APPLICATION OF NUMERICAL MODELING TO GROUNDWATER ASSESSMENT AND MANAGEMENT IN PRINCE EDWARD ISLAND

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ABSTRACT

Numerical groundwater flow models are developed for selected watersheds to examine the physics and dynamics of groundwater flow and evaluate existing groundwater management policy in Prince Edward Island (PEI). The simulations faithfully reproduce the observed behaviors with respect to the timing and magnitude of fluctuations in water level and stream flow discharges. The analysis indicates that under current the groundwater management regime, local groundwater concerns are adequately addressed, and aquifer dewatering is unlikely to occur, however the protection of aquatic habitat may require more sophisticated and possibly more stringent groundwater management approaches.

RÉSUMÉ

Des modèles numériques d'écoulement d'eaux souterraines sont mis au point pour la ligne de partage de certaines eaux choisies afin d'étudier la physique et la dynamique des eaux souterraines, et d'évaluer la politique de gestion actuelle des eaux souterraines à l'Île-du-Prince-Édouard (Î.-P.-É.). Les simulations en ce qui a trait à la synchronisation et à l'importance des fluctuations du niveau d'eau et du débit d'eau reproduisent fidèlement les comportements observés. L'analyse montre que sous le régime de gestion des eaux souterraines actuel, on répond bien aux préoccupations locales à propos des eaux souterraines, et il ne devrait pas se produire de déshydratation de la couche aquifère; toutefois, la protection de l 'habitat aquatique exigerait des méthodes de gestion des eaux souterraines plus complexes et peut-être plus rigoureuses.

1. INTRODUCTION

Groundwater is the sole source for the potable water supply as well as for the vast majority of the industrial supply in Prince Edward Island (PEI). In addition, base flow contributes significantly to freshwater stream flow and as a consequence, the withdrawal of groundwater can also impact aquatic habitat. The potential for growing demand from municipal, industrial and agricultural uses for groundwater has raised questions regarding the sustainability of the Province's groundwater resources and the adequacy of existing groundwater management policies.

The approach used for the assessment of high capacity wells in PEI has focussed primarily on a case-by-case evaluation of effects on local water table conditions, generally, considered to be those affects occurring within 500 metres of the well. While this procedure provides a reliable assessment of local impacts, it is not particularly amenable to evaluation of the combined impact of multiple wells on a watershed scale. Furthermore, while this approach recognizes the potential impact of pumping on surface water resources in a semi-quantitative manner, it does not permit a rigorous, quantitative evaluation of surface water/groundwater interaction.

In response to these concerns, the Department of Environment and Energy undertook a comprehensive review of the Province's hydrogeological regime and the influence of high capacity wells on local water table conditions and on stream flow conditions. The study includes a review and assessment of available hydrogeological and hydrometric data and current water use patterns, and detailed groundwater flow modelling for three selected watersheds. Mill River Watershed (Mill R.W.), Wilmot River Watershed (Wilmot R.W.) and Winter River Watershed (Winter R.W.), which represent the range of physical and water demand circumstances relevant to the current discussion, are simulated (See Figure 1). The ultimate objective of this work is to establish sustainable levels of groundwater extraction and recommend appropriate water management policies for the long-term protection of water resources in PEI. This document focuses on technical issues and is not intended to address policy considerations or specific regulatory or statutory requirements. The following aspects from this work are presented:

- Model development, calibration and verification
- Groundwater resource assessment
- Assessment of impacts on water table and stream flow due to groundwater extractions
- Evaluation of existing groundwater management policy with respect to protecting aquatic habitat

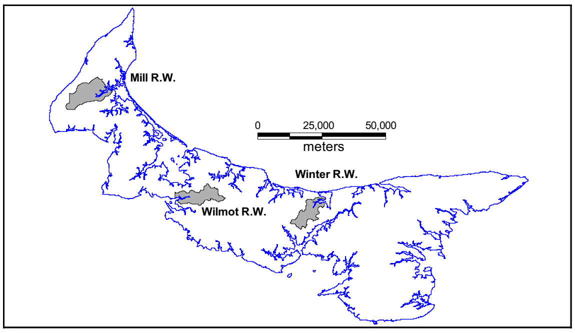

Figure 1. Locations of simulated watersheds in PEI

2. GEOLOGYAND PHYSICAL HYDROGEOLOGY

Prince Edward Island is underlain by a red bed sandstone formation. The uppermost portion of this bedrock formation forms a fractured-porous aquifer. The bedrock formation with thickness exceeding 850 m consists of a sequence of Permo-Carboniferous red beds ranging in age from Carboniferous to Middle Early Permian (van de Poll, 1983). Sandstone is the dominant rock type with a texture ranging from very fine to very coarse. Regionally, the bedrock is either flat lying or dips gently to the east, northeast, or north. There has been little structural deformation of the bedrock; however, steeply dipping joints in excess 75° are common (van de Poll, 1983). The bedrock is covered with a thin veneer (1-5 m) of glacial deposits. This overburden is primarily basal till of local origin, and covers approximately 75% of the island.

