Estimating Summer Low-Flow in Streams in a Morainal Landscape using Spatial Hydrologic Models

L. W. Stanfield, B. Kilgour, K. Todd, S. Holysh, A. Piggott, and M. Baker

Abstract: This study evaluated the capability of four spatial hydrologic models to estimate summer low-flow stream discharge, as a surrogate for baseflow, and assessed the influence of land cover/land use on these flows, in small streams across the Oak Ridges Moraine. Low-flow discharge varied predictably with area of the upstream catchment, but also with reach slope and a measure of land cover disturbance (LDI). Low-flow volumes were lowest in streams with moderate agricultural and/or urban development (LDI of eight to 12%), and high over a range of development intensities. Each of Baseflow Index (BFI×Area), Darcy Index (DI), MODFLOW (MF) and a finer resolution MODFLOW model (FMF) were about equal in their capability to estimate low-flow discharge, with MF and FMF having a somewhat stronger relationship and Darcy Index having a somewhat poorer relationship, particularly in smaller catchments. Each of the models generally predicted low-flow discharge volumes to within about 400 L/s of the actual observed low-flow discharge. The models, therefore, were generally unable to predict whether a stream was flowing during periods of low-flow when the upstream catchment was smaller than about 17,800 ha. It was found that these methods cannot be reliably applied in small catchments as there is too much natural variability in flow conditions. This paper suggests that these methods do not reflect local conditions, but rather provide generalized information about water flows. As a result, it is recommended that until spatial model predictions are improved for local applications, water managers should invest in field surveys to confirm flow conditions in small catchments.

Résumé : La présente étude avait pour objectif d'une part d'évaluer quatre modèles hydrologiques spatiaux afin d'en dégager la capacité d'estimation du débit d'étiage d'été, en tant que substitut du débit de base, et, d'autre part, d'évaluer l'incidence sur ces débits de la couverture terrestre et de l'affectation des terres dans les petits cours d'eau à l'échelle de la moraine d'Oak Ridges. Les débits d'étiage variaient de manière prévisible selon la zone du bassin hydrographique en amont, mais également selon la pente du bief et selon une mesure de la perturbation de la couverture terrestre (PCT). Les volumes en période

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de basses eaux étaient plus bas dans les cours d'eau touchés par des activités agricoles et/ou un développement urbain modérés (PCT de 8 à 12 %) et ils étaient élevés en fonction d'un éventail d'intensités sur le plan du développement. Chacun des modèles suivants : indice de débit de base (IDB × surface), coefficient de Darcy (CD), modèle MODFLOW (MF) et modèle MODFLOW à plus haute résolution (MFHR) étaient à peu près égaux en ce qui concerne leur capacité d'évaluer les débits d'étiage, le modèle MF et le modèle MFHR ayant une relation un peu plus forte et le coefficient de Darcy ayant une relation un peu plus médiocre, en particulier dans les bassins plus petits. Chacun des modèles ont permis en général de prédire des volumes d'étiage dans des limites de 400 litres/seconde environ par rapport au débit d'étiage réel observé. Par conséquent, en général les modèles ne pouvaient pas prédire si un cours d'eau s'écoulait pendant les périodes d'étiage lorsque la superficie du bassin en amont était inférieure à 17 800 ha environ. Il a été constaté que ces méthodes ne peuvent être appliquées en toute fiabilité aux petits bassins car il existe trop de variabilité naturelle dans les conditions d'écoulement. Le présent article donne à entendre que ces méthodes ne reflètent pas les conditions locales, mais qu'elles fournissent plutôt des renseignements généralisés sur les processus d'écoulement de l'eau. Il est donc recommandé que, jusqu'à ce que les prédictions du modèle spatial soient améliorées pour les applications locales, les gestionnaires de l'eau auraient intérêt à investir dans les études sur le terrain afin de confirmer les conditions d'écoulement dans les petits bassins hydrographiques.

Introduction

Groundwater contributions to streamflow strongly influence flow volumes and water temperature and thus impact the population of plants and animals that a stream will support. The specific location and timing of groundwater discharges can be critical to species such as brook trout (*Salvelinus fontinalis*), which require these areas for spawning and refuge habitat. Many brook trout populations in southern Ontario, for example, are restricted to smaller catchments (Stanfield *et al.*, 2006) where small volumetric changes in groundwater contribution can significantly impair cold-water habitats. Following massive deforestation in the late 1800s and early 1900s, many streams in the Oak Ridges Moraine area lost large volumes of baseflow (Buttle, 1994) and headwater streams went dry (Richardson, 1944). Those impacts led to reforestation efforts that ultimately improved baseflow discharges in many areas. Recently, development pressures from the Toronto area into the moraine have heightened concerns regarding repetition of historic impacts in redeveloped areas.

Management of these streams requires an understanding of the location of high discharge areas, whether these flow levels are comparable to pre-European levels, and how land/water use might alter existing discharges from both the current and potential condition in a catchment. Groundwater will discharge to a stream where the stream intersects with the water table while the amount of discharge varies with catchment area, climate, local geology and the hydraulic gradient of the water table. Identification of high discharge areas in headwater catchments has, to date, relied on field inventories. With decreasing resources, management agencies have been relying less on field studies and more on spatial hydrologic models to obtain information on flow conditions in streams and how they may respond to development pressures (Sear *et al.*, 1999; Vidon and Hill, 2004; Ouarda *et al.*, 2008). These tools can aid in the development of resource planning and management strategies, including maintenance of natural flow regimes (Conservation Ontario, 2005) and protection of the quality and quantity of regional groundwater resources (Holysh *et al.*, 2001). However, it is critical that users of these tools understand the uncertainty in flow predictions and whether regional frequency analysis can be reliably applied in all areas of interest (Ouarda *et al.*, 2008). Bradford and Heinonen (2008) suggest that the cumulative uncertainties are large enough that traditional modelling approaches may be inadequate to ensure that impacts to flows are avoided and fish populations are protected.

