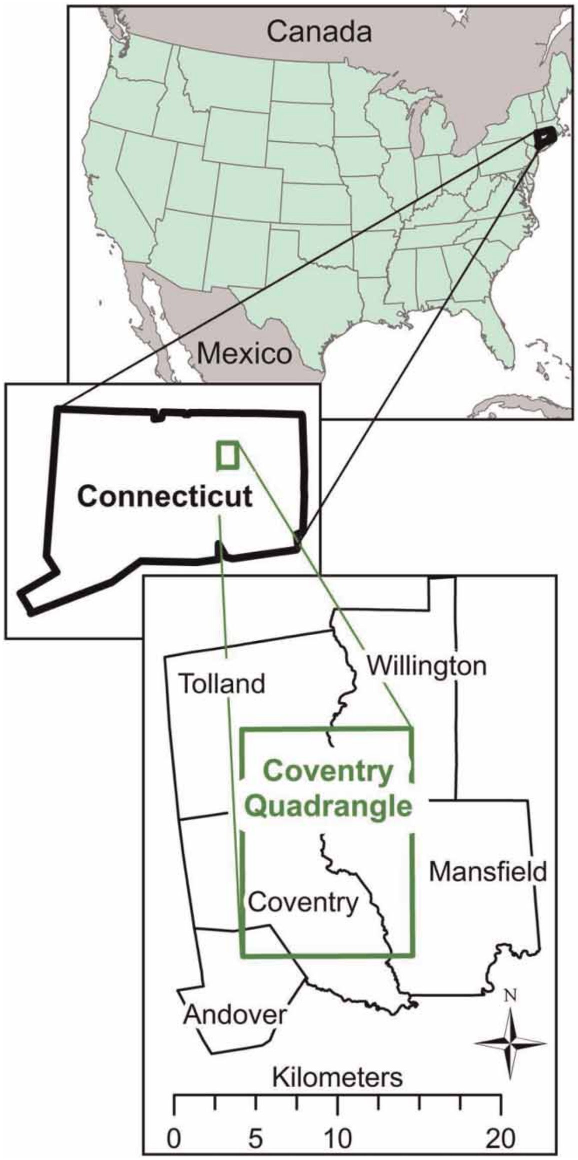

Figure 1 | Location of the Coventry Quadrangle in the state of Connecticut.

DATA SOURCES

As part of a US Geological Survey funded STATEMAP project, in collaboration with the Connecticut Geological Survey, a pilot study was initiated to digitize well completion reports for the Coventry Quadrangle in Connecticut (Meyer *et al.* 2009; Metcalf & Robbins 2010). This pilot study included the development of a well completion report database, the digitization of records, the incorporation of quality assurance elements in digitizing records, and the use of the databases for performing geologic and water resource related assessments (Meyer *et al.* 2008a, b, c). The locations of more than 2,500 wells that were used in this study are shown in Figure 2.

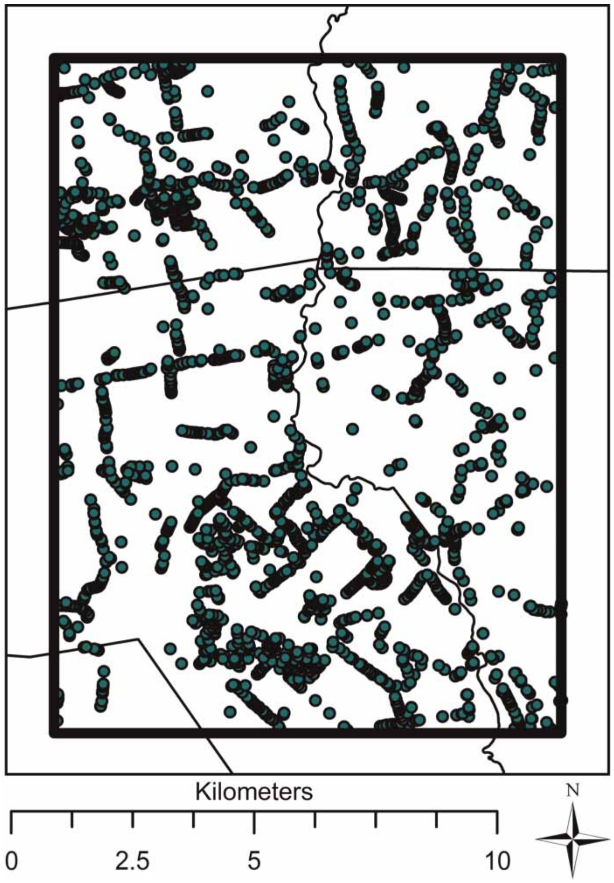

Figure 2 | Location of wells with well drilling information within the Coventry Quadrangle.