The aquifer is fractured with significant fracture permeability. It also has an intergranular porosity. Fractures decrease in both number and aperture with depth, and, as a result, the bulk hydraulic conductivity of the aquifer decreases with depth by an order of magnitude for each 60 m (Francis, 1989). From the viewpoint of water supply, the permeability of the bedrock reduces to near negligible levels at depth over 160 m. Horizontal layering of the aquifer along with the predominance of horizontal bedding plane fractures results in a stratified aquifer with vertical component of hydraulic conductivity ranging from one to three orders of magnitude less than horizontal values (Francis, 1989). Well yields are highly variable across the province and well yields ranging from 300 to 2000 m^3/d are common.

Mean annual precipitation in PEI is 1100 mm. Most part of the precipitation occurs as rain (80%) and the rest as snow. The aquifer receives precipitation recharge through the till or outcropped red beds, and discharges as base flow, evapotranspiration, coastline seepage and pumping withdrawal. Discharge mainly occurs along stream channels, fresh water wetlands and the coastline. GIS analysis shows discharge areas account for 3.4% of aquifer area. The regional water table mimics topography and groundwater shows obvious 3D flow pattern in higher areas and stream areas. The aquifer demonstrates rapid hydraulic response to recharge stress because of infiltration. Generally a major recharge event due to snow melting occurs in April followed by a recession throughout the summer and early fall. A second recharge event often occurs in October or November with fall rains and lack of evapotranspiration.

Stream-aquifer interaction is one of the key processes governing groundwater flow pattern in a watershed. Streams and their tributaries receive groundwater discharge through seeps and springs along most segments in a watershed. Through water balance analysis Francis (1989) reported base flow accounts for about 80% of stream flow in the late summer and fall months of many years in a typical Prince Edward Island watershed. Stream length varies from hundreds of meters to 20 km. Stream width ranges from about 0.1 m at the head and 30 m at estuary segment. Streambeds are typically comprised of a mixture of sand, silt, and clay. Seepage meter measurements in the Winter R.W. (Francis, 1989) showed vertical hydraulic gradient exists within the streambed. The streambed, typical 1 to 1.5 m thick in the Winter R.W., acts as weakly permeable materials, reducing the hydraulic link between surface water and groundwater.

Currently, groundwater development in the Province is estimated at 1 to 3% of total recharge on annual basis. However in some heavily developed watersheds, such as the Winter R. W. and Barbara Weit, the combination of industry and municipal water uses approach to 20 to 50% of annual recharge.

3. GROUNDWATER FLOW MODELS

The Mill R.W., Wilmot R.W. and Winter R.W. are selected for modeling (see Figure 1) using Visual ModFlow. These watersheds represent a variety of hydrogeology, land use and water use in PEI. Modeling these typical watersheds sheds light on numerous watersheds (about 240) in PEI because the watersheds bear hydrogeological similarities. The Mill R.W., located in west of PEI, has a flat landscape and very low stream flow in the dry season. Both long-term groundwater level (1967-present) and stream flow (1962-present) measurements are available for model calibration in this watershed. The Wilmot R.W. is located in the west-central part of PEI. Seventy percent of the land is farmland and the potential water use for irrigation is high. Long-term stream flow measurements (1972-present) are available in the Wilmot R.W.. The Winter R.W. is located in the central of PEI. It represents heavily developed cases and has detailed hydrogeological data sets for model calibration and verification.

3.1 Hydrogeological conceptual model

The sandstone aquifer plus the saturated portion of the till is simplified as a heterogeneous, vertically anisotropic and three-dimensional laminar flow system. Groundwater divides are assumed following surface water divides. The model domains are extended to adjacent watersheds when groundwater divides are believed to be inconsistent with surface water divides. Sources and sinks, including precipitation infiltration, wells, stream/aquifer interaction and evaporation, are represented in the system.

