Groundwater recharge and in storage at the scale of Canada

Alfonso Rivera
Geological Survey of Canada, Natural Resources Canada, Quebec City arivera@nracn.gc.ca

and

Harold Vigneault
INRS-ETE, Quebec City

Summary

As Canadian freshwater comes under increasing stress, decisions about this natural resource will need to be made with a more complete understanding of its availability and how that is expected to change over time. However, decisions are currently being made with incomplete information on some of the most fundamental aspects of water availability, such as the availability of groundwater resources. How much groundwater do we have in Canada? Sounds like a simple question to Canadian citizens, yet no one really knows, as groundwater scientists have not yet answered that simple question. This contribution shares the latest data and analysis on the availability of fresh groundwater at the country scale based on two components: groundwater recharge and groundwater in storage. The volume of groundwater recharge in Canada is revised to higher values against previous published estimates. The volume of groundwater in storage in Canada is published for the first time as the volume of fresh groundwater stored in the upper 200 meters of the aquifers and hydrogeological regions of Canada.

Introduction

Groundwater as a resource can be characterized by two main variables: rate of renewal (recharge) and volume in storage. These two variables are difficult to quantify, but both must be estimated before resource management plans can be implemented.

Data on the groundwater resources in Canada is incomplete and contains large uncertainties. Recharge typically varies from 10% to 30% of precipitation in Canada (Rivera, 2007). However, the volume in storage at the country scale is unknown, but some values at the regional scale are available.

Groundwater recharge is an important part of the water cycle and it can be used as an indicator of aquifer replenishment or aquifer overexploitation. For Canada, the only estimate of groundwater recharge at the country scale has been repeatedly published (or cited) by various sources (Gleick 2004, WWAP-II, 2006; FAO, 2005) and is more or less "officially" accepted at 375 km^3 in one given year. However, this number seems rather small for the whole country and seems to be underestimated. Thus we contribute this new estimation at the scale of the country to verify the recharge value officially published in the international literature and to use the latest data and information available to make an updated evaluation of that recharge.

Furthermore, the volume of groundwater in storage in Canada has not been previously estimated; we contribute this estimate for the first time as the volume of fresh groundwater stored in the upper 200 meters of the aquifers and hydrogeological regions of Canada.

Groundwater recharge

Groundwater recharge is the total volume of water entering aquifers within a country's borders from precipitation and surface water flow at various scales. Groundwater resources are generally estimated by measuring rainfall in arid areas where rainfall is assumed to infiltrate into aquifers. In humid areas it is a general practice to consider groundwater resources as equivalent to the base flow of rivers where data are available. Very often, however, groundwater recharge is overestimated in arid regions and underestimated in humid regions.

There are several ways of evaluating recharge (use of numerical models, base-flow estimates, analysis of water well levels, etc.). To estimate the groundwater recharge over Canada we chose the base-flow approach. We employed this method to calculate the recharge over the country with the base-flow of the principal rivers with watershed area smaller than 5000 km^2. This condition assumes that the hydrological response is more likely to be related to the streamflow measured at a station for basins with areas ≤5000 km^2. The existing literature provides sufficient evidence that this is an acceptable criterion, despite its potential limitations.We used a database file containing the base-flow data of 8000 watersheds, kindly provided by Environment Canada (Piggott, 2009).

Method and results

The hydrograph separation method evaluates the base flow of rivers. This method makes the use of filters to separate the base flow and the surface flow from a total stream-flow. The main assumption in this approach is that the base flow within the catchment area represents the infiltration (i.e. a potential recharge) over that area.

The method to evaluate base-flow is based on hydrograph river separation over a selected period of time (e.g., months), the result is the mean base-flow per month. A numerical algorithm was developed to retrieve the data from the database of watersheds with areas equal to or smaller than 5000 km^2 (2407 rivers, figure 1) following Statistics Canada yield model (larger contributing basins would contain a more diverse mixture of hydrologic conditions; Bemrose et al., 2009) and calculated the recharge for each watershed selected. The recharge was evaluated with the following function:

Groundwater recharge = mean month base-flow (m^3/month) / watershed area (m^2)

The result was transformed in mm per year with an average value for the whole country.