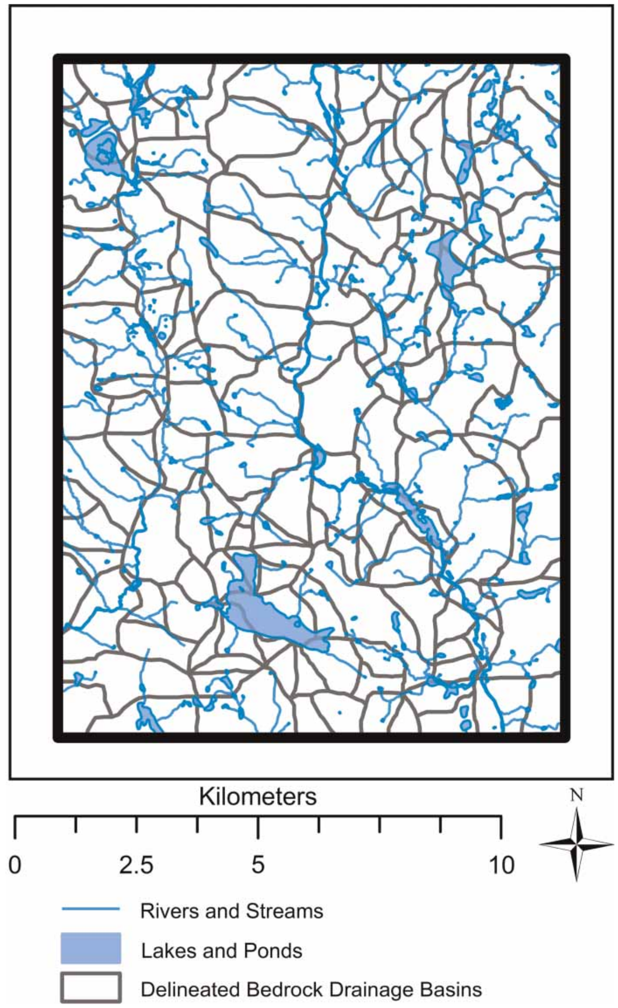

Figure 3 | Bedrock groundwater drainage basins defined by Metcalf *et al.* (2013).

METHODOLOGY FOR DETERMINING SUSTAINABILITY OF BEDROCK DRAINAGE BASINS

As described by Metcalf *et al.* (2013) in detail, a hydraulic head map of the groundwater flow in the fractured rock of the Coventry Quadrangle was developed by using ArcGIS® to map water level data from well completion reports. The groundwater flow direction was used to delineate groundwater drainage basins for the fractured rock, as shown in Figure 3. Divergent flow lines defined recharge areas within the Quadrangle and convergent flow lines defined areas of discharge. The bedrock groundwater drainage basins and the physical characteristics of the wells associated with each basin were used to estimate the rate of groundwater recharge. Parameters necessary for estimating the rate of recharge per basin per year using Equation (1) were the average transmissivity (T) defined by Huntley *et al.* (1992) using the specific capacity of the wells, the average hydraulic gradient (dh/dL) of the drainage basin, the area of each basin (A), and the length of the discharge boundary (L) for each basin. The following equation was used to determine an average rate of recharge (i) for each basin:

$$i = \frac{TL(dh/dL)}{A} \tag{1}$$

The rate of groundwater usage for each basin was calculated by multiplying the number of homes within each basin (extracted using ArcGIS®) by the average domestic residence water use of 414.722 cubic meters (109,558 gallons) per year (Rockaway *et al.* 2011) and dividing by the area of each basin. The sustainability of the groundwater in the fractured rock was determined by taking the difference between estimates of the water availability (i.e., recharge estimates) and estimates of water usage within a 1 year period for each fractured rock groundwater basin delineated in Figure 3. Groundwater drainage basins that have a greater quantity of water recharging the bedrock than consumed are, thus, considered sustainable.