3.2 Model discretization

The model domains are discretized into grid with spacing ranging from 25 to 120 m and vertically into three layers. The top altitude of Layer 1 is interpolated from 30 m by 30 m digital elevation map. The top and bottom elevations of each layer are determined by specifying uniform layer thickness. The thickness of Layers 1 and 2 varies from 20 to 40 m for the three models and the thickness of Layer 3 is 100 m. The total simulated thickness is 158 m. The layering is mainly designed to account for vertical gradual change of hydraulic parameters and 3D flow pattern. In the Wilmot and Winter R. W. models, Layer 1 is thicker than Layer 2 because available water level measurements represent open-hole value, which is approximately equal to averaging along the thickness of Layer 1. This vertical discretization will make most of the water level measurements comparable with the simulated values in Layer 1.

The temporal discretization consists of one-month stress period for time spans ranging from 3 to 8 years.

3.3 Model boundaries

Watershed boundaries surrounding the simulated watersheds are assumed as no-flow boundaries except when surface water divides are believed inconsistent with groundwater divides and the model domains extend to adjacent watersheds. The coastlines are specified constant head boundary with a head value of 0.0 m amsl, which only applies to the upper most model layer. At the tidal estuary areas the rivers are defined as third type boundary, which is simulated using the River Package of Visual ModFlow and applies only to the upper most layer. For this boundary, the river stage is set as 0.0 m amsl. The streambed is assumed 1 m thick and has a vertical hydraulic conductivity=2.8×10^{-5} m/s, which is the mean measured value from the Winter R.W. (Francis, 1989). Please note that the boundaries of the second and third model layers along the coastlines are assumed impermeable. This configuration approximates the effect of salt and fresh water interface.

3.4 Sources and sinks

Sources and sinks in the models include recharge due to infiltration of precipitation, evapotranspiration, stream-aquifer interaction and pumping stresses.

3.4.1 Recharge

Aquifer recharge rates on the island were reported to range between 30% and 40% of annual precipitation (Francis, 1989). These values were derived from watershed water budget analysis. There are no direct measurements, which can be readily used to determine annual distribution of this recharge within the water year.

The stream flow hydrographs at the gauging stations within the simulated watersheds are employed to estimate recharge and its temporal distribution. The base flow is assumed to represent the groundwater recharge and annual recharge rate is assumed approximately equal to base flow. The initial temporal distribution of the recharge is approximated by reference to stream discharge and where available observation data. Monthly recharge rates can then be determined by multiplying the total recharge rate to the temporal distribution percentage. Both the recharge rates and temporal distributions are again treated as default model entries and the values used in the models are finalized through calibrating model simulations to match separated base flow and water level observations.

3.4.2 Evapotranspiration

There may be no doubt that the matrix structure of the overburden and porous-fractured red beds in PEI maintains a capillary zone facilitating groundwater evapotranspiration. Unfortunately there are not measured data to evaluate evapotranspiration rate. Maximum groundwater evapotranspiration rate, known as the evapotranspiration rate when groundwater table is on or above ground surface, is required in ModFlow to calculate evapotranspiration loss. Mean evaporation from water surface (lake) is estimated 400.0 mm/yr. (calculated from "Class A Pan" data) in Truro, Nova Scotia and mainly occurs in summer (Vaughan and Somers, 1980). Using 400 mm/yr as mean evaporation from water surface in PEI, the maximum groundwater evapotranspiration rate is estimated at 245 mm/yr. This value is approximately considered as default maximum groundwater evapotranspiration rate. In the model groundwater evapotranspiration is assumed linear with water table elevation within the water table depth from 0 m to 3 m and groundwater evapotranspiration is evenly distributed in July, August and September.

3.4.3 Stream-aquifer Interaction

Stream-aquifer interaction is one of the major processes governing water balance and regional groundwater level configuration in PEI. The Stream Package with Visual ModFlow is employed to simulate the interaction process. The Stream Package, incorporated with stream routing, can compute stream stage and water balance in the stream channel. Dry stream segments caused by streamside pumping or surface water diversion can be simulated. Water exchange rate between the stream and aquifer is proportional to the difference between stream stage and groundwater table. This formulation well simulates the process of the stream-aquifer interaction in PEI.

The rivers as well as its tributaries are simulated using multiple segments. Stream width is read from the digital map (30 m by 30 m) or defaults to 2 m when it can't be identified from digital map. Streambed top and bottom elevations are evaluated from a digital elevation map with the assumption of streambed thickness=1.0 m. Seepage meter measurements performed in the Winter R.W. (Francis, 1989) showed mean streambed hydraulic conductivity is 2.4 m/d, which is assigned as the vertical hydraulic conductivity of streambed in this work.