In the Great Lakes region, three spatial hydrologic models have been used for predicting groundwater contribution to streams. The first model, MODFLOW

(MF), is widely used by hydrogeologists across North America and is the main hydrologic tool supported by the United States Geological Survey (Prudic, 1989). Two versions of the MF model were used in the study; a regional five-layer model that had a 240 m uniform cell size and a more detailed eight-layer model that had a uniform 100 m cell size. The second model, Baseflow Index (BFI), provides a single measure for each catchment based on a ranked sum of the surficial geology. When combined with local climatic inputs and catchment area, the BFI has been demonstrated to be a good predictor of stream baseflow in several studies (Sear *et al.,* 1999; Piggott *et al.,* 2002). The third model, Darcy Index (DI), has been found to be a good predictor of baseflow in Michigan and has been proposed to provide a reliable index of relative baseflow levels in other glaciated areas, particularly where groundwater flow is high (Baker *et al*., 2003). The DI model is a topographically-driven empirical model for estimating potential energy available for driving subsurface discharge to streams. The index is based on measurements of slope and conductivity along a series of topographic profiles, which are carried out systematically across a landscape. The research evaluated the degree to which each of these hydrologic models, and the one variable that is core to each of these models — catchment area (Area), could predict summer low-flow volume at a site, and the degree to which local conditions influence the predictive power of the models. In southern Ontario low–flow volumes as defined by Smakhtin (2001) are considered to reflect mainly groundwater contributions (Hinton, 1995).

Stanfield and Kilgour (2006) demonstrated that increased development in southern Ontario affected the suitability of these streams to rear sensitive fish species and hypothesized that flow alteration was a major contributing factor. There is support for the hypothesis that land cover alterations contribute to altered flows from both anecdotal reports in historical documents (Richardson, 1944) and other studies (Leopold, 1968; Klein, 1979). There is also considerable evidence that alterations in flow can result in altered fish communities (see Bradford and Heinonen (2008) for a recent synthesis on low flows and Paul and Meyer (2001) for linkages to high flows). This study focuses on low-flow discharges as other efforts are being directed at understanding alterations in peak discharges (Stanfield, 2009).

Disturbances to the groundwater table and resultant low-flow volumes can result from a variety of factors, including aquifer pumping (Chen and Shu, 2002). Reduced infiltration rates can occur due to changes in vegetation (Dunne and Leopold, 1978), increased impervious cover (Leopold, 1968; Lorup *et al.,* 1998) and changes in storage and release rates due to loss of wetlands. This variability is not always reflected in information used to make management decisions. Most users must rely on a few GIS layers and typically one land cover layer, to understand alterations in flow. Therefore the degree to which a GIS based model similar to that used by Stanfield and Kilgour (2006) could predict low flow conditions was also tested. Understanding the quantitative relationship between low-flow volumes and different land uses provides a tool for predicting low-flow volumes for unaltered and altered landscapes (Kilgour and Stanfield, 2006), as well as objective support for progressive land-management approaches.

Methods

The study area for this project is the Oak Ridge Moraine (Figure 1), an interlobate moraine that extends from west to east along the north shore of Lake Ontario, Canada. The geology consists of mainly coarse-grained highly-porous materials on the height of the moraine, to finer-grained materials (clays and silts), on the flatter lands north and south of the moraine. The Greater Toronto Area in the west and agriculture in the east dominate land use in the area. Forest cover and wetlands are predominant on top of the moraine, while urban areas are predominant close to Lake Ontario and in the western part of the study area.

Single measures of stream discharge were collected from 1995 to 2002 during summer low-flow periods at 1172 sites. The Geological Survey of Canada (GSC) collected the majority of the data (83%) in 1995 and 1996 (Hinton *et al.,* 1998; Hinton, 1995). Sites were typically located close to road crossings. Standard methods were employed to collect the field data. Depending on the size of the stream, either a point-transect survey and pygmy meter or volume-over-time measurements were used (Terzi, 1981).

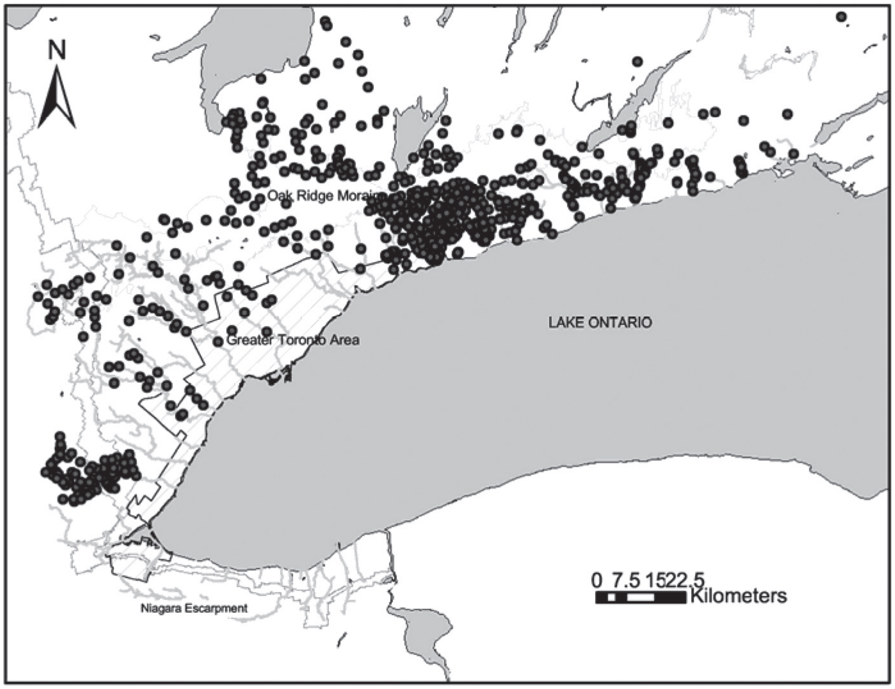

Figure 1. Major features and sample sites within the study area.