METHODOLOGY FOR DETERMINING GROUNDWATER SUSTAINABILITY AS IT RELATES TO URBAN GROWTH

Well productivity (defined by well yield), depth to water, and the number of wells installed were analyzed as a function of time to determine whether the demands on the groundwater resource have been altered due to increased housing and/or population growth in the Coventry Quadrangle. The well completion report database devised for the STATEMAP project resulted in the use of 2,538 wells (Figure 2) to observe these temporal trends. The wells were sorted by completion date and grouped into the following time periods: 1965–1970, 1970–1975, 1975–1980, 1980–1985, 1985–1990, 1990–1995, 1995–2000, 2000–2005, and 2005–2010. Given the log normal distribution of observed well yields for the study area, demonstrated in Figure 4, the geometric mean of the observed well yields was calculated for each time period, as well as the average depth to water.

RESULTS AND DISCUSSION

Sustainability of bedrock drainage basins

Figure 3 shows the 136 bedrock groundwater drainage basins that were delineated using the hydraulic head map. Ninety-four of these basins have been delineated completely within the Quadrangle and provide the basis for this study. Table 1 shows the summary statistics for

Table 1 | Summary statistics for recharge and usage in the 94 basins delineated within the Quadrangle

	Average	Minimum	Maximum	Standard Deviation
Recharge (cubic meters/year)	7.3×10^{-3}	7.0×10^{-4}	9.8×10^{-2}	2.0×10^{-3}
Basin area (meters^2)	9.8×10^{5}	2.1×10^{5}	4.9×10^{6}	7.7×10^{5}
Number of homes	19.2	0	71	15.7
Usage (cubic meters/year)	1.1×10^{-2}	0	4.8×10^{-2}	1.0×10^{-2}
Recharge - usage (cubic meters/year)	-0.4×10^{-3}	-4.2×10^{-2}	1.4×10^{-1}	2.1×10^{-2}

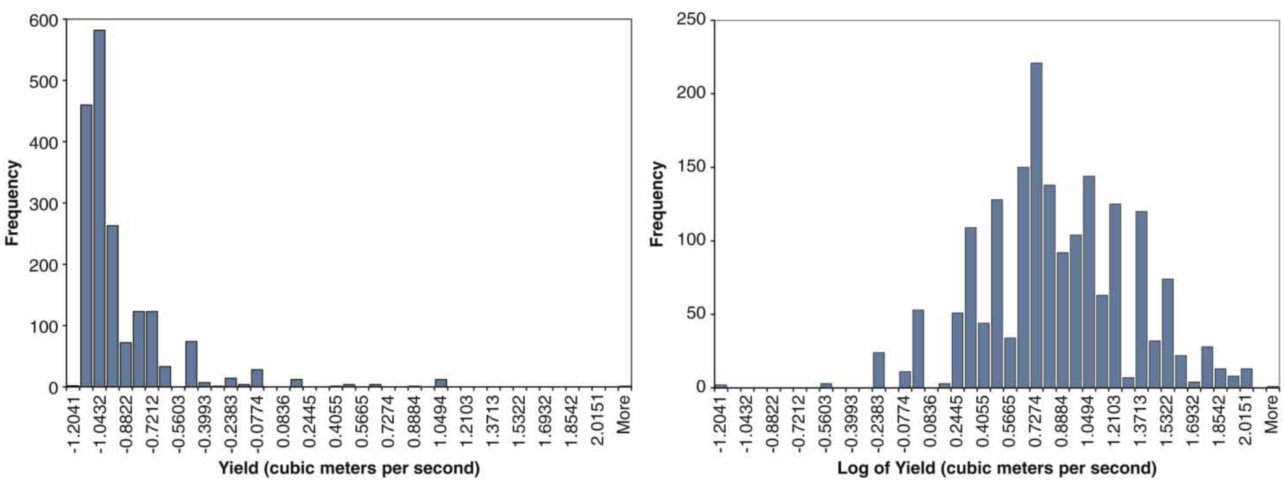

Figure 4 | Frequency distribution of well yield (left) and the log of well yield (right) demonstrating the log normal nature of well yield.

recharge and usage in the delineated drainage basins. Although on average it would appear that the usage and recharge were almost the same for the Quadrangle, it was found that 51 of the basins proved to be using groundwater at a rate greater than recharge, 37 of the basins had recharge values that exceeded the rate of usage, and recharge and usage were equal within a 10% difference in six of the basins. Figure 5 shows the distribution of these basins along with the percent difference (100% × ((recharge-usage)/recharge)) between recharge and usage across the study area. It should be kept in mind that these estimates are based on the assumption that the average recharge and usage are the same every year (no net gain or loss). Thus, the groundwater bedrock supplies for the majority of the basins in this study area appear to be unsustainable.