3.5 Subsurface properties

Much work has been done to characterize the hydraulic parameters of the porous-fractured aquifer in PEI (Francis, 1989; Carr, 1969). It was found from recent modeling work by PEI Department of Environment and Energy that the upper most 58 m of the aquifer has a mean horizontal hydraulic conductivity of 3.5×10^{-5} m/s and the mean horizontal hydraulic conductivity from 58 m to 158 deep reduces to 1×10^{-6} m/s; vertical hydraulic conductivity, which is 2 orders smaller than horizontal values, is about 1×10^{-7} m/s. It should be noted that hydraulic conductivity is scale-dependent and these values apply to finite difference grid sizes ranging from 20 m to 150 m in horizontal direction and 5 m to 40 m in vertical direction. These values are used as initial model entries. Initial specific storage and specific yield values are set at 1×10^{-4} m^{-1} and 0.03-0.1 respectively. The used hydraulic parameters are to be finalized through model calibration.

3.6 Model calibration and verification

The models are calibrated using a trial-and-error process in which the initial estimates of model parameters are tuned to improve the match between simulated water levels, base flows and measured heads and separated base flows. The models are initially calibrated to steady state conditions and then transient state conditions. Selected hydrological windows, which span a period of 2 to 7 years and ideally include the lowest monthly stream flows, are specified as transient conditions. If the models reproduce recorded hydrological series within acceptable error levels, the models are considered calibrated.

3.6.1 Steady state calibration

Hydraulic conductivities are finalized through steady state calibration. The hydraulic conductivities used in the models should ensure the models well respect mean regional water level configuration and base flow measurements. One obstacle for steady state calibration is that the available water level measurements are not enough to characterize the regional mean water level configuration in the Mill and Wilmot river watersheds. Groundwater outcrops, such as fresh water ponds and small streams etc., represent local water levels and are approximately considered as steady state water level measurements. The water levels of these points are approximately set at ground elevations and are directly read from the digital elevation map.

The fit between measured and calculated water levels are showed in Figures 2. Root mean squared errors (RMS) for the fit are summarized in Table 1. The simulated heads are within 2.2 to 3.4 m of measured water levels and the maximum normalized RMS is 8.4%. It should be noted that the measured water levels represent transient water level and the simulated water levels are steady state values. If one intends to make a strict comparison between the measured and simulated water levels, 2 to 4 m fluctuations should be added to the measured water levels. The fluctuations are approximately equal to the RMS values. This fact indicates a very good fit between the measured and simulated values. Table 1 also illustrates that the simulated base flows match the separated values very well. Used model parameters are tabulated in Table 2.

3.6.2 Transient state calibration

Specific storage (storativity), specific yield and temporal distribution of recharge are finalized through matching measured water levels and separated base flows within selected hydrological windows. Both boundary conditions and stream parameters are assumed time independent. One concern is how to determine the initial condition, namely the water level field at the starting point of the simulated window. There are insufficient observed data to characterize the initial water level fields. Initial condition for transient simulation is generated through simulating a yearly hydrological window with monthly mean recharge following the steady state. This simulation is checked against monthly mean water levels and separated base flows. The simulation for the first years of the selected window will not start until good water level and base flow fit is reached for the mean year simulation. From this point the temporal distribution of recharge rates and specific storage and specific yield are tuned so that both simulated water levels and base flows match the measured values very well. The simulated hydrological windows for the Mill, Wilmot and Winter river watersheds are 1996-2001, 1995-2001 and 1984-1988 respectively. To use up-to-date hydrometric and groundwater withdrawal data the Winter R.W. model is also calibrated against the hydrological series of 2000-2001.

The fit of water levels and base flows is illustrated in Figure 3 and Figure 4 respectively. There are 8 long-term water level monitoring wells in the Winter R.W. in the 1980s and only the fit of the Airport Well is presented for illustration purpose due to limited space. The model yields similar simulated effects for the rest observations. A glance at these figures one can see the models produce very good fits both for water level and for base flow measurements. Storativity parameters used in the models are also summarized in Table 2.

3.6.3 Model verification

The models are verified where independent data are available. The Wilmot R.W. model is verified against water level measurements, which were obtained in the summer of 2003. Figure 2B shows comparison between measured (verification) and simulated water levels. Allowing seasonal fluctuations of 3~4 m for the measurements, one can see the simulated heads compare favourable to the independent measurements.

The Winter R.W. model is examined against stream flow observations at Union gauging station, which is located approximately 8.0 km upstream of Suffolk gauging station where hydrometric data are used for calibration. The stream flow records of Union station are independent data set. One problem for this verification is the model is only calibrated to simulating the base flow processes of multi-year mean, 1984-1988 and 2000-2001, and the Union gauging station has stream flow data of 1992-1999 when this work is done. Timing inconsistency does not allow a year-by-year verification. Because the pumping rates only increased by 0.024 m^3/s (=18.9%) from 1988 (10900 m^3/d) to 1999 (=12968 m^3/d) in the Winter R.W. above Union gauging station, multi-year mean stream flows for the two periods of time are approximately comparable. Figure 5 shows the calculated base flow matches the separated base flow very well. The visible deviations of January to June could be derived from error of base flow separation and inaccurate initial condition.