Landscape Data

Discharge sites were matched to the Ontario Ministry of Natural Resources (OMNR) stream layer (OMNR, 2002). Since the origin of this layer is the 1:10,000 topographical map series, many headwater (1st order) streams are not shown. This resulted in 168 headwater sites being excluded from this analysis. Landscape variables for the catchment upstream of each of the 904 remaining sites were derived through use of a GIS. Measured attributes from a Digital Elevation Model (DEM) with 30 m resolution included drainage area, elevation, stream length and reach slope (determined from the difference in elevation at 100 m upstream and downstream from each site). The OMNR developed a 28-Class Provincial Land Cover at a 30 m resolution (OMNR, 1999). Land classifications were based on a supervised (maximum likelihood) classification of Landsat images collected in 1992. From this classification, the amount of forest, urban, pasture, intensive agriculture (row crops and orchard) and water (lake, river and wetland) in each catchment were quantified.

A land cover disturbance index (LDI) was calculated as a surrogate measure of the amount of impervious cover in the basin. This approach is widely used as a means of integrating various types of human development activities in catchments (Klein, 1979; Shaver and Maxted, 1995; Steedman, 1988; Wang *et al.*, 2001; Stanfield and Kilgour, 2006). Stanfield and Kilgour (2006) evaluated the land use/land cover data for this study area and determined coefficients of disturbance for the land cover data as follows: urban = 0.2; intensive agriculture = 0.1; pasture and rangeland = 0.05; forests = 0.01; water = 0.0. The LDI rating for each catchment was estimated as the sum of the products of percent cover by each land use/land cover class and the associated disturbance coefficient of each class through

$$LDI = \sum_i (\%land\ useLandcover_i \times LD\ coefficient_i) \quad (1)$$

Estimating Baseflow

Baseflow is the more slowly varying component of total streamflow that, in certain settings, is largely the result of groundwater discharge to surface water. Biologists are often interested in knowing how groundwater discharge affects flow conditions throughout a watershed because of its impact on important ecological functions. However, groundwater flow is dynamic, varying seasonally and annually. Therefore, quantifying the degree to which survey data reflects baseflow conditions is challenging. Summer spot flow surveys are typically carried out at locations where gauge data are not available to provide a quantitative description of baseflow. Hydrologists often define baseflow conditions based on proportional distributions of flow over a specified time period. There was concern that some of the low flow survey data collected for this analysis were not reflective of baseflow conditions and further that temporal variability might reduce the predictive power of the models. Therefore, a baseflow metric was developed and used to rate the degree to which summer low-flow discharge, collected at non-gauged survey sites, approximated baseflow. Exploratory analysis determined that a seven–day estimate of the baseflow relative to total stream discharge was a useful metric for confirming that the measured streamflow was representative of baseflow conditions at gauged stations. For example, the seven–day value of baseflow at a given site that approaches one indicates that the majority of streamflow is baseflow. To calculate this metric, the baseflow and streamflow for each of the seven days preceding an observation were first calculated and the average baseflow condition was calculated from these data. The hydrograph separation method of Piggott *et al.* (2005) was used to separate baseflow from streamflow. This was carried out for each gauge station over the time period of this study (May 1995–October 2002). Finally, using the 174 available gauge stations, inverse distance weighting was used to interpolate the locally weighted average baseflow conditions at each site. Any site interpolated to have been collected on a date when the baseflow metric was more than 50% of the total discharge was included in the analysis. This reduced the dataset by an additional 22% to 704 sites. These interpolated estimates were used to generate a standardized estimate of baseflow by multiplying the measured discharge by the baseflow metric for each sample site/date. For example, if the measured discharge at a site was 1 m^3/s but the date was representative of a period when it was determined that 70% of discharge actually represented baseflow, then the standardized value for this site would be adjusted to 0.7 m^3/s.

Flow Predictors

MODFLOW (MF) Model

MF produces a summed measure of groundwater flux over the catchments of interest, based on a three-dimensional flow grid and a dynamic water level layer (Hsieh and Winston, 2002). For this area, the MF model was set up with a 240 m grid resolution (Kassenaar and Wexler, 2006). Recently a concerted effort has improved the resolution of the geology grids in the western half of the Oak Ridges Moraine enabling a finer resolution (100 m grid) MODFLOW model (FMF) to be developed as described in detail in Kassenaar and Wexler (2006). The refined mesh was set up to better represent streams, and headwater streams in particular, in the groundwater flow model. For regional groundwater flow models, several headwater streams are often lumped into one large cell, and therefore are poorly reflected in the groundwater model results. By having a uniform 100 m cell sized mesh, several cells are generally positioned between headwater streams. This allows for the hydraulic head to build up between tributaries and for the groundwater flow model to better represent discharge to smaller tributaries.

The boundary conditions for both groundwater flow models extended from Lake Simcoe in the north to Lake Ontario in the south. This ensured that the entire groundwater flow system, right to the bedrock surface, was effectively represented in the model (Figure 1) and to ensure that boundaries were not influencing any analyses in the upper parts of the Oak Ridges Moraine (Kassenaar and Wexler, 2006). While streams can act as either sinks or sources with respect to the groundwater system, the headwater streams are typically found to be drains. Groundwater discharges to these headwater streams on the flanks of the moraine from the elevated recharge areas located on the top of the moraine. In the case of both the MF and FMF estimates in this study, streams with a Strahler class ranging from one to three were treated as gaining streams or drains. With this assumption in mind, both models only allow groundwater to enter into the stream and not leak out. With the FMF estimates for streams exceeding a Strahler class of three, rivers and groundwater were allowed to leak out the stream bottom if the water table was at depth. This treatment of the headwater streams provides a consistent and reasonable estimate of groundwater discharge to streams and reflects the typical baseline condition that would be applied by managers in the absence of more detailed knowledge of the streams. In the MF and FMF models, the conductance (a measure of the permeability) of the streambed sediments, which controls the movement of water from the groundwater system to the surface water system, was varied from 5×10^{-5} to 5×10^{-7} s^{-1} based on the Strahler classification of the stream (Kassenaar and Wexler, 2006).

