A Spatial Estimation of Groundwater Recharge in Southern Ontario, Canada

حساب توزيع تغذية الأحواض الجوفية باستخدام معلومات محدودة

Abdelhaleem Khader

عبد الحليم خضر

Department of Civil Engineering, Faculty of Engineering,
An-Najah National University, Nablus, Palestine

E-mail: a.khader@najah.edu

Received: (28/10/2015) Accepted: (24/1/2017)

Abstract

Efficient management of groundwater resources is needed, due to their importance and susceptibility to depletion and contamination. This requires better understanding and accurate quantification of groundwater recharge, which is the main source for replenishment of groundwater aquifers. Choosing a method for estimating recharge is largely dependent on the objectives of recharge estimation, spatial and temporal scales, availability of data, and the available resources in terms of time and expense. The focus of this paper is estimating the spatial distribution of groundwater recharge for the objective of designing a groundwater monitoring network. In this case, the ability to capture spatial variation of recharge is the key attribute of the chosen method for estimating recharge. At the same time, the data needed for the method should be readily available so that the method can be applied in different regions that might differ in data availability. Precipitation-Runoff Modeling System (PRMS) has been utilized in this paper to estimate recharge in a study area in southern Ontario, Canada. The data on climate, geomorphology and geology needed to parameterize the model, and streamflow data needed to calibrate and validate the model were available online from federal and provincial agencies websites. Calibration and validation results show a good match between simulated and observed streamflow. An independent estimate of recharge was provided by a recession-curve displacement method, which uses only streamflow data. A comparison of the two methods shows a large difference in recharge estimates due to fundamental differences in recharge definition. PRMS results will be used in the groundwater monitoring network design because they are spatially distributed, and because PRMS conceptual model better represents the physical processes.

Keywords: Groundwater Recharge, PRMS, RORA, Spatial estimation.

ملخص

نظرا لأهمية الأحواض المائية الجوفية كمصدر أساسي للمياه العذبة، ولسهولة تعرض هذه الأحواض للتلوث، تنبع الحاجة لإدارة فعالة لهذه الأحواض. هذه الإدارة تستدعي فهما أعمق وأدق للتغذية لهذه الأحواض، والتي هي المصدر الأساسي لتجديد كميات المياه في هذه الأحواض. إن اختيار طريقة معينة لحساب كميات التغذية يعتمد بشكل كبير على الهدف من هذا الحساب والمقاييس الزمانية والمكانية وتوفر المعلومات اللازمة وتوفر الموارد المالية والوقت الكافي. تركز هذه الورقة البحثية على حساب التوزيع الجغرافي للتغذية بهدف تصميم شبكة مراقبة للمياه الجوفية. في هذه الحالة، من الأهمية بمكان قدرة الطريقة المختارة على معرفة تفاوت كميات التغذية وتوزيعها مكانيا. بالإضافة إلى ذلك، يجب أن تكون المعلومات اللازمة لهذه الطريقة يسهل توفيرها لكي يتسنى تطبيقها في مناطق مختلفة تتفاوت في المعلومات المتوفرة. في هذه الورقة، تم استخدام النموذج الرياضي لحساب التدفق من الهطول لحساب التغذية للأحواض الجوفية في منطقة جنوب مقاطعة أونتاريو في كندا. المعلومات المناخية والجيولوجية اللازمة للنمذجة تم الحصول عليها من المواقع الرسمية للجهات الحكومية المختصة على مستوى الدولة والمقاطعة. أظهرت نتائج معايرة والتحقق من صحة النموذج الرياضي مدى مطابقة قيم التدفق المحسوبة للقيم الحقيقية المقاسة. تم استخدام طريقة أخرى لحساب التغذية تعتمد فقط على معلومات التدفق في الأودية وهي طريقة إزاحة منحنى الانحسار. تظهر مقارنة قيم التغذية من الطريقتين اختلافا كبيرا في القيم المحسوبة نظرا للاختلاف المبدئي بين الطريقتين في تعريف التغذية. سيتم اعتماد نتائج الطريقة الأولى نظرا لأنها موزعة جغرافيا، ونظرا لأن النموذج المفاهيمي لهذه الطريقة يمثل الواقع الفيزيائي بصورة أفضل.

الكلمات المفتاحية: تغذية الأحواض الجوفية، توزيع مكاني

1. Introduction

Groundwater is often considered the main source of freshwater in many places throughout the world. Even in countries that have vast surface water resources such as Canada, more than 30% of the population relies on groundwater as their drinking water source (Lesage 2005). This precious resource is susceptible to depletion due to over pumping to fulfil domestic, agricultural, and industrial needs and contamination by anthropogenic sources of contaminants. To address these problems better management of groundwater resources is needed. Efficient groundwater resource management requires better understanding and accurate quantification of groundwater recharge, which is the main source for replenishment of groundwater aquifers.

Groundwater recharge (which will be called recharge afterwards) is defined in a general sense as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir in three principal mechanisms (De Vries and Simmers 2002): (i) Direct recharge, which is water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration by direct vertical percolation through the vadose zone; (ii) Indirect recharge, which is percolation to the water table through the beds of surface water courses; and (iii) Localized recharge, which is an intermediate form of groundwater recharge resulting from the horizontal (near-) surface concentration of water in the absence of well-defined channels. In many locations, combinations of the three types occur, but direct recharge is likely to become less important than the other two types as aridity increases. On the other hand, artificial recharge systems are engineered systems where surface water is put on or in the ground for infiltration and subsequent movement to aquifers to augment groundwater resources (Bouwer 2002). This paper will focus on natural recharge, and artificial recharge will not be mentioned afterwards.

Recharge is known to be highly variable in both space and time (De Vries and Simmers 2002 and Cherkauer 2004). There are various methods for estimating recharge which can be divided into five different categories (USGS 2013): (i) groundwater methods, (ii) streamflow methods, (iii) tracer methods, (iv) unsaturated zone methods, and (v) water budget methods. Examples of these methods are shown in Table 1. The choice of one method is largely dependent on the objectives of recharge estimation, spatial and temporal scales, availability of data, and the available resources in terms of time and expense. It is desirable to apply and compare multiple independent methods to increase reliability of recharge estimates (De Vries and Simmers 2002; Scanlon et al. 2002).

The spatial and temporal scales of recharge estimates are especially important due to the fact that different study goals require recharge estimates over different space and/or time scales. Some studies estimate recharge for water-resource assessment where spatial variability might not be important, whereas others estimate it for contaminant transport or aquifer vulnerability to contaminants studies where spatial variability in recharge is critical (Scanlon et al. 2002). In the same manner, a decadal time scale is generally accepted in water-resource planning, whereas time scales required for contaminant transport studies range from days to thousands of years, depending on the particular contaminant being used (Scanlon et al. 2002).

The availability of data on climate, geomorphology (including topography, soil, and vegetation), and geology of the study area is also important. These data can be used to develop a conceptual model of recharge in the system, which describes location, timing, and likely mechanisms of recharge and provides initial estimates of recharge rates (Scanlon et al. 2002).

The focus of this paper is estimating the spatial distribution of groundwater recharge for the objective of designing a groundwater monitoring network. Choosing the appropriate method for estimating the recharge was based on scanning the methods in Table 1 for the ones that can fulfill this objective with the available data and resources. For designing monitoring networks, spatial scale is a key attribute of the method to be chosen. For that purpose, a method that can estimate regional recharge and the variability of recharge within the region is needed. On the other hand, the data needed for the method should be readily available so that the method can be applied in different regions that might differ in data availability. And finally, for cost efficiency, the required time and monetary resources should be minimized as much as possible.