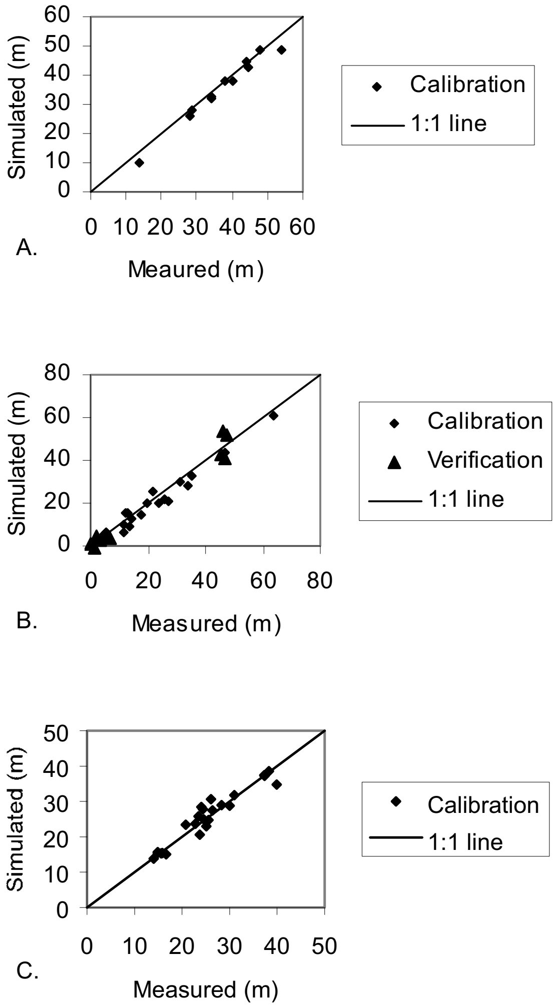

Figure 2. Simulated and measured water levels (steady state) for: A. Mill R.W., B. Wilmot R.W. and C. Winter R.W.

Table 1. Comparison of simulated and measured data (steady state)

Watershed	Mill	Wilmot	Winter
RMS (head, m)	2.28	3.4	2.2
Normalized RMS (head)	5.7%	5.7%	8.4%
Separated base flow (m^3/s)	0.61	0.61	0.46
Simulated base flow (m^3/s)	0.61	0.57	0.38

3.7 Sensitivity analysis

The simulated base flow and water level processes are found to be most sensitive to the change of S_y (specific yield) during model calibration. Sensitivity analysis is performed to demonstrate the effect of S_y for the case of the Mill R.W.. A range of S_y is tested through fixing all other parameters. Comparisons between measured and simulated base flow and water level are summarized in Table 3.

Table 2. Model parameters

Parameter	Watershed	Layer 1	Layer 2	Layer 3
K_x=K_y (m/s)	Mill	3.5×10^{-5}	3.3×10^{-5}	1.0×10^{-6}
	Wilmot	3.1×10^{-5}	2.8×10^{-5}	1.0×10^{-6}
	Winter	$1.5\sim7.0\times10^{-5}$	3.0×10^{-5}	1.0×10^{-6}
K_z (m/s)	Mill	1.0×10^{-7}	1.0×10^{-7}	1.0×10^{-7}
	Wilmot	1.0×10^{-7}	1.0×10^{-7}	1.0×10^{-7}
	Winter	1.0×10^{-7}	1.0×10^{-7}	1.0×10^{-7}
Specific storage (m^{-1})	Mill	-	1.0×10^{-4}	1.0×10^{-4}
	Wilmot	-	1.0×10^{-4}	1.0×10^{-4}
	Winter	-	1.0×10^{-4}	1.0×10^{-4}
Specific yield	Mill	0.04	-	-
	Wilmot	0.05	-	-
	Winter	0.06	-	-
Thickness (m)	Mill	29.0	29.0	100.0
	Wilmot	40.0	18.0	100.0
	Winter	44.0	14.0	100.0