Baseflow Index (BFI) Model

The BFI for each site was calculated as a weighted average of the percentage of the upstream catchment classified as a Quaternary surficial geology unit and the "baseflow coefficient" (BF) for each unit (Table 1), following Piggott *et al.* (2002)

$$BFI = \sum_i (\%\, geology\ type_i \times BF\ coefficient_i) \qquad (2)$$

The BF coefficients were determined by comparing the baseflow at Ontario gauge stations (as determined using the hydrograph separation procedure) to the proportion of upstream area in each geologic type. Proportion estimates of baseflow were calculated for each gauge station and then a non-linear optimization algorithm was used to determine the overall BF rating for each geologic unit (Piggott *et al.,* 2002). The BFI is multiplied by the catchment area and average precipitation to provide a measure of predicted baseflow in m^3/day. For this study, the precipitation coefficient was not used since the entire study area is within one category. The amount of area covered by each quaternary surficial geology unit was based on the 1:250,000 Quaternary geology layer (OGS, 1997).

The Darcy Index

The DI model is based on Darcy's Law, which states that the velocity of flow through a porous medium is proportional to the difference in hydraulic head over a given flow path length (hydraulic slope), and the hydraulic conductivity of the medium (Freeze and Cherry, 1979; Baker *et al.*, 2003). A template of 12 linear transects was applied at 30° intervals around each DEM grid cell (Figure 2). Along each transect, sampling of elevation and conductivity values proceeded outward every 100 m for up to 4 km. Groundwater potential (P) was calculated for every interval as

$$P_i = \left(\frac{\sum_{j=0}^{i} K_j}{i} \right) \times \left(\frac{h_i - h_0}{L_i} \right) \qquad (3)$$

where P is the groundwater potential for transect interval i (0 to 40), K is hydraulic conductivity (m/d), h_i is elevation (m) at each location along the transect, h_o is the elevation at the focal cell, and L is the length of the flow path along the transect (100i). Estimates of K were obtained by cross-referencing a quaternary geology map with general values from Freeze and Cheery (1979). Portions of transect profiles that remained continuously higher in elevation than the focal cell were considered a potential source of groundwater (i.e., sources with $h_i > h_0$). If any portion of a transect profile fell below the focal elevation, the remainder of the transect was not considered a potential groundwater source. Transect profiles that fell below the focal elevation were considered to be a potential groundwater sink, drawing water away from the focal cell (i.e., sinks subject to the condition $h_i < h_0$). Transect potential (P_t) was determined by averaging all relevant interval source and sink values. The sum of

Table 1. Baseflow index (BFI) ratings for Quaternary geology units (OGS, 1997 and Piggott *et al.,* 2002).

Geology Unit	BFI rating
Bedrock (Paleozoic)	0.40
Tavistock Till (Huron–Georgian Bay lobe)	0.29
Port Stanley Till (Ontario–Erie lobe)	0.27
Newmarket Till (Simcoe lobe)	0.43
Wentworth Till (Ontario–Erie lobe)	0.68
Kettleby Till (Simcoe lobe)	0.38
Halton Till (Ontario–Erie lobe)	0.39
Clay till	0.28
Till	0.40
Glaciofluvial ice-contact deposits	0.67
Glaciofluvial outwash deposits	0.77
Glaciolacustrine deposits	0.14
Glaciolacustrine deposits	0.77
Fluvial deposits	0.38
Organic deposits	0.35

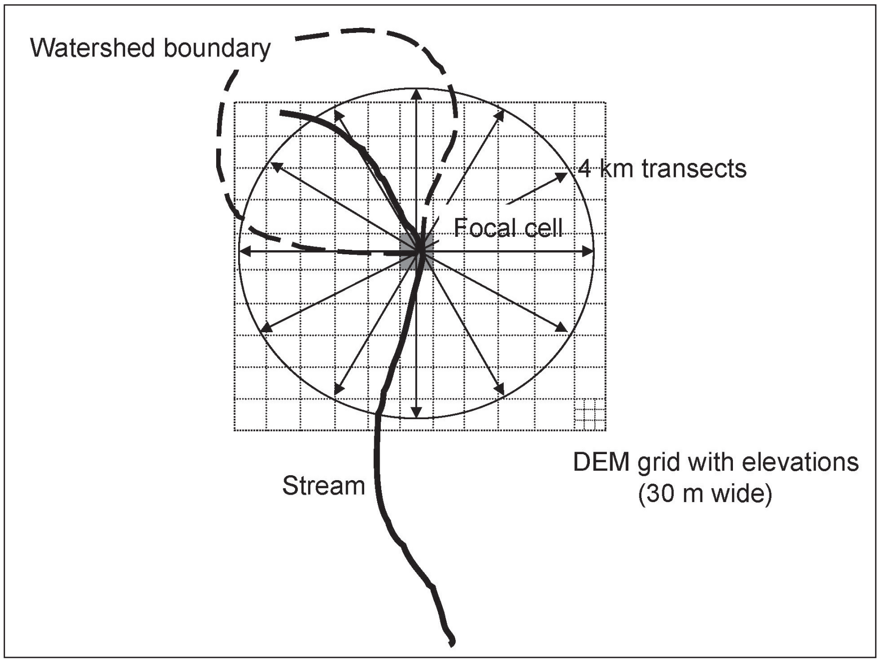

Figure 2. Schematic of methods employed to estimate Darcy Index for one focal cell. The procedure would be applied to every cell within the catchment.

all 12 transects thus provided a net DI value for each cell of the DEM. Following Baker *et al*. (2003), stream baseflow was estimated at each site with the sum of all net-negative (recharge) DEM cells within its upslope catchment. In this way, larger contributing areas or steeper and more conductive terrain generated greater baseflow estimates.