Recent advances in GIS and remote sensing technology, and the availability of spatially distributed data on climate, geomorphology, and geology, opens up the possibility of utilizing distributed watershed models that can be calibrated with the readily available streamflow data. Examples of such models are: HSPF (Bicknell et al. 1997), CREAMS (Knisel 1980), and PRMS (Leavesley et al. 1983). PRMS (Precipitation-Runoff Modeling System) was chosen for this study due to: (i) its flexibility of spatial and temporal scales, (ii) its ability to be calibrated and validated with available streamflow data, and (iii) its inclusion of subsurface modules which limits the need for groundwater flow models. PRMS has been utilized in the past for the purpose of groundwater recharge estimation (Cherkauer 2004; Vaccaro and Olsen 2007; Burns et al. 2012). In this paper, PRMS was used to estimate recharge to a study area in southern Ontario, Canada (Figure 1) for the purpose of designing groundwater monitoring network in that area. An independent estimate of recharge was provided by a recession-curve displacement method using the computer programs RECESS and RORA (Rutledge 1998, 2000, and 2007).

Table (1): Comparison between selected methods of recharge estimation (Scanlon et al. 2002 and USGS 2013).

Category	Method	Special scale	Temporal scale	Data needs	Relative cost
Groundwater	Groundwater Modeling	Local to Regional	Month to Years	High	High
	Water-Table Fluctuations	Local	Day to Years	Low	Low
Streamflow	Recession-Curve Displacement	Watershed	Event to Years	Low	Low
	Seepage Meters	Point	Event to Months	Low	Low
	Stream Base-Flow	Watershed	Years	Low	Low
	Streamflow Gain/Loss Measurements	Local	Instantaneous	Low	Low
	Watershed Models	Watershed to Regional	Days to Years	High	High
Tracer	Chloride	Point	Years	Moderate	Moderate
	Chlorofluorocarbons	Local	Month to Years	Moderate	High
	Temperature	Point	Days to Years	Moderate	High
	Tritium	Point	Month to Years	Moderate	High
Unsaturated Zone	Darcian Unit-Gradient	Point	Long-Term Average	Low	High
	Zero-Flux Plane	Point	Day to Years	High	High
	Zero-Tension Lysimeters	Point	Day to Years	Low	High
Water budget	Deep Percolation Model	Regional	Day to Years	Moderate	Moderate
	HELP3 Model	Point to Regional	Day to Years	Low to Moderate	Moderate

2. Study Area and Data Collection

The study area of this paper is located in southern Ontario, Canada (Figure 1). It extends from Orangeville in the north to the city of Hamilton in the South. The total area is about 2,300 Km^2. The area is managed by three conservation authorities: (i) Hamilton Conservation, which manages Spencer Creek watershed; (ii) Conservation Halton, which manages Bronte Creek and Sixteen Miles Creek watersheds; and (iii) Credit Valley Conservation, which manages Credit River watershed. The area includes four of the big urban centers on Lake Ontario: Hamilton, Burlington, Oakville, and Mississauga, in addition to many rural towns and villages.

Figure (1): Location of Hamilton-Halton-Credit Valley study area.

Ground surface elevation in the study area ranges from about 68 m above mean sea level (AMSL) at Lake Ontario in the southeast to 525 m AMSL near the town of Orangeville in the northwest, as shown in the 10-m digital elevation model in Figure 2 (OMNR 2006). The Niagara Escarpment (Figure 2) extends through the study area. It is a bedrock escarpment characterized by steep cliffs on the eastern side and gently sloping terrain to the west (AquaResource 2009; Earthfx 2010). Paleozoic geology mapping in the area (OGS 2011) indicates 6 geological formations (Figure 2): Armabel Formation, Clinton Group, Georgian Bay Formation, Guelph Formation, Lockport Formation, and Queenston Formation. The major rock types are sandstone, shale, dolostone, siltstone, and limestone. The soil type map in Figure 2, which was obtained from OMNR (2012), indicates that the prevalent soil types are loam, clay loam, sandy loam, and silt loam.

The climate of southern Ontario is characterized by warm summers, mild winters, a long growing season, and usually reliable precipitation (Brown et al. 1974). Climate normals of the study area for the years 1961-1990 were obtained from Environment Canada website (http://res.agr.ca/cansis/nsdb/ecostrat/district/climate.html). The mean annual precipitation is about 905 mm, about 180 mm of which is snow. Temperature normals show that mean annual temperature is about 7.1 ^{o}C, whereas minimum and maximum annual temperatures are 2.3 ^{o}C and 11.7 ^{o}C, respectively. Long-term annual precipitation ranges from 800 to 925 mm (Figure 3, top right), and monthly precipitation ranges from 55 to 90 mm (Figure 3, bottom) Finally, annual potential evapotranspiration (Penman method) is about 637 mm. Daily climate data for modeling purposes were obtained from 7 Environment Canada climate stations (Figure 3, top left).

Long-term streamflow data was obtained from 11 streamflow gauges (Figure 3) from the HYDAT network (http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1) monitored by Environment Canada. These gauges are listed in Table 2.

Land use/land cover data (Figure 4), obtained from OMNR (2008), shows that about 20% of the study area is considered urban (pervious and impervious built-up area). Forests cover about 13%, whereas other green areas and wetlands cover 12%. Roads cover about 7%. The rest of the area is either open water, exposed bedrock, extraction, or undifferentiated, which includes all agricultural lands as well as urban brown fields, hydro right-of ways, the edge of transportation corridors and clearings within forests.

Table (2): Streamflow gauges summary.

Gauge ID	Name	Drainage area (Km^2)	Period of record
02HB013	Credit River near Orangeville	62.2	1967 – present
02HB001	Credit River near Cataract	205	1915 – present
02HB020	Credit River Erin Branch above Erin	32.3	1983 – present
02HB018	Credit River at Boston Mills	402	1982 – present
02HB008	Credit River west branch at Norval	127	1960 – present
02HB025	Credit River at Norval	615	1988 – present
02HB024	Black Creek bellow Acton	18.9	1987 – present
02HB004	East Oakville Creek near Omagh	199	1956 – present
02HB022	Bronte Creek at Carlisle	117	1989 – present
02HB012	Grindstone Creek near Aldershot	82.6	1965 – present
02HB007	Spencer Creek at Dundas	169	1959 – present