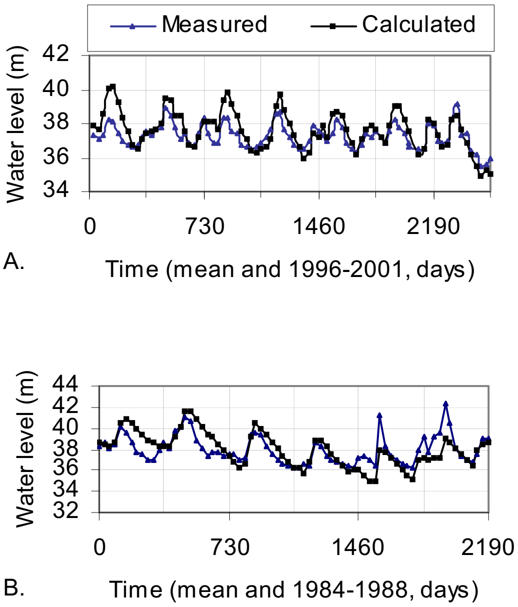

Figure 3. Simulated and measured water levels (transient): A. Bloomfield, Mill R.W. and B. Airport, Winter R.W.

One can see from Table 3 the base case represents the best S_y estimation in terms of both head and base flow matches.

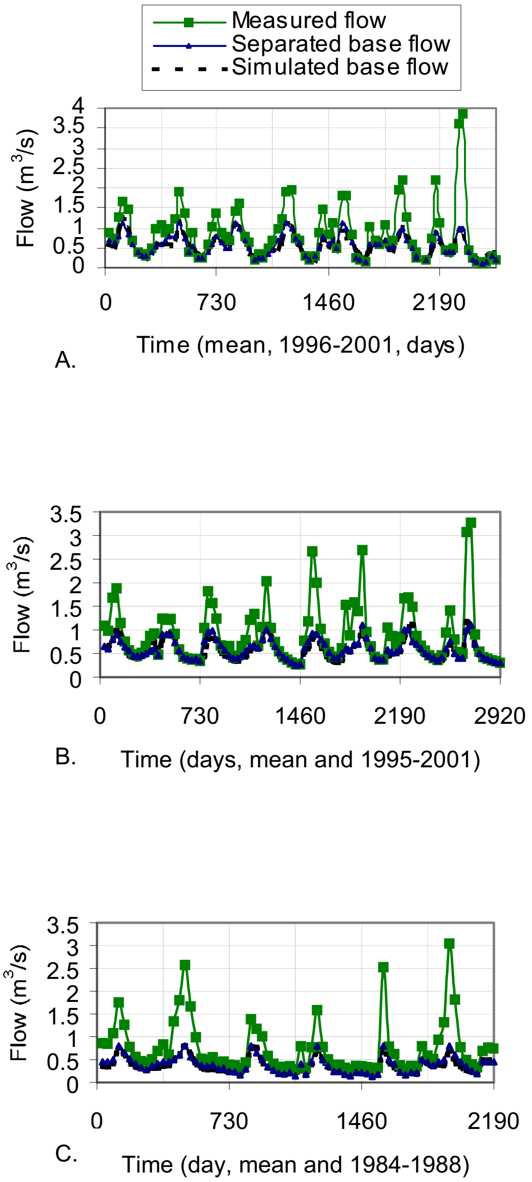

Figure 4 Simulated and separated base flows: A. Mill R.W., B. Wilmot R.W., and C. Suffolk, Winter R.W.

Table 3. Results of Sensitivity analysis of Mill R.W. Model

S_y	0.4	0.05	0.04 (base)	0.03	0.01
RMS (head)	0.789	0.605	0.738	0.833	1.753
RMS (base flow)	0.178	0.101	0.095	0.093	0.129

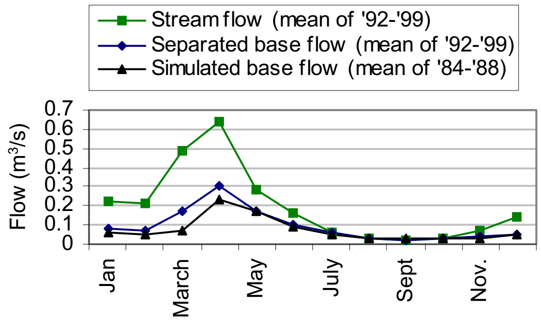

Figure 5. Comparison between simulated and separated base flows at Union, Winter R.W.

4. MODEL APPLICATIONS

4.1 Application to groundwater assessment

The calibrated models are utilized to conduct water budget analysis based on steady state simulations for the simulated subwatershed areas above the gauging stations. The results are listed in Tables 4-6.