Analytical Procedures

Comparing Model's Capabilities to Predict Flow Volumes

Regression was used to quantify the relationship that each of the four spatial models (BFI×Area, DI, MF and FMF), as well as upstream catchment area, had with measured low-flow discharge. Confidence intervals for the r-values were calculated and tested for overlap between each model to assist with interpretation of model predictive capabilities. The residual mean-squared error (MSE) was calculated for each model as a measure of the unexplained noise. The noise indicates roughly the range of values that the true low-flow volume might fall within, given a predicted value. The square root of the MSE is the standard deviation (SD) of residuals. The range defined by ± 2 SDs has 95% likelihood of containing the true low-flow volume. When that range includes zero discharge, the model is unable to distinguish a flowing stream from a non-flowing stream. The MSE was used for the best model (i.e., lowest MSE) to predict the conditions under which a flowing stream could not be distinguished from a non-flowing stream. The relationship between catchment area and low-flow volume was further used to determine the catchment area below which flow-status is uncertain. It is acknowledged that this approach provides a conservative estimate of the predictive power of the models as a result of the bias introduced by extracting a model prediction from one model to another, but this can be used as guidance for project managers.

Both the overall relationship between observed and predicted flux (discharge per unit area) and the 10% of sites with the highest flux were examined to determine whether any of the predictive models (DI, MF and FMF) were correlated with sites that were significant contributors of baseflow. Such sites would indicate areas of potential high quality brook trout habitat.

Successful models would correctly classify the highest flux sites as having a flux (discharge index/area) greater than the median for each model.

Relating Flow Volume to Land Cover/Land Use

Backward stepwise multiple regression was used to evaluate the overall influence of LDI on observed low-flow discharge. Following Stanfield and Kilgour (2006), three models (full and reduced) were developed. The first full models involved a stepwise analysis to determine which variables (catchment area, stream slope, BFI, and LDI) were the best predictors of low-flow discharge. BFI was included as a means of providing an integrated measure of physiography. The second (reduced) model included only the primary landscape variables and excluded LDI, thereby providing a measure of the variation attributable to primary landscape conditions alone. Residuals from the second (reduced) model were regressed against LDI to determine the residual variation attributable to LDI alone. The squared terms of catchment area, slope, BFI, and LDI were also used in the models to account for curvilinearity in the relationships. To illustrate the relationship the predicted discharge for a hypothetical site were plotted with BFI, area and slope conditions equal to the median values in the study area. In this way the effect of LDI on flow is shown after the influence of the other landscape features are considered.

Results

The sample sites provided considerable contrast in the measures included in this analysis and covered a large portion of the Oak Ridges Moraine ecosystem (Table 2). The largest stream was only 87,000 ha and the majority of the sites were in very small catchments (< 516 ha). LDI varied from one to 20, averaging eight. Measured discharge varied considerably, including 23% of sites with zero flow and a maximum discharge of 2,500 l/s.

There were statistically significant correlations between observed and predicted discharge for each of the models and the results were similar between the

Table 2. Descriptive statistics for landscape characteristics, observed and predicted flows. Statistics are based on catchment summaries.

Variable Landscape Characteristic	Minimum	Maximum	Median
Site Elevation (masl)	77	455	232
Catchment Area (ha)	0.1	87,985	516
Stream slope (% over 200 m)	-0.5	12.6	0.9
% Urban	0	100	0
% Pasture	0	69	10
% Crop (intensive agriculture)	0	100	60
% Forest	0	98	19
Land Cover Disturbance Index (LDI)	1	20	8
Observed Flows			
Discharge (l/s)	0	2,472	6
Spotflow Correction Factor[1]	0.08	1.0	0.7
Standardized Low Flow (l/s)	0	1,714	4.3
Predicted Flows			
Base flow index (BFI)	14	77	40
Modflow prediction (l/s)	0	3,528	0
Darcy Index (Σ positive values) (m^2)	0	19,538,000	23,181

[1] discharge at gauge station on date of spot flow measurement/ baseflow discharge.

measured and standardized baseflow discharge data (Figure 3). There was a stronger correlation between summer low-flow discharge and predicted flow using the coarse MF model and the FMF model (r for both = 0.71, Figure 3). These two models were not significantly different from each other, but they were different from each of the other predictors. Area (r = 0.66) and DI (r = 0.56) were comparable to each other; both are modestly poorer predictors of low-flow discharge, although the models were significantly different from all of the other predictors. BFI×Area (r = 0.69) was only marginally less predictive than either of the MF models and was only significantly different from the DF model.

A few sites with large catchment areas (> 5,000 ha) had high influence on observed relationships. Correlation coefficients obtained with catchments < 5,000 ha were lower but comparable for the four models (FMF = 0.71; BFI×Area = 0.68; MF = 0.71; DI = 0.62; Area = 0.66).

The scatter observed in this dataset, including a site with a catchment area of 22,000 ha and a discharge of only 22 l/s, ensured wide confidence bands for each of the models. Even the most refined model (FMF) intersected the x-axis at a predicted FMF discharge of 400 l/s. The regression line for area and discharge (Figure 3h) suggests that this flow occurs in a catchment with an area of 10,000 ha. These results suggest that the FMF model could not reliably separate flowing from dry streams in catchments that are smaller than this threshold. In this study 91% of the sites had catchment areas lower than this threshold. The correlation coefficients were within 2% between the observed and standardized measures of discharge and the model predictions and therefore, it was deemed unnecessary to use the standardized flows for all further analysis.

As expected, each of the models are not suitable predictors of significant contributions of baseflow relative to catchment area (flux) with only about 50% probabilities associated with correct classification of the highest 10% sites. In fact, there was a non-linear relationship between the estimates of flux (estimated baseflow/catchment area) and the measured fluxes (discharge/catchment area) (see Figure 4 for an example plot using FMF). Many sites with high flux tended to be in the smallest catchments and therefore had lower cumulative predicted discharge, and conversely many sites with low or zero discharge also had high catchment areas and higher FMF estimates of flow and therefore flux.

General linear regression models showed significant relationships between discharge, area, and LDI (Figure 5, Table 3). However, the influence of LDI was minor relative to that of area. This was confirmed by analysis of the residuals suggesting that there was only a minor loss in discharge, with even large changes in LDI. This effect was not consistent as there was an increase in discharge at the highest LDI levels, as captured by the strong squared term for this parameter. These sites are all located in the Greater Toronto Area, where municipal water sources are taken from Lake Ontario. While it is possible to use this model for both hindcasting reference conditions and forecasting changes due to alterations in land cover, because the confidence limits are so broad, the predictions of flow volume will only be accurate to within about ±200 l/s.