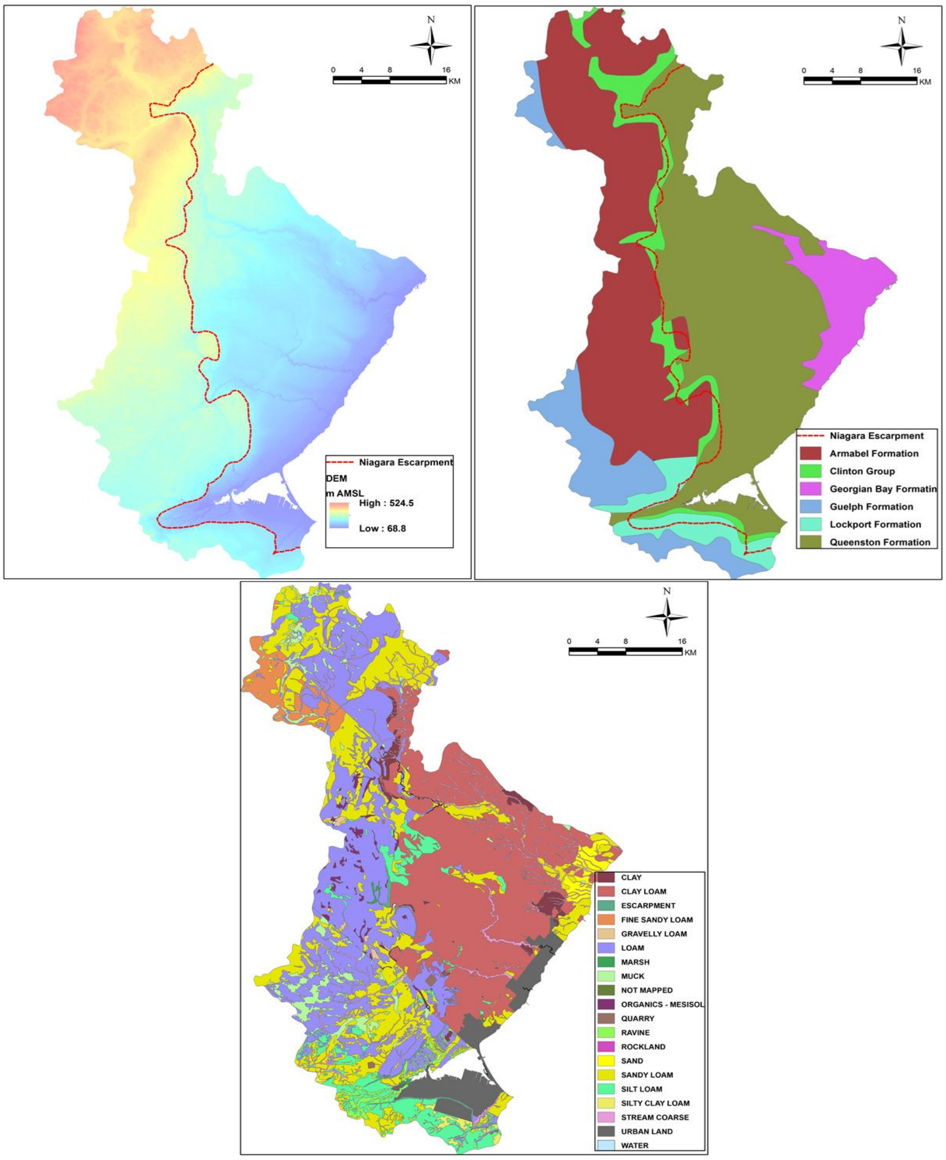


Figure (2): Digital elevation model (top left), bedrock formation (top right), and soil type distribution (bottom) in Hamilton-Halton-Credit Valley study area.

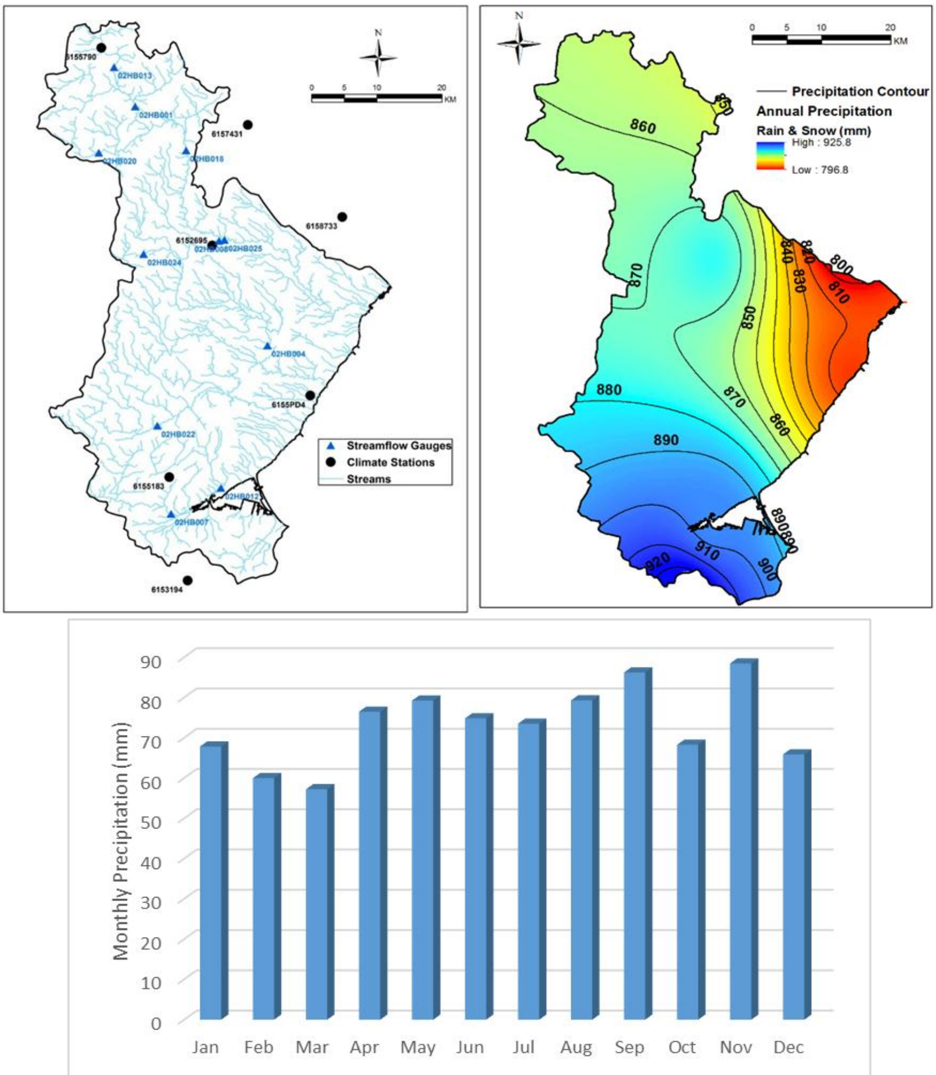


Figure (3): Locations of streamflow gauges, climate stations, and streams in Hamilton-Halton-Credit Valley study area (top left), long-term average annual precipitation distribution (top right), and long-term average monthly precipitation in station 6152695 (bottom), which is a typical monthly distribution in the area.

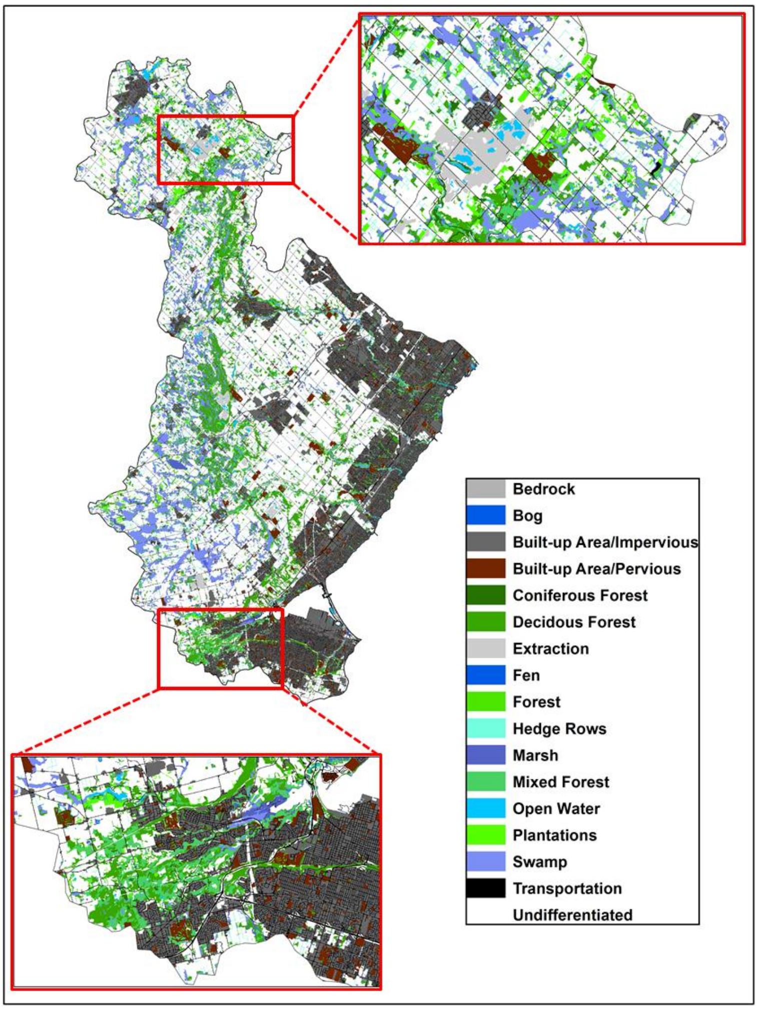


Figure (4): Land use/land cover map for Hamilton-Halton-Credit Valley study area.