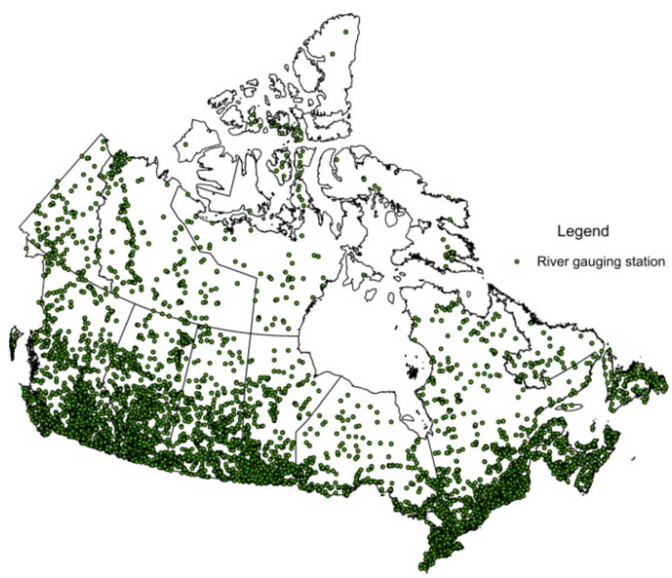

Figure 1. The river gauging stations in Canada used for the estimation

A first set of results from these estimates provided a range of recharge for the whole country between 201 and 314 mm in one year, representing 1990 and 3110 km^3/year, respectively. These results would mean a recharge between 36% and 56% of total precipitation (P= 5500 km^3/year, Statistics Canada, 2003) in Canada over one average year. As those percentages seem unrealistically high, we performed a geological analysis to evaluate hydrogeological regions within watersheds and made some comparisons with other existing water balances in Canada.

The water yield model of Statistics Canada (Bemrose et al, 2009; Soulard et al., 2002) estimates a total runoff for the country at 3262 km^3/year (2002), or at 3435 km^3/year (2009). In both of those studies, however, the recharge to aquifers was not included in the total water balance. The resulting runoff in those studies implicitly includes the recharge to aquifers by infiltration from precipitation. Other water balance estimates of Canada include recharge at 7 % of total precipitation (Rivera, 2008) equivalent to *c.* 390 km^3 in one given year. In those estimates the percentages for runoff and ET relative to precipitation are 53% and 40%, respectively. Thus, it is conceivable that the recharge (base flow) in the runoff estimates of the Statistics Canada models, is about the same percentage; providing a consistent picture of the balance for Canada.

On the other hand, a detailed evaluation of the nine hydrogeological regions of Canada (Sharpe et al., 2010; Michel et al., 2010), indicate that the hydrogelogical condition on the northern parts of Canada (Shield) would not allow for important volumes of recharge to aquifers by direct infiltration from precipitation. Thus, the base flow in those regions would be at its minimum, or negligible. Therefore, we opted to eliminate the Shield hydrogeological region from our analysis.

Using both of these analyses, we revised the recharge numbers and obtained a mean annual recharge for Canada of 201 mm equivalent to 550 km^3. The later seems more realistic and consistent than the 370 km^3 which has been published in the international literature for long time.

Groundwater in storage

The experiences with the use of groundwater in many parts of the World have shown that groundwater can offer a limited water supply because of its low flow velocity, the need for pumping, and the need to maintain water barriers to avoid and control seawater intrusion and land subsidence, among other potential problems that might appear with time. However, in order to have a good control and good management of the groundwater resources, a prerequisite is that the storage capacity of aquifers must be known and its changes monitored as a function of time. In a time when the sustainability of groundwater is much discussed (CCA, 2009), concerns of long-term groundwater exploitation continue to increase due to the lack of adequate knowledge on the replenishment and sustainable yields of this resource. In addition to the yearly recharge rates, the groundwater volumes stored in aquifers need to be estimated in light of linkages with other parts of the water cycle and the environment: to sustain ecosystems; to maintain base-flow in rivers; to overcome droughts; to maintain or recover water levels in aquifers; to evaluate surpluses and deficits to be managed in times of water shortages; to fight against climate changes; and to support full integrated water resources management policies.

The Canadian conditions on climate, geology, hydrology, hydrogeology and population make the presence of groundwater in this country very interesting. Most of the pumping in Canada is done in relatively shallow aquifers with relatively “recent” conditions of their replenishment. Thus shorter groundwater renewal times are expected most across Canada making the groundwater in storage a very important factor in its management as a resource.