Simulations indicate the mean recharge rates are 400, 400 and 450 mm/yr. in Mill, Wilmot and Winter river watersheds respectively, which represent 36~40% of mean annual precipitation (=1100 mm/yr.). Annual recharges vary from 200 to 500 mm/yr depending on annual precipitation and its temporal distribution. Figure 5 illustrates a comparison between calibrated monthly recharge rates and precipitations over time for the multi-year mean condition in the Winter R.W.. The figure indicates recharge of April exceeds precipitation within the month. The carried-over snow from previous months compensates for the difference. The recharge processes occurring from March to May appear to be complicated with snow melting. Other than these months, monthly recharges are 10~25% of monthly precipitation. Lower recharge occurs in the dry season (July, Aug and Sept) when high evapotranspiration occurs.

Although the recharge rates are very close for the three simulated cases, the Mill R.W. demonstrates relatively extreme base flow process (see Figure 4A). Mean normalized stream flows of September (basically base flows) are 0.0107 $m^3/s/km^2$, 0.0094 $m^3/s/km^2$ and 0.0055 $m^3/s/km^2$ in the Winter, Wilmot and Mill river watersheds respectively. Mean normalized stream flow of September in the Mill R.W. is only 50% of that in the Winter R.W.. The combination of site-specific hydraulic parameters (mainly low specific yield) and topography are important contributing factors for the relatively extreme base flow process in the Mill R.W.. This suggests the combination of local heterogeneity and topography dominate groundwater dynamics and total recharge may appear to be favourable for more groundwater use, but extreme low base flow may not allow large groundwater extraction if an adequate in stream use is required.

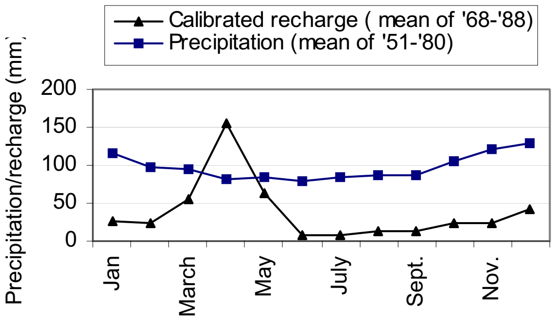

Figure 6. Comparison between precipitation and calibrated recharge at Winter R. W. (multi-year mean)

Table 4. Simulated groundwater budget of Mill R.W.

Subwatershed area=48.8 km^2	Inflow (m^3/d)	Outflow (m^3/d)
Recharge	53486.0	-
Stream leakage	91.6	52785.0
Evapotranspiration	-	957.0
Flow between budget zones	3741.6	3609.4
Sum	57320.0	57352.0

Table 5. Simulated groundwater budget of Wilmot R.W.

Subwatershed area=48.0 km^2	Inflow (m^3/d)	Outflow (m^3/d)
Recharge	52598.0	-
Stream leakage	1682.8	51088.0
Evapotranspiration	-	250.7
Flow between budget zones	1006.1	3964.8
Sum	55287.0	55303.0

Table 6. Simulated groundwater budget of Winter R.W. (mean of the 1980s)

Subwatershed area=37.8 km^2	Inflow (m^3/d)	Outflow (m^3/d)
Recharge	46688.0	-
Pumping	-	16320.0
Stream leakage	3640.0	32459.0
Evapotranspiration	-	154.0
Flow between budget zones	9187.1	10617.3
Sum	59515.1	59550.3

Simulations of the Winter R.W. demonstrate current average groundwater extraction rates are equivalent to 35% of annual recharge and the peak demand represents up to 49% of annual recharge. Under these water demand scenarios, simulated stream flows are 60% and 67% below those expected with no groundwater withdrawals respectively during the dry season of an extremely dry year.

In PEI high capacity wells (such as Charlottetown municipal wells in the Winter R.W.) are usually sited near streams and such practices intensifies stream-aquifer interaction. Although pumping rates are strictly restricted to less than 50% of annual recharge, in cases of excessive groundwater extraction, the most immediate response is a reduction in base flow rather than declining water level in the aquifer. In addition, impacts on water table due to groundwater withdrawals are usually very local because both pumping rates and hydraulic conductivity are relatively low. However stream flow reduction due to groundwater extractions has raised the concern for aquatic habitat protection. This will be discussed in next section.

4.2 Groundwater management

In PEI the allocation of groundwater is based on a percentage of average annual recharge and not seasonal conditions. While 50% of annual recharge is left for protection of surface water, it does not consider impacts of seasonal changes in the flow regime, especially during low flow periods of the year. A comparison with New England Aquatic Base-Flow (U.S. Fish and Wildlife Service, 1981; Lang, 1999) method for management of in-stream flow requirements for aquatic habitat protection, is made to examine if the current policy of allowing extractions up to 50% of annual recharge adequately address aquatic habitat protection.