Hydrostratigraphic analysis of the area (AquaResource 2009; Earthfx 2010) indicates the existence of multiple aquifers (high permeability materials) and aquitards (low permeability materials) in both, the overburden and the bedrock. The stratigraphy of the study area is highly complex, which can be reflected in the reliability of conceptual models needed for groundwater flow modeling.

3. Methodology

In this study, the precipitation-runoff modeling system (PRMS) is used to estimate groundwater recharge distribution in the Halton-Hamilton-Credit Valley study area. PRMS is a deterministic, distributed parameter modeling system developed to evaluate the impacts of precipitation, climate, and land cover/land use on streamflow, sediment yield, and general basin hydrology (Leavesley et al. 1983). The schematic diagram in Figure 5 shows how PRMS uses climate inputs (precipitation, temperature, and solar radiation) to simulate basin hydrology. In this case, groundwater recharge is the amount of water entering the groundwater reservoir, which equals the sum of groundwater discharge to lakes or streams (base flow) and groundwater sink.

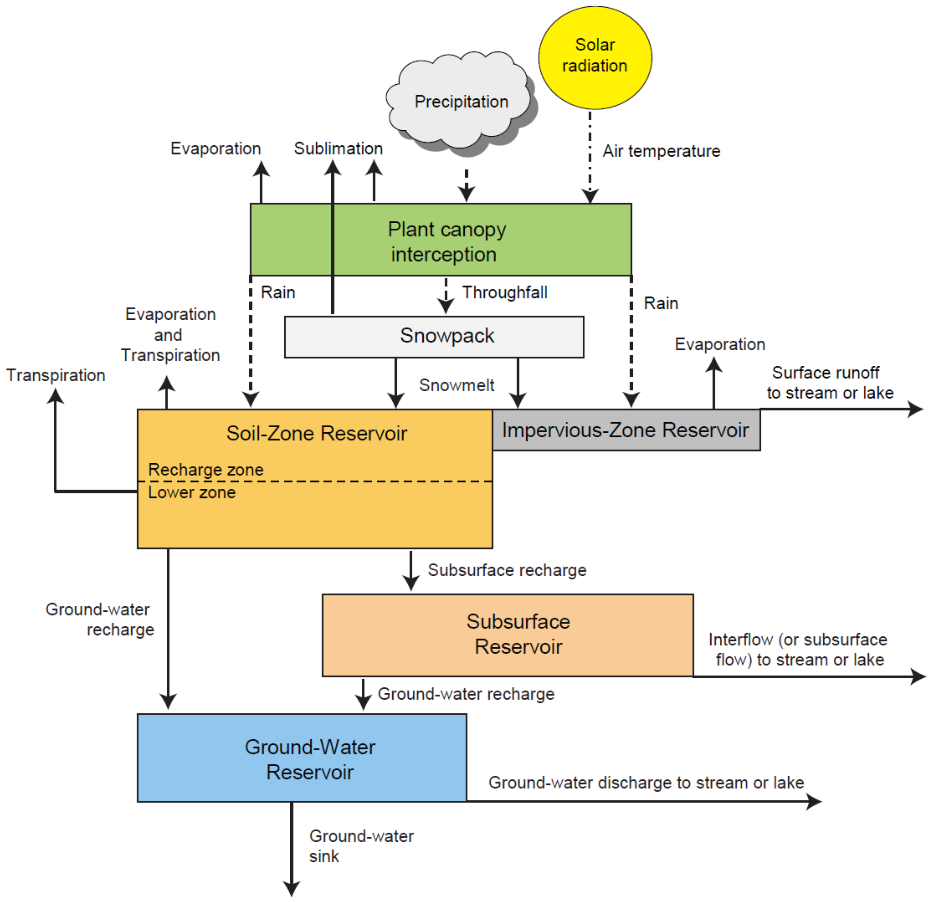


Figure (5): Schematic diagram of the precipitation-runoff modeling system (from Markstrom et al. 2008).

Cherkauer (2004) used PRMS and GIS to quantify groundwater recharge at multiple scales. It presented a procedure to define most inputs from GIS and hydrological inputs, which simplifies PRMS calibration by reducing the degrees of freedom. Vaccaro and Olsen (2007) used two models to estimate groundwater recharge to the Yakima River Basin aquifer system, Washington, USA for predevelopment and current land use/land cover conditions. The two models are PRMS and the Deep Percolation Model (DPM). The results show an increase in recharge between predevelopment and current land use/land cover conditions mainly due to the application of irrigation water to croplands. Burns et al. (2012) estimated recharge as part of evaluating long-term water-level declines in basalt aquifers near Mosier, Oregon, USA. PRMS was the primary method used to estimate recharge over the entire study area. RORA was used to estimate the long-term rate of recharge that returns to streamflow upstream of the gauging stations.

The methodology for estimating groundwater recharge using PRMS is illustrated in Figure 6, and can be summarized in the following steps:

1. HRU delineation: Hydrologic response units (HRUs) are assumed homogeneous with respect to hydrologic and physical characteristics such as drainage boundaries, land-surface altitude, slope, aspect, and many other characteristics (Markstrom et al. 2008). In this study, HRU delineation was performed by processing the DEM using Arc Hydro tools in ArcGIS (Maidment 2002). The desired spatial scale of groundwater estimation dictates the number of HRUs in the study area.
2. PRMS parameterization: In this step, attributes from the DEM, soil map, and land use/land cover map were distributed over the HRUs delineated in step1. The distribution was performed using ArcGIS capabilities. At this point, the PRMS Parameter File can be created by using these attributes as the values of corresponding PRMS parameters. The reset of parameters were kept at default values to be changed later in the calibration process if needed.
3. Data File preparation: Daily climatic data (T_{min}, T_{max}, and precipitation) from the 7 Environment Canada climate stations (Figure 3), in addition to observed daily streamflow from the 11 gauge stations (Figure 3) are arranged in the PRMS Data File.
4. Control File preparation: This is the file used to specify model input and output file names, simulation starting and ending dates, selected modules (for precipitation, temperature, solar radiation, and evapotranspiration), and output options.

5. PRMS calibration: The values of parameters controlling the rate of movement of water from the subsurface to the groundwater reservoir (Figure 5), from the subsurface and groundwater reservoirs to the steam, and from the groundwater reservoir to the groundwater sink, were adjusted within recommended bounds (Markstrom et al. 2008). The values of the parameters were set based on the comparison between simulated and observed streamflow. A multiple-objective, stepwise, automated procedure called Luca (Hay and Umemoto 2006; Hay et al. 2006) was utilized for calibration. Luca uses the Shuffled Complex Evolution global search algorithm.
6. PRMS results: After calibrating and running the PRMS model, recharge for each HRU was estimated as the sum of groundwater discharge to lakes or streams (base flow) and groundwater sink (Figure 5).

An independent estimate of recharge in the gauged basins was provided by analysis of streamflow hydrographs using the computer programs RECESS and RORA by Rutledge (1998; 2000; 2007). The procedure is based on the recession-curve displacement method introduced by Rorabaugh (1960; 1964), and hence the name of the program (RORA). The method is based on the premise that the streamflow recession curve is displaced upward during periods of groundwater recharge. Figure 7 summarizes the methodology, which starts by analysing the streamflow time series by the computer program RECESS to determine the recession index (K) (time per log cycle of streamflow recession) for each gauged basin. The next step is to use these K values and the streamflow time series in the computer program RORA to estimate mean annual groundwater recharge in each gauged basin.

Lee et al. (2006) used RORA coupled with a water-balance approach to estimate long term mean annual groundwater recharge of Taiwan. The results show that the contours of long term mean annual groundwater recharge are well matched with the topographical distribution of Taiwan. Delin et al. (2007) estimated groundwater recharge in Minnesota, USA using RORA, which is a basin scale method, and 3 local scale methods: unsaturated zone water balance, water table fluctuations, and age dating of groundwater. Lorenz and Delin (2007) used recharge estimates from RORA in developing a regional regression model to estimate the spatial distribution of groundwater recharge in sub-humid regions.