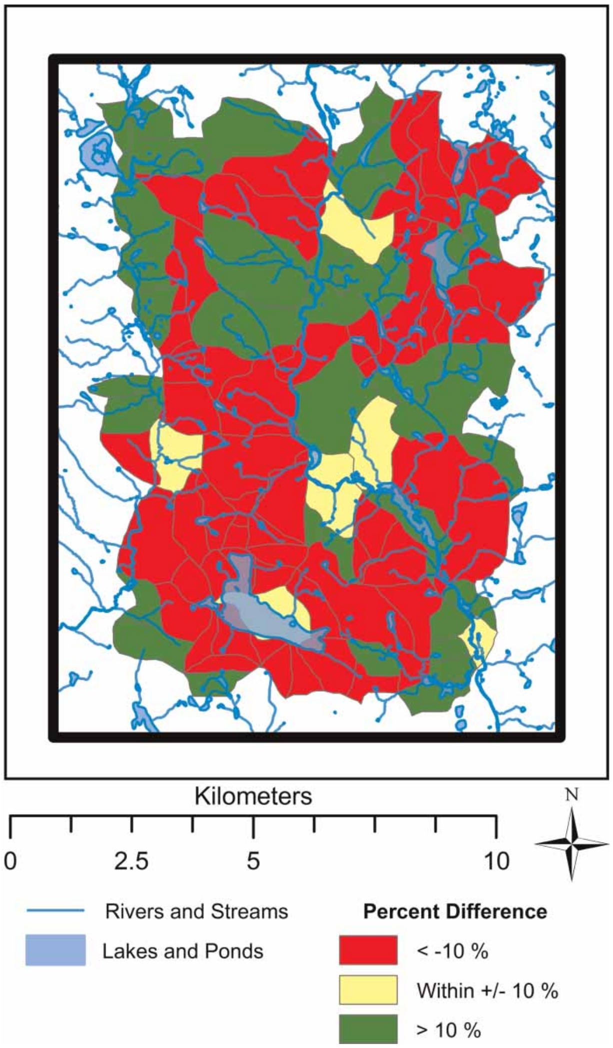

Figure 5 | Distribution of drainage basins and the percent difference (100% × ((recharge-usage)/recharge)) between recharge and usage for each completely delineated basin within the Coventry Quadrangle.

Groundwater sustainability as it relates to urban growth

Well completion reports for this study dated from December 1965 to December 2007. The total number of wells, the geometric mean of the well yields, and the average depth to water are shown in Table 2 for each time period. Due to the inadequate number of wells available for the time periods 1965–1970 and 2005–2010, the cumulative number of wells and geometric mean of well yields were analyzed from 1970 to 2005. Figure 6 demonstrates that as more wells were installed between the years 1980 and 2005, the cumulative geometric mean of the well yields had decreased by 20%. The average depth to water had remained relatively constant during this period, until more recently as shown in Figure 7. The more recent decline in water level does not appear to be due to an increase in the number of homes, but rather an increase in well yields on a per home basis. This may reflect wells being drilled to greater depths in order to increase yields for larger homes or perhaps as a result of more homes being constructed at higher elevations as shown in Figure 8.