For free-flowing, unregulated rivers, the ABF Method establishes summer stream flow requirements from the August median flow. August median flow is assumed to represent the month of greatest stress for aquatic organisms because of low flows and high temperatures. The U.S. Fish and Wildlife Service (USFWS) calculates the ABF August median-flow statistic as the median of the annual monthly mean flows for August (U.S. Fish and Wildlife Service, 1981).

The USFWS (1981) recommends calculating seasonal stream flow requirements for free-flowing, unregulated streams from discharges normalized for drainage area. The discharges are determined from gauging stations with drainage areas of 130 km^2 (50 mi^2) or more, which have 25 years of good- or excellent-quality record. For ungauged or regulated streams, the ABF method sets a default stream flow requirement of 0.0055 m^3/s/km^2 (0.5 ft^3/s/mi^2) for the summer period; this default value was designed to be a resource-conservative flow for habitat protection. In this study, stream flow requirements determined by the ABF summer default flow are compared to the median of monthly mean flow values for August determined from observed and simulated natural (i.e. non-pumping) flows for the Winter River case.

The median of the simulated natural stream flow of August in Winter R.W. is 0.0077 m^3/s/km^2, which is larger than 0.0055 m^3/s/km^2 and the ABF requirement would be fully satisfied without any pumping. Under current pumping condition the median of August stream flow would be 0.0031 m^3/s/km^2, which is far less than 0.0055 m^3/s/km^2, and the ABF criteria for habitat protection is violated. This comparison is not strict because the drainage area of Winter R.W. is smaller than the value

(130 km^2) applied to the ABF approach. However this large deviation does indicate aquatic habitat may not be appropriately protected even though pumping rates do not exceed the specified threshold, which is 50% of annual recharge.

This analysis indicates current groundwater management (high capacity wells) policy may not adequately address aquatic habitat protection although it can prevent aquifer dewatering and steady water table decline. While current policy fully considers how much water is available on an annual basis, it does not explicitly address what seasonal impacts on aquatic habitat will result if a given amount of water is withdrawn. This question cannot be answered by simply examining recharge. Discharge reduction, especially stream flow reduction, and its ecological implications should be assessed when groundwater allocation is issued. While the models can well demonstrate what base flow reduction can be expected on watershed basis through examining various pumping scenarios against the selected windows, it cannot show what base flow depletion is acceptable for aquatic habitat protection. Further study should be conducted in PEI to address this problem.

5. SUMMARY AND CONCLUSIONS

Watershed-scale groundwater flow models are developed to examine groundwater dynamics and impacts of groundwater extractions on the environment in PEI. Mill, Wilmot and Winter river watersheds, which represent the range of physical and water demand circumstances, are selected for simulation. The models are employed to conduct groundwater assessment and assess current high capacity well management policy.

The simulations conducted for the three test cases faithfully reproduce the observed behaviors with respect to the timing and magnitude of fluctuations in water table and stream flow discharges. This suggests the modelling approach can be employed to evaluate the combined impact of multiple wells and surface water/groundwater interaction on a watershed scale given existing data sets in the PEI setting.

Typically, groundwater recharge uses up to 37-40% of annual precipitation. Annual recharges vary from 200 to 500 mm/yr depending on annual precipitation and its temporal distribution. Recharges from March to May use a high portion of available precipitation. Other than snow melting months, monthly recharges are 10~25% of monthly precipitations.

Comparison of three test cases implies hydrogeological characteristics are not entirely uniform across the Island and local heterogeneity and topography govern groundwater dynamics in a watershed. Mill R.W. demonstrates relatively extreme base flow process. In September base flow of Mill R.W. is only about 50% of that of Winter R.W.. Care should be taken in extrapolating specific modeling results from one watershed to another.

Stream-aquifer interaction is one of the key processes dictates groundwater dynamics in PEI. Streamside groundwater pumping intensifies stream-aquifer interaction. Because pumping rates have been strictly restricted to less than 50% of annual recharge, water balance is well maintained in a watershed and steady water table decline has not been observed. Impacts on water table due to groundwater withdrawals are usually very local because both pumping rates and hydraulic conductivity are relatively low.

Current high capacity well management policy is examined through comparing observed/simulated stream discharge with in stream use specified by the ABS method. Analysis indicates under current pumping rates in-stream flow in the Winter River is less than recommended by the ABS method for the protection of aquatic habitat, although aquifer dewatering and steady water table decline have been prevented. It is stressed that the ABS method is borrowed from other jurisdictions and may not be fully applicable to local conditions. What level of base flow reduction is acceptable in PEI for aquatic habitat protection should be further studied.

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