As shown in the above methodology, the data needed for both methods (DEM, soil maps, land use maps, daily climatic data, and streamflow readings) is becoming readily available nowadays from national and international database, especially with the Recent advances in GIS and remote sensing technology as mentioned earlier. The availability of this level of required data indicates the possibility of applying this methodology in different areas of the world.

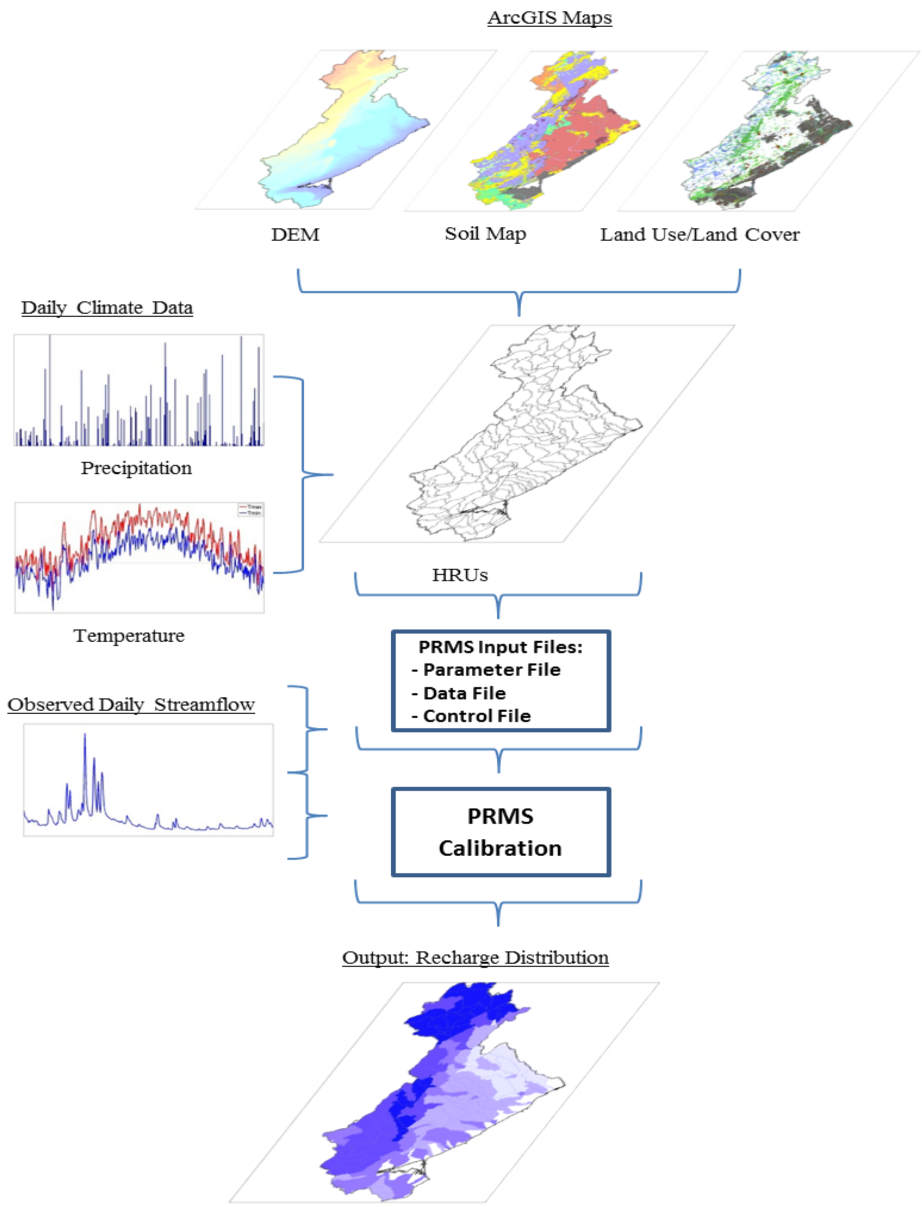


Figure (6): Methodology for estimating recharge using PRMS

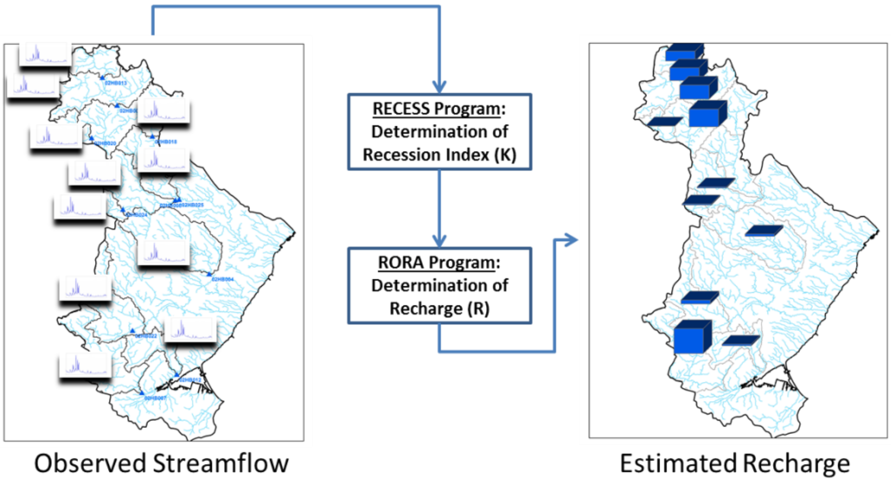


Figure (7): Methodology for estimating recharge using RORA method

4. Model Calibration

Following the methodology discussed above, the study area was delineated into 130 HRUs. These HRUs were parameterized using available data from the maps in Figures 2-4 to generate the parameter file. After that the data file was generated by arranging the daily climatic data from the climate stations and the observed daily streamflow data from the streamflow gauges. The control file was generated by entering the needed information and options.

The only available data for calibration is streamflow from streamflow gauges. Five sub-basins where delineated by Arc Hydro based on the gauge location (Figure 8). Since gauges 02HB013, 02HB001, 02HB020, 02HB018, 02HB008, and 02HB024 are upstream of gauge 02HB025, they were all considered in one sub-basin.

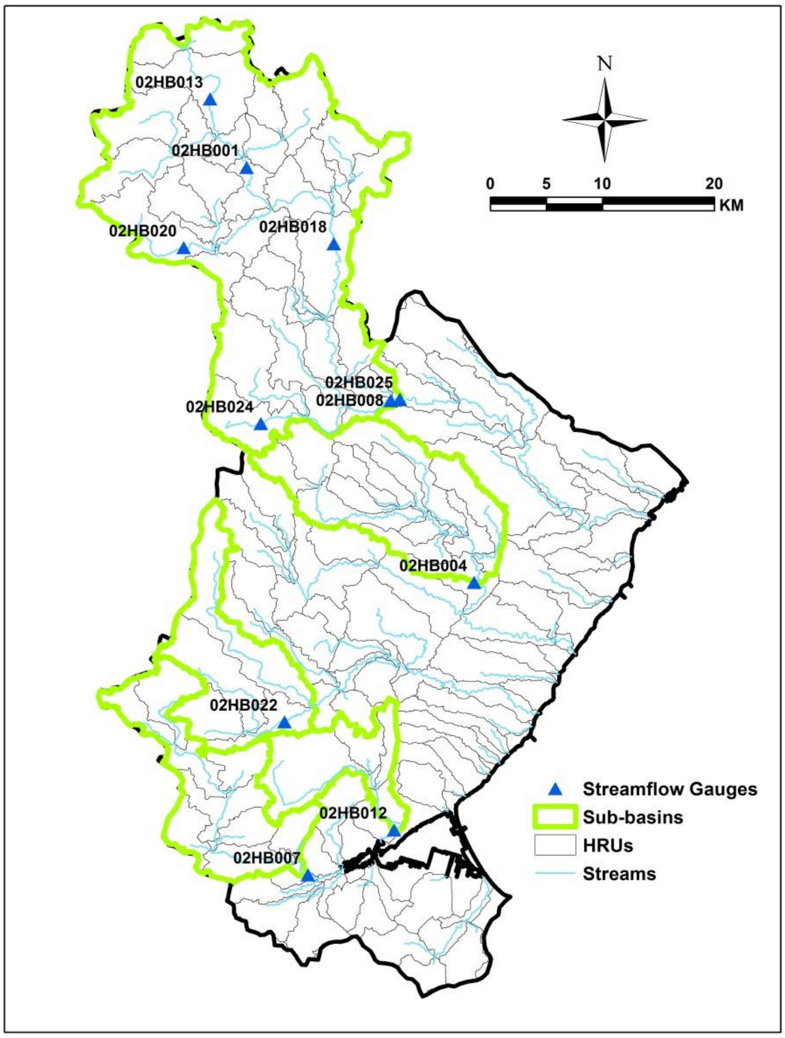


Figure (8): Location of sub-basins used for PRMS calibration.