Table 3. Regression models relating observed discharge and flux (observed discharge/catchment area) and landscape and land cover disturbance (LDI) variables. A second attempt was made to develop a model on the residuals of these models, using the significant landscape predictors from each model but not including LDI; no model was generated.

Effect	Discharge Model 1	Flux Model 1
Constant	2995.2	16.1
Log (Area)	-992.8	
Log ($Area^2$)	83.7	
Slope	13.9	
$Slope^2$	-1.7	
Land cover disturbance	-20.3	-2.8
Land cover $disturbance^2$	0.8	0.1
MSE	0.22	0.11
R^2	0.72	0.24

Discussion

Despite the different approaches used to modify the contribution of catchment area in the predictors of stream discharge, the models were similar in their capability to predict low-flow discharge. Selecting

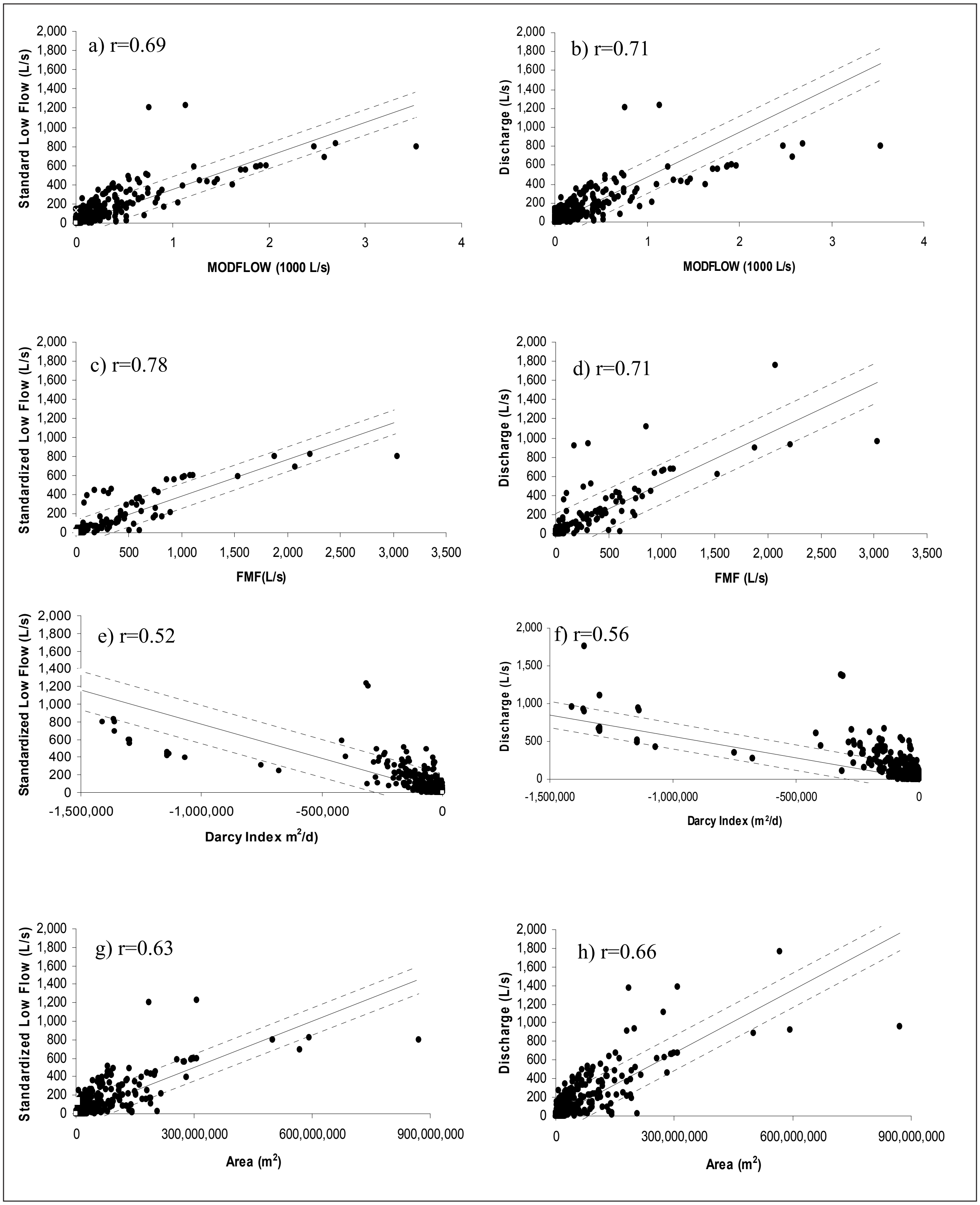

Figure 3. Relationship between standardized low flow discharge and observed discharge and the model predictions of flow: baseflow index (BFI)_area, Modflow (MF), fine resolution Modflow (FMF), Darcy Index (DI) and catchment area. R values on graph represent the adjusted r² values for each model.