Table 2 | Summary statistics for well completion reports for each time period

Time Period	Total Number of Wells	Geometric Mean of Yield (cubic meters per second)	Average Depth to Water (meters)
1965–1970	5	2.19×10^{-4}	9.51
1970–1975	143	4.67×10^{-4}	7.99
1975–1980	354	5.21×10^{-4}	8.15
1980–1985	318	4.20×10^{-4}	8.49
1985–1990	546	4.38×10^{-4}	8.55
1990–1995	401	4.01×10^{-4}	8.13
1995–2000	348	3.89×10^{-4}	8.33
2000–2005	349	5.20×10^{-4}	10.41
2005–2010	77	4.73×10^{-4}	8.94

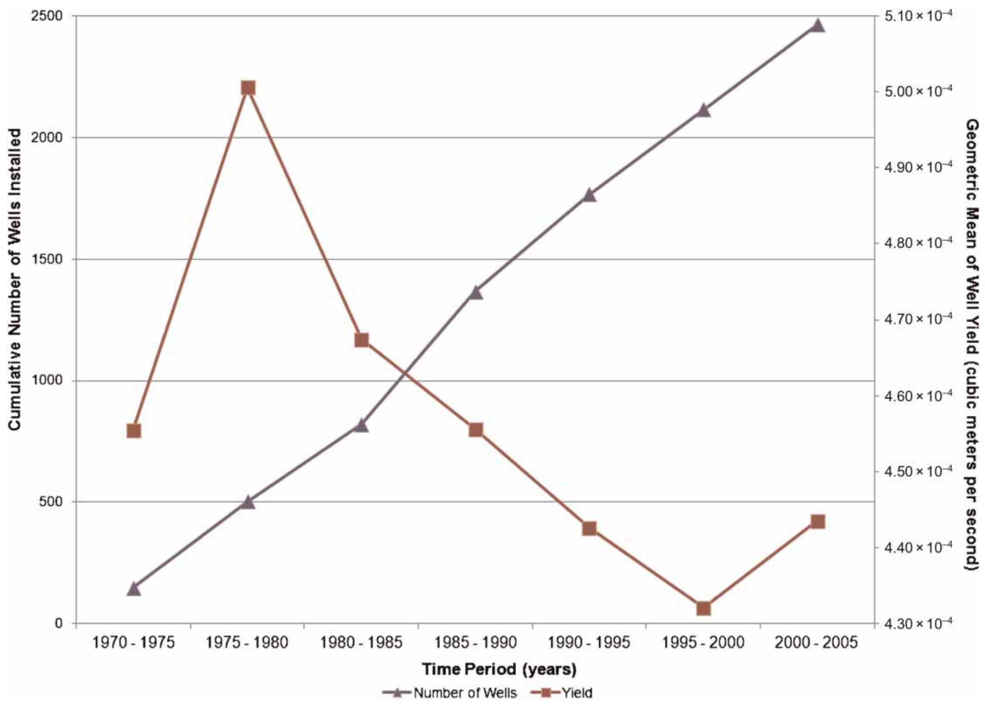

Figure 6 | Cumulative number of domestic wells installed and the cumulative geometric mean of observed well yields for the years 1970–2005.