A multiple-objective, stepwise calibration scheme was used to calibrate PRMS to each sub-basin. For this study, 2 steps were used in the calibration procedure:

Step1-Water Balance

In this step we used annual mean (one average of daily values over all months in the period per year), monthly mean (one average of daily values over one month per each month in the period), and mean monthly (one average of daily values for a given month over entire record per each month in the period) runoff. The parameters which were adjusted in this step are mainly those related to rain and snow adjustment.

The step 1 objective function (OF_1 in Eq. 1) is the weighted sum of 3 objective functions: OF_{ann}, OF_{mon_mean}, and OF_{mean_mon}

$$OF_1 = 0.33 \times OF_{ann} + 0.33 \times OF_{mon\_mean} + 0.33 \times OF_{mean\_mon} \quad (1)$$

where OF_{ann} is the annual objective function, OF_{mon_mean} is monthly mean objective function, and OF_{mean_mon} is the mean monthly objective function.

OF_{ann}, OF_{mon_mean}, and OF_{mean_mon} were computed as absolute difference (ABS in Eq. 2). The objective is to minimize ABS.

$$ABS = \sum_{n=1}^{ntotal} abs((OBS_n - SIM_n)/OBS_n) \quad (2)$$

where OBS are the observed values and SIM are the simulated values.

Step2-Runoffs

In this step we used daily and monthly mean runoff. The parameters which were adjusted in this step are mainly those controlling the rate of movement of water from the subsurface to the groundwater reservoir (Figure 5), from the subsurface and groundwater reservoirs to the steam, and from the groundwater reservoir to the groundwater sink.

The step 2 objective function (OF_2 in Eq. 3) is the weighted sum of 2 objective functions: OF_{daily}, and OF_{mon_mean}

$$OF_2 = 0.7 \times OF_{daily} + 0.3 \times OF_{mon\_mean} \quad (3)$$

where OF_{daily} is the daily objective function. As noted in Eq. 3, larger weight is given to OF_{daily}, since the daily flows represents the physical response of the catchment more than the aggregated monthly mean flows.

OF_{daily}, and OF_{mon_mean} were computed as Nash-Sutcliffe Efficiency (E in Eq. 4). The objective is to maximize E which ranges from -∞ to 1. A value of one indicates a perfect fit between OBS and SIM, whereas a value of zero indicates that the model fits as good as the mean observed value.

$$E = 1.0 - \sum_{n=1}^{ntotal} (OBS_n - SIM_n)^2 / \sum_{n=1}^{ntotal} (OBS_n - OBS_{mean})^2 \qquad (4)$$

Where OBS_{mean} is the average of the observed values.

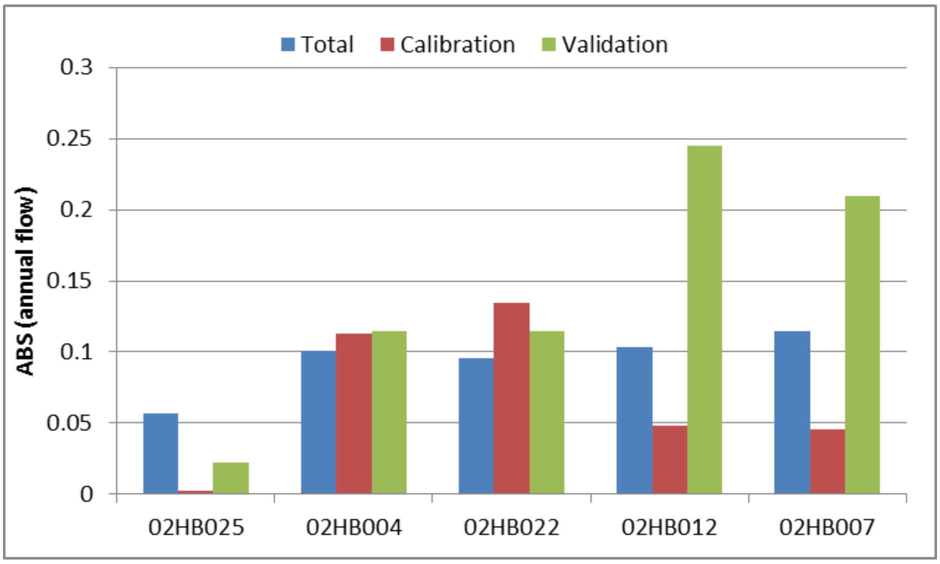
5. Results and Discussion

After examining the streamflow gauges records, we found that there is a continuous period of data from 1990 to 2010. The first year was used for model initialization. Years 1991 to 2000 were used for model calibration. The last period (2001-2010) was used for validation.

Figure 9 shows the model performance in the five sub-basins. As shown in the figure, the model performed better in terms of water balance in sub-basin 02HB025. The best performance for daily flows was in sub-basin 02HB012. Overall, Figure 9 indicates that the model performed better in the calibration period, although the performance in the validation period was satisfactory as well. Figure 10 indicates a good match between the time-series of the observed and simulated streamflow for sub-basin 02HB025.

Due to the lack of observed streamflow data for the areas outside of the five sub-basins (Figure 8), the same sets of calibrated parameters applied to the neighbouring gauged sub-basins where applied to these areas. Figure 11shows the distribution of annual recharge as simulated by PRMS for the years 1991 to 2010.

An independent estimate of recharge was provided by analysis of streamflow hydrographs using RORA method. This method gives one value of recharge for each gauged sub-basin. For comparison, PRMS estimates of recharge were averaged over the five sub-basins. The results are shown in Figure 12 which shows big difference in the two estimates. The difference may be attributed to fundamental difference in the definition of recharge between RORA and PRMS (Burns et al. 2012). RORA derives recharge from each peak in the streamflow hydrograph, while PRMS does not include subsurface flow from individual storms.



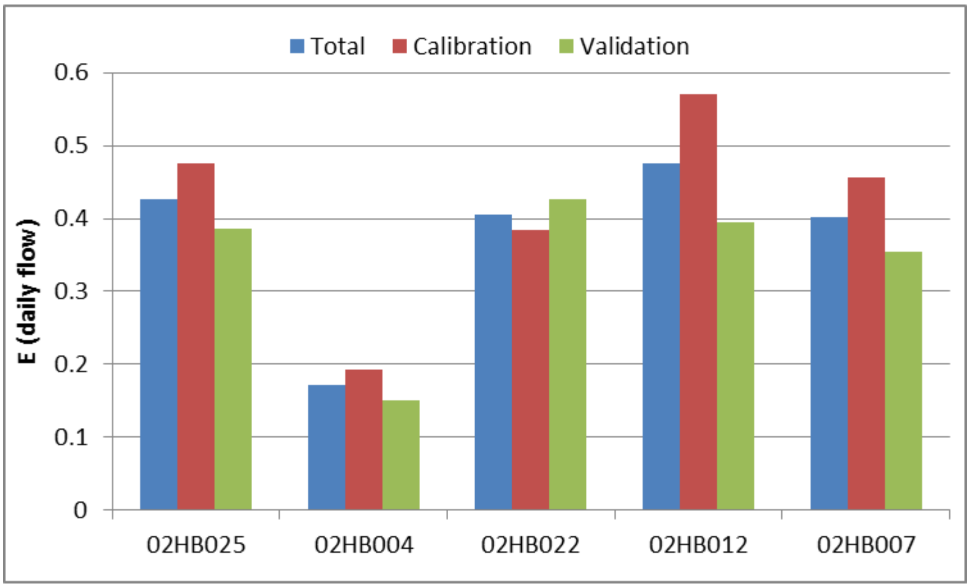


Figure (9): ABS values (top) and E values (bottom) for the 5 sub-basins. Blue bars are for the entire period, red bars are for calibration period, and green bars are for validation period.