Method and results

The volume of groundwater stored in an aquifer is a function of storativity, the volume of water released from (or taken into) storage per unit surface area of aquifer, per unit decline (or rise) in hydraulic head. To compute storage volumes in an aquifer we considered two different parameters: specific yield and specific storage coefficient. Specific yield applies to aquifers in unconfined conditions, which is the part of the porosity that can be drained from the aquifer under the influence of gravity. Specific storage coefficient applies to confined aquifers and it is solely a function of the compressibility of pore water and the mineral matrix of the aquifer.

Values of specific yield, S_y (sometimes also called drainage porosity or effective porosity) can be several orders of magnitude larger than the specific storage coefficient, S_s. Values of specific yield can vary anywhere form 0.01 to 0.4, whereas values of specific storage coefficient can vary anywhere from 10^{-3} to 10^{-7} m^{-1}, depending on the material of the aquifer. The literature provides a range of values for these parameters for various types of rocks, either as drainage porosity or as storage coefficients (Fetter, 1988, de Marsily, 1986; Freeze and Cherry, 1979, etc).

For this study we used the nine hydrogeological regions (Sharpe et al., 2010; see figure 2), as a starting point for our estimation of groundwater in storage, minus the Shield, Cordillera, and Appalachians hydrogelogical regions as we considered them with no having significant amounts of groundwater in storage. Furthermore, we only considered the upper 200 meters of the aquifers located in those regions. Because we concentrate our research in regional-scale aquifers, we kept things simple as a first estimate on a national evaluation scale. Using values of specific yields between 0.05 and 0.1 for shallow, unconsolidated, unconfined aquifers, and a range of specific storage coefficients between of 10^{-2} to 10^{-5} m^{-1} for confined aquifers, we obtained a total volume of 70 000 km^3 of groundwater stored in the upper 200 meters in the nine hydrogeological regions.

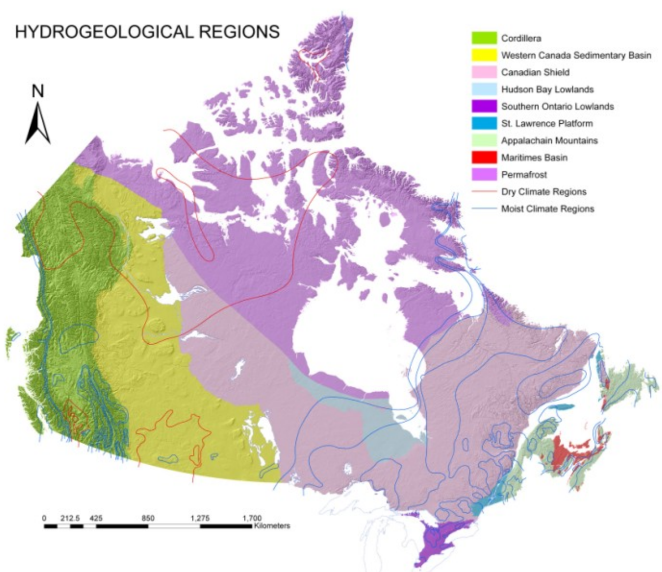

Figure 2. Hydrogeological Regions of Canada (Sharpe et al, 2010)

Conclusions

The volume of groundwater recharge at the scale in Canada was revised to higher values against previous published estimates. Up to now the "officially" accepted published (or cited) recharge value had been of 375 km^3; we revised that figure to 550 km^3 and found it in a reasonable agreement with other published water-balance estimates in Canada.

The estimate of groundwater in storage presented in this study represents a volume of 70 000 km^3 of fresh groundwater stored in the upper 200 meters of the aquifers and hydrogeological regions of Canada. At a later stage and depending on the objectives and scales of other studies (groundwater sustainability, mass transport etc), these estimates will need to be refined. The estimated volume in storage does not mean that it can be exploited completely; only the annual renewable groundwater can be exploited to avoid water depletion. Moreover, fraction of the amount which the resource managers will determine must be kept to sustain streams (base-flows) and aquatic habitats. These practices have to be integrated and developed using the sustainable development concepts. For example, the Province of Nova Scotia is currently using a threshold of 50%.

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