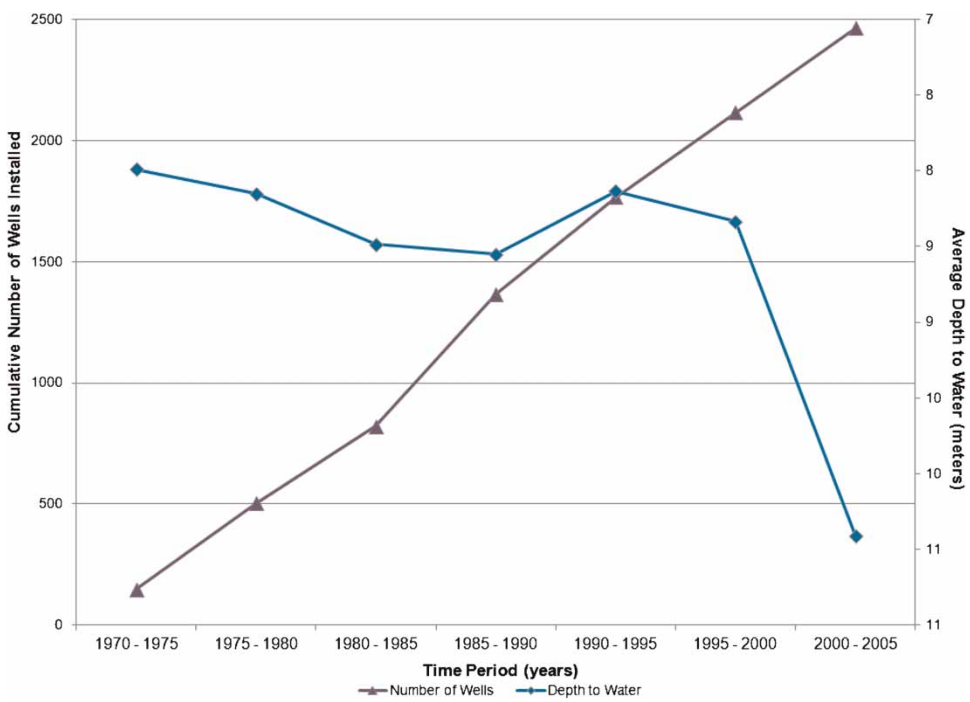

Figure 7 | Cumulative number of domestic wells installed and the average depth to water for wells within the Coventry Quadrangle for the years 1970– 2005.

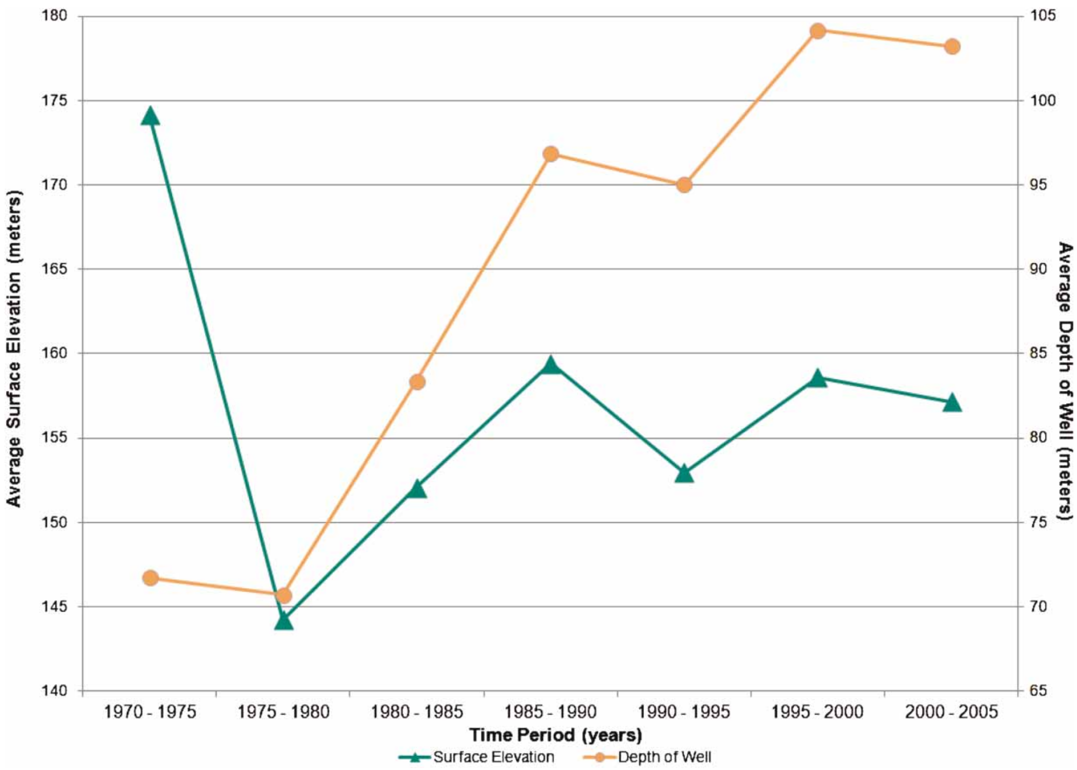

Figure 8 | Average surface elevation and average depth of completed well for wells within the Coventry Quadrangle for the years 1970–2005.

CONCLUSIONS

A method has been presented that is useful for estimating the sustainability of the fractured bedrock groundwater. The calculations represent conditions on average and do not address the impact of season variations on groundwater sustainability. However, it is expected that where groundwater usage far exceeds recharge for specific bedrock drainage basins, wells in these areas may be most susceptible to seasonal drought conditions. The method demonstrated here would be useful to assess the viability of a development that relies on the bedrock groundwater and in planning and zoning decision making.

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First received 15 January 2013; accepted in revised form 1 July 2013. Available online 12 September 2013