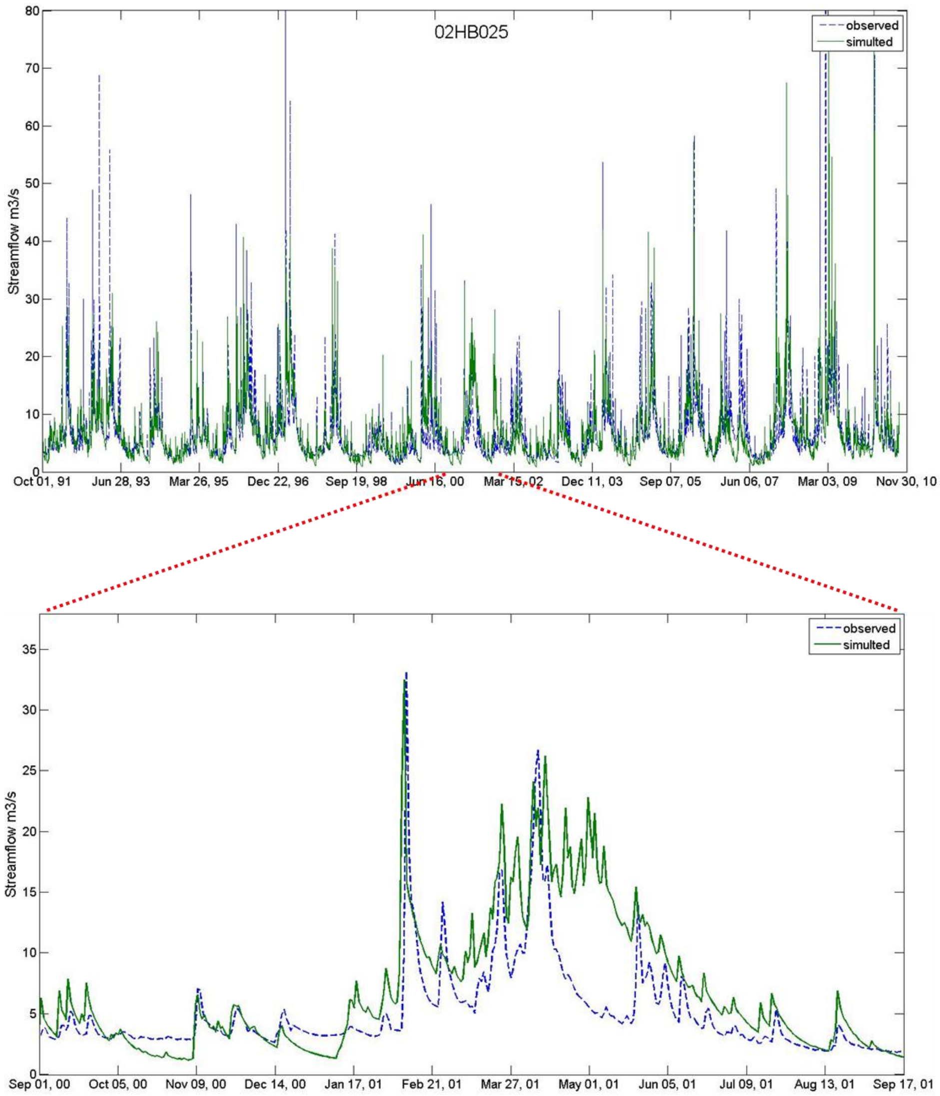


Figure (10): Observed vs. simulated streamflow for sub-basin 02HB025.

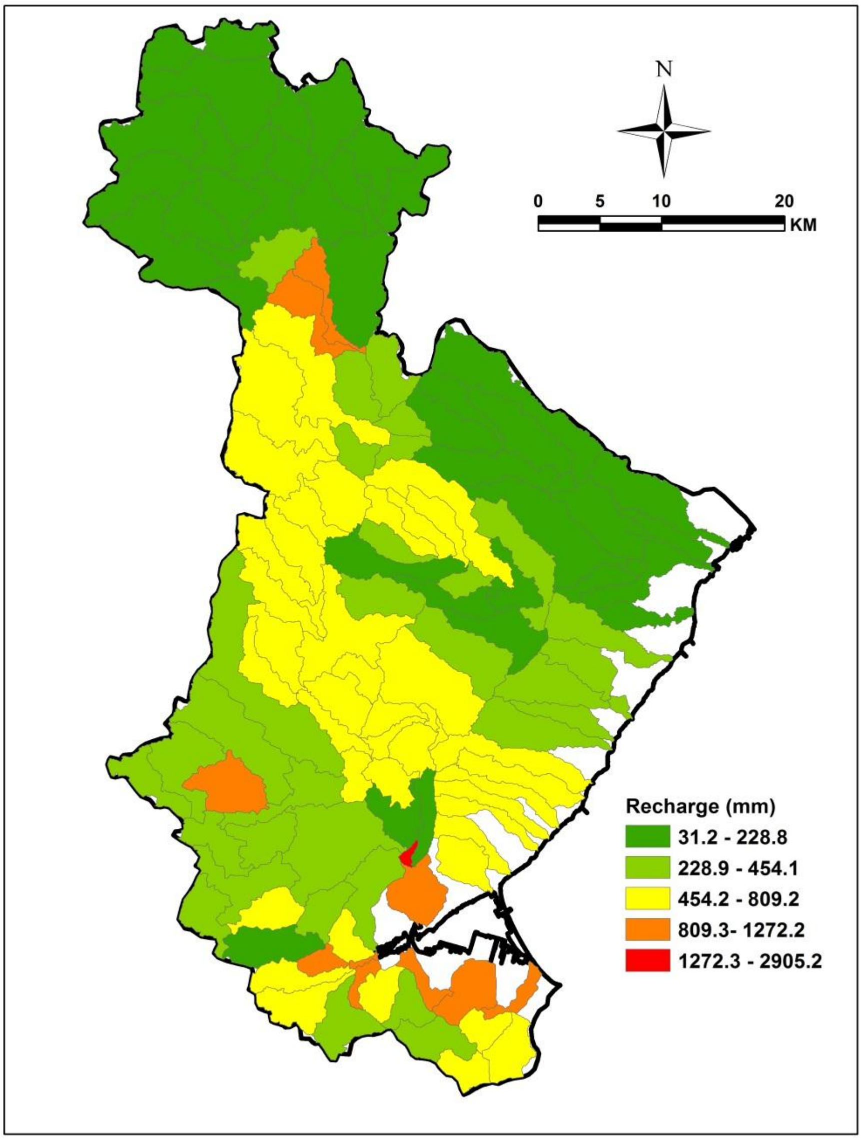


Figure (11): PRMS simulated annual recharge for the period 1991-2010.