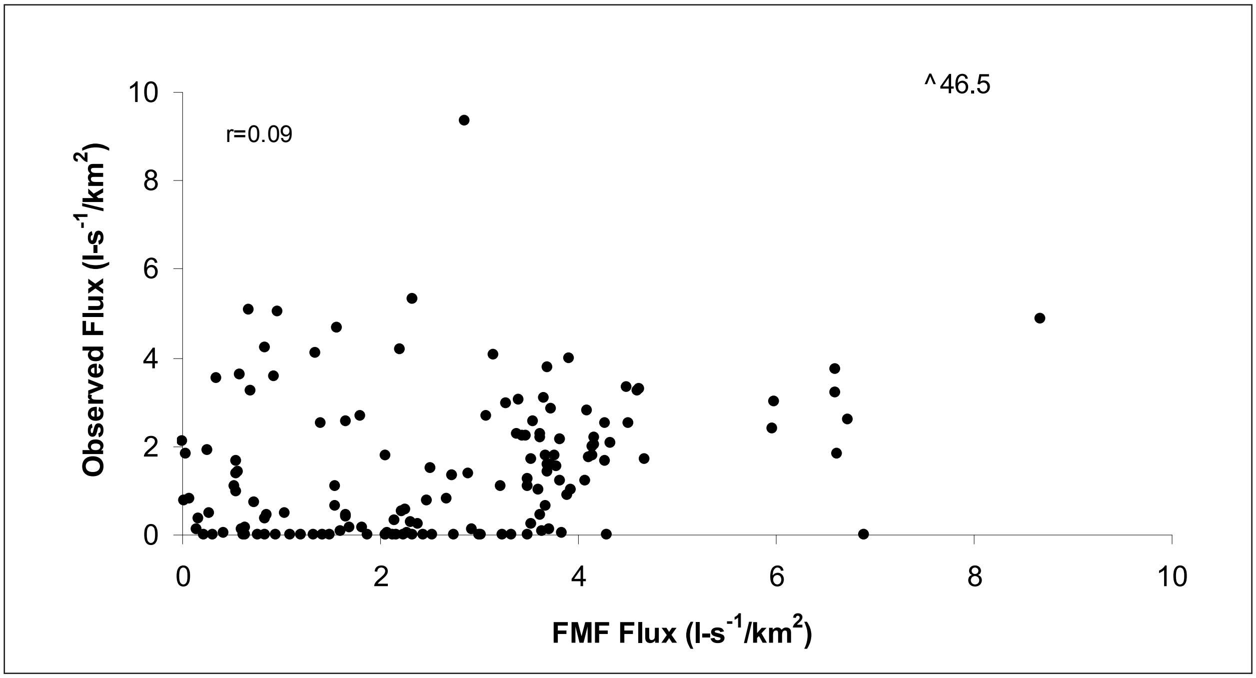

Figure 4. Relationship between observed flux in low flow discharge (discharge/catchment area) and the model predictions of flow from the fine resolution Modflow (FMF), model. R values on graph represent the adjusted r^2 values for each model.

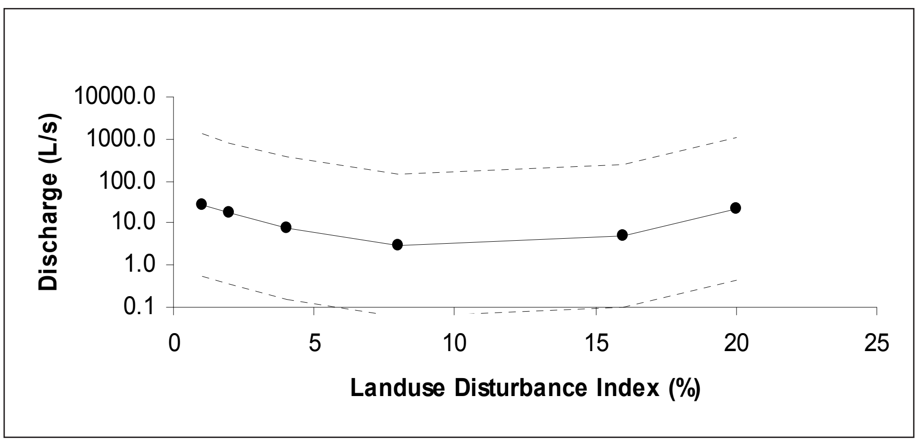

Figure 5. Illustration of the relationship between the general linear model for observed discharge and an example catchment with catchment characteristics of the median values of this study.

which model to use to predict flows will be based on the resolution required for a given study and the available resources. The reliability of these models has been quantified and it has been demonstrated that as catchment area decreases below about 17,800 ha, the ability to detect dry versus flowing streams is greatly diminished, regardless of which modelling approach is used. Further, none of these models helped identify high discharge sites. It is of concern to fisheries managers, who are trying to evaluate high risk streams using predictive modelling, that the predictive power of these models at present does not enable managers to reliably differentiate dry from flowing streams or high quantity flux (e.g., brook trout spawning areas).

Clearly these results call for greater efforts to improve the resolution of predictive models of flow, but until these improvements can be demonstrated, managers should continue to rely on high quality field data in small catchments to identify areas of high baseflow contribution and important fish habitats. Finally, this study documents what might be a unique effect in our study area—a curvilinear relationship between low flow discharge and land disturbance levels. Each of these main points will be expanded on and linked to management implications below.

This study has confirmed that the models provided comparable estimates of low-flow discharge and the regression equations have been used to enable comparisons between results where each model has been applied independently. An unexpected outcome of the study was that there were not greater differences in the predictive power of each model. Several explanations are offered for this finding.

Since each of the three models incorporate a measure of catchment area, differences in the predictive power between each model reflected their capability to build on the residual variation, from the other variables in the dataset, after area was considered. DI did not perform better than BFI, which is likely related to the differences in the assumptions for each model. BFI ratings for each geology type were derived from an analysis of measured conditions at gauge stations within the upstream catchment. This black box approach incorporates a variety of processes without defining their origin. For example, geological features foster similar land use, generally have comparable slopes and often have similar depths to bedrock that would all be amalgamated into the overall rating. DI does not quantify water movement, but reflects the topography of the surrounding landscape. In small catchments with hummocky topography, there is a greater potential for the water table to have a different level than indicated by the surrounding terrain. Therefore, the correlations between the DI and observed discharge in these instances tend to be poor, as observed in this study. While DI was more successful at differentiating high and low baseflow discharges in Michigan, this success may be due in part to the greater contrast in K values for the geology of lower Michigan, which results in greater contrast in DI values than was observed in this study.

Since few other studies have attempted to test these models in smaller catchments, it cannot be said whether similar findings are likely in other areas. However, a general conclusion from a recent low-flow prediction workshop was that regardless of the hydrologic model employed, predictions of low flows are likely to have high uncertainties (Davison and van der Kamp, 2008), as has been shown here.