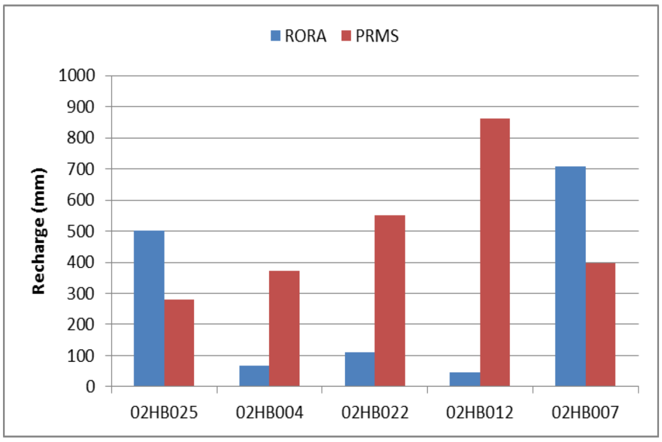


Figure (12): Comparison between PRMS and RORA estimates of recharge.

6. Conclusions

Groundwater recharge estimation is an essential part of efficient water resources management. Choosing the best method for recharge estimation is highly dependent on the objectives of recharge estimation, spatial and temporal scales, availability of data, and the available resources in terms of time and expense. For the purpose of groundwater monitoring network design, spatial distribution of groundwater recharge is important. PRMS, which is a distributed watershed model, was utilized to estimate spatial distribution of recharge in a study area in southern Ontario, Canada. The model was parameterized with available data on climate, geomorphology (including topography, soil, and vegetation), and geology. It was calibrated with streamflow data in the period 1991-2000, and validated in the period 2001-2010. The results show good performance of the model in both, calibration and validation periods. An independent estimate of recharge was provided by a recession-curve displacement method called RORA. Large differences were found in recharge estimates from the two methods due to fundamental differences in recharge definition. PRMS results should be considered for groundwater monitoring network design due to two reasons: (i) it can provide spatial distribution of recharge while RORA can't, and (ii) the conceptual model of PRMS is more representative of the physical processes than RORA.

Acknowledgment

This research was funded by the Mcmaster Water Resources and Hydrologic Modeling Lab, Hamilton, ON, Canada, and by Dr. Paulin Coulibaly.

References

- AquaResource, Inc. (2009). *Integrated water budget report – Tier 2, Credit Valley source protection area*. Prepared for Credit Valley Conservation Authority. Available at: http://www.ctcswp.ca/technical-documents-credit-valley-source-protection-area.html.
- Bicknell, B. R., Imhoff, J. C., Kittle, J. L., Donigan, A. S., & Johanson, R. C. (1997). *Hydrologic simulation program—Fortran, user's manual for version 11*. (EPA/600/R-97/080). Athens, GA: US EPA, Ecosystems Research Division, Environmental Research Laboratory.
- Brown, D.M., McKay, G.A., & Chapman, L.J. (1974). *The climate of southern Ontario*. Climatological Studies Number 5, Environment Canada, Atmospheric Environment Services, En57-7/5.
- Bouwer, H. (2002). Artificial recharge of groundwater: hydrology and engineering. *Hydrogeology Journal*, 10:121-142
- Burns, E.R., Morgan, D.S., Lee, K.K., Haynes, J.V., & Conlon, T. D. (2012). *Evaluation of long-term water-level declines in basalt aquifers near Mosier, Oregon*. U.S. Geological Survey Scientific Investigations Report 2012–5002, 134 p.
- Cherkauer, D. S. (2004). Quantifying ground water recharge at multiple scales using PRMS and GIS. *Groundwater*, 42(1), 97-110.
- De Vries, J. J. & Simmers, I. (2002). Groundwater recharge: an overview of processes and challenges. *Hydrogeology J.*, 10, 5-17.
- Delin, G. N., Healy, R. W., Lorenz, D. L. & Nimmo, J. R. (2007)."Comparison of local- to regional-scale estimates of groundwater recharge in Minnesota, USA". *J. Hydrology*, 334, 231-249.
- Earthfx, Inc. (2010). Vulnerability assessment and scoring of wellhead protection areas, city of Hamilton, Ontario. *Final reportprepared for the city of Hamilton public works department*, environmental and sustainable infrastructure division. Available at:

http://www.protectingwater.ca/uploads/Hamilton%20Vulnerability%20Report%20v32 finalcompresssecured.pdf.

- Hay, L. E., Leavesley, G. H., Clark, M. P., Markstrom, S. L., Viger, R. J. & Umemoto, M. (2006). Step wise, multiple objective calibration of a hydrologic model for a snowmelt dominated basin. *J. American Water Resources Association*, 42 (4), 877-890.
- Hay, L. E. & Umemoto, M. (2006). Multiple-objective stepwise calibration using Luca. U.S. Geological Survey Open-File Report 2006–1323, 25 p.
- Knisel, W. G. (1980). *CREAMS: a fieldscale model for chemical, runoff, and erosion from agricultural management systems*. USDA, Science and Education Administration, Conservation Report No. 26, Washington, D.C.
- Leavesley, G. H., Lichty, R.W., Troutman, B. M. & Saindon, L. G. (1983). *Precipitation-runoff modeling system: user's manual*. U.S. Geological Survey Water-Resources Investigation Report 83–4238.
- Lee, C. -H., Chen, W. -P. and Lee, R. –H. (2006). Estimation of groundwater recharge using water balance coupled with base-flow-record estimation and stable-base-flow analysis. *Environmental Geology*, 51, 73-82.
- Lesage, W. G. (2005). *Groundwater quality in Canada: a national overview*. Bringing groundwater quality research to the watershed scale (proceedings of GQ2004, the 4th international groundwater quality conference, held at Waterloo, Canada, July 2004). IAHS Publ. 279.
- Lorenz, D. L. & Delin, G. N. (2007). A regression model to estimate regional groundwater recharge. *Groundwater*, 45(2), 196-208.
- Maidment, D. R., ed., (2002). *Arc Hydro: GIS for Water Resources*. ESRI Press, Redlands, Ca.
- Markstrom, S. L., Niswonger, R.G, Regan, R.S., Prudic, D. E. & Barlow, P. M. (2008). *GSFLOW – coupled groundwater and surface-water flow model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005).*U.S. Geological Survey Techniques and Methods 6-D1, 240.

- Ontario Geological Survey (2011). *1:250 000 scale bedrock geology of Ontario*. Ontario Geological Survey, Miscellaneous Release–Data 126 - Revision 1.
- Ontario Ministry of Natural Resources. (2012). *Soil survey complex* Land Information Ontario, data description.
- Ontario Ministry of Natural Resources. (2008). *Southern Ontario Land Resources Information System (SOLRIS)*. version 1.2.
- Ontario Ministry of Natural Resources. (2006). *Digital elevation model (DEM) – provincial tiled dataset*. version 2.0.0.
- Rorabaugh, M.I. (1960). Use of water levels in estimating aquifer constants in a finite aquifer"*International Association of Scientific Hydrology,* Commission of Subterranean Waters, 52, 314–323.
- Rorabaugh, M. I. (1964). Estimating Changes in Bank Storage and Groundwater Contribution to Streamflow. *International Association of Scientific Hydrology*, 63, 432–441.
- Rutledge, A. T. (1998). *Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflowdata-update*. U.S. Geological Survey Water-Resources Investigation Report 98–4148, 43 p.
- Rutledge, A. T. (2000). *Considerations for the use of the RORA program to estimate ground-water recharge from streamflow records*. U.S. Geological Survey Open-File Report 00–156, 44 p.
- Rutledge, A. T. (2007). Update on the use of RORA program for recharge estimation. *Groundwater*, 45(3), 374-382.
- Scanlon, B. R., Healy, R. W. & Cook, P. G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology J.*, 10, 18-39.
- United States Geological Survey (USGS)(2013). *Methods for estimating groundwater recharge in humid regions*. http://water.usgs.gov/ogw/gwrp/methods/. Accessed April 19, 2013
- Vaccaro J.J., & Olsen, T.D. (2007). *Estimates of ground-water recharge to the Yakima River Basin aquifer system, Washington, for predevelopment and current land-use and land-cover conditions*. U.S. Geological Survey Scientific Investigations Report 2007-5007, 30 p.