An unexpected result was that the FMF model implemented at a finer resolution (100 m) only resulted in marginal improvements in relationships with flow.

The importance of the differences in predictive power of the models should not be underestimated since they will be important to studies that require the most accurate model predictions possible. Finally, while the limitations of models to predict low-flows (Davison and van der Kamp, 2008) are acknowledged, it is expected that predictions from MF and FMF will continue to improve as new data are collected and assembled into the model's geological layers and into the estimation of hydrogeological parameters.

These models were found to have comparable predictive power for streams of similar size in other studies (Sear *et al.,* 1999; Wang *et al.,* 2001; Baker *et al.,* 2003). This suggests that the patterns observed here are also transferable across broad areas. However, this study included many more sites from smaller catchments than previous studies and confirmed that the broad confidence bands for each model continued into the smaller catchments. From a management perspective, this observation is problematic since historically it has been demonstrated within the study area that the greatest impacts to flow result from the loss of forest cover in headwater catchments (Carman, 1940; Richardson, 1944). Clearly these models should be used with caution when making management decisions that are dependent on flow conditions within smaller catchments. Several explanations are offered for these findings.

The degree to which a stream is flowing is dependent on the upstream conditions. It is not surprising then that catchment area is the most important variable in predicting discharge (Beven and Kirkby, 1979; Wang *et al.,* 2001; Baker *et al.,* 2003; Shaman *et al.*, 2004). This study was no different with area explaining 66% of the variance in the data. The probability that somewhere in the catchment the groundwater table intersects the stream and contributes to flow increases with catchment area. Conversely, as catchment area decreases, unique properties of catchments result in greater variance in flow conditions that are difficult for models to capture.

It is not surprising that none of the models tested were able to differentiate the contribution of local effects in small catchments. The magnitude of the error bars for the observed relationships in this study is at least in part a function of the fact that data were collected over several years. However, it is also likely that the high degree of development is contributing to the variation in flow regimes within this study area.

Several explanations are offered here with regard to the inability to replicate the strong relationship between LDI and low-flow discharge, that has been demonstrated in other studies (Klein, 1979; Wang *et al*., 2001; McCuen and Moglen, 1988). The Oak Ridge moraine strongly influences the development and flow patterns in the study area, thereby confounding the effect of LDI on discharge. The measure of LDI may have been too coarse to capture the true impacts of development on discharge. There is substantial use of both the groundwater and surface water resources for activities that are likely not accounted for in the measure of LDI. For example, there are many golf courses and agricultural activities permitted to use surface water irrigation and there are several major pumping facilities that extract groundwater for municipal use. These activities can significantly affect base-flow as has been demonstrated by several authors (see Gore (1994), for pumping effects and Wang *et al*. (2001) for proximal land use). Where flow data are available, as was the case for this study area, measurements are often explicitly incorporated into MF prediction models. It is likely that, just as smaller catchments have higher variability in flow condition, their response to land and water use is also more variable, making predictions of impacts from LDI more challenging. Finally, Burn *et al*. (2008) compared low-flow discharges from six regions of Canada and found that southern Ontario streams had the greatest deviation from expected conditions of all six regions. This suggests that one explanation for the poorer relationships with landscape variables are due to this region having higher heterogeneity in low-flow discharges than in other study areas.

While others have observed increased flows in urban streams (Latour, 1993; Fitzpatrick *et al*., 2005), the magnitude of the increase in this study was a surprise. These findings are likely the result of several factors. All of the urban centres in proximity to Lake Ontario use the lake as a source of drinking water. This not only reduces consumptive pressure on aquifers but could contribute direct discharge to the streams through leakage of water and sewage pipes, lawn watering, permitted discharges and other water uses. The combination of withdrawals in headwater areas and potential inputs in lower reaches are likely combining to mask the capability to quantify the spatial effect of development on baseflow.

The findings emphasize the importance of the iterative approach to refinements of the MF estimates. While traditional approaches utilize mean flow data to calibrate models, biologists are typically more concerned about extreme flow conditions, such as occur during low flow or even drought conditions. Explicitly incorporating these measures of flow into the MF calibration exercises could greatly improve both the predictive capabilities of the models and their utility as a management tool to biologists. This should be a focus of current initiatives in Ontario.

Regardless of future efforts to improve model performance, this study supports Sear *et al.* (1999), in that there will always be a high degree of uncertainty in predicting the precise location of zones with high discharge relative to area and intermittent streams. Because of this uncertainty, it is recommended that practitioners invest in the collection of field data to measure stream discharge, particularly in catchments < 1,100 ha in size. Ideally, flow data should be collected over a short period of time, to ensure that water budgets reflect true differences along the stream network and are not subject to seasonal variations. While these surveys are labour intensive, it may be possible to utilize qualified volunteers to cover large areas on a single day. These surveys will also confirm the location of high and low-flow areas that can direct geological surveys to areas of uncertainty and/or of critical importance to fisheries resources. This should be coupled with improvements to base GIS layers that include headwater systems so that future analysis can utilize all collected data. Regardless of whether field derived or modelled flows are used in an analysis, as per the suggestion of Giles (2002) and Bradford and Heinonen (2008) among others, it is important that statistical confidence limits always be attached to model predictions.

Finally, this study offers one of the first examples of an effort to evaluate the predictive power of hydrometric models for low-flow conditions using point in time low-flow discharge data. Results suggest that, for the most part, these models should not be used to predict impacts to fishable waters. These findings confirm the findings of Bradford and Heinonen (2008) and Davison and van der Kamp (2008) and the predictions of Ouarda *et al.,* (2008) and Hamilton (2008). Additional research is needed to determine whether predictive power can be improved by applying stratification criteria, by using other types of multivariate or non-linear models as is suggested by Ouarda *et al.* (2008), by improvements in both the base data layers and specific impacts such as water withdrawals, or through improved field techniques as suggested by Whitfield (2008). Clearly much work remains if we are to better predict changes to this critical component of stream ecosystems in a rapidly evolving landscape. This dataset can be provided to future researchers attempting to address these challenges.

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