Modelling the relationship between discharge and lake level in Ontario’s inland lakes

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Abstract

Chu, C. and C. K. Minns. 2004. Modelling the relationship between discharge and lake level in Ontario's inland lakes. Can. MS. Rpt. Fish. Aquat. Sci. 2671.

Climate change is expected to increase temperatures and decrease lake levels and runoff in freshwater lakes and rivers worldwide. Given these potential changes, Mason *et al.* (1994) (hereafter Mason *et al.*) developed a model predicting the response of lake levels and surface areas to climate change. In this study, we modified the water balance equation developed by Mason *et al.* to create a regional model describing the relationships between lake level, discharge and surface area of lakes in Ontario. Mason *et al.* assume a linear relationship between discharge rate and lake water level. Our study was conducted to determine if the linear model accurately describes the discharge-lake level relationship recorded in Ontario and, whether that relationship can be predicted from morphometric lake characteristics. Discharge and lake level data from seventeen lakes in Ontario indicated that the assumption of linearity in the model is appropriate and that the slope of the relationship between discharge and lake level can be estimated from lake surface area. This therefore extends the usefulness of the Mason *et al.* model because lake surface area, a readily available metric can be indirectly used to estimate lake level or response to changes in runoff.

Résumé

Chu, C. and C. K. Minns. 2004. Modelling the relationship between discharge and lake level in Ontario's inland lakes. Can. MS. Rpt. Fish. Aquat. Sci. 2671.

On s'attend à ce que le changement climatique engendre des élévations de la température et un abaissement du niveau des lacs et du ruissellement d'eau douce dans les lacs et cours d'eau, et ce, à l'échelle mondiale. Étant donné ces changements potentiels, Mason et coll. (1994) (ci-après, Mason et coll.) ont élaboré un modèle de prévision de la réponse des lacs au changement climatique en termes de superficie et de niveau. Dans la présente étude, nous avons modifié l'équation du bilan hydrique élaborée par Mason et coll. pour créer un modèle régional qui décrit les relations entre le niveau, le débit et la superficie des lacs en Ontario. Mason et coll. supposent qu'il y a une relation linéaire entre le débit et le niveau d'un lac. Notre étude a été menée afin de déterminer si le modèle linéaire décrivait avec exactitude la relation débit-niveau observée pour les lacs en Ontario et si cette relation pouvait être prévue d'après les caractéristiques morphométriques des lacs. Les données sur les niveaux d'eau et les débits pour dix-sept lacs en Ontario indiquent que l'hypothèse de la linéarité du modèle est valide et que la pente de la relation entre le débit et le niveau d'un lac peut être estimée d'après la superficie du lac. Par conséquent, l'utilité du modèle de Mason et coll. est accrue étant donné que la superficie d'un lac, paramètre facilement disponible, peut être indirectement utilisée pour estimer le niveau du lac ou la réponse à des changements du ruissellement.

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Introduction

Climate change scenarios suggest that global air temperature has increased by an average of 0.5°C over the past century (Jones 1994) and will increase 1°C by 2025 (Smith *et al.* 1998). Climate change is expected to raise sea levels, alter precipitation patterns and decrease lake levels and flows in lakes and rivers (Smith *et al.* 1998). In Ontario, specific climate change impacts include an increase in air temperature of 2.5°C by 2050 (Environment Canada 2003) and record low lake levels in the Great Lakes during the latter part of the 21st century. All of these factors suggest that climate change will affect freshwater supply and quality by altering lake levels and surface areas (Mason *et al.* 1994). This will ultimately impact fish habitat. Warmer temperatures may cause the loss of coldwater habitats for important recreational species such as lake trout and brook trout. These habitats may then become more suitable for warmwater invaders from southern watersheds (Schindler 2001).

Mason *et al.* (1994) modelled the equilibrium response time of closed and open lakes to lake geomorphology and climate. Using a water balance equation, they found that closed lakes respond as low pass filters to variations in aridity with water balance response times of 1.5 to 350 years. They found the water balance in many open lakes to be driven by basin surface runoff (inflow) and discharge (outflow) rather than precipitation or evaporation. For open lakes, they assumed a linear relationship between lake level and discharge based on plots of discharge versus lake levels for a sample of five lakes.

The objective of this study was 1) to test the assumption that the relationship between discharges and lake levels is linear and 2) extend the usefulness of the Mason *et al.* model by predicting the relationship between discharge and lake levels from lake morphometric parameters.

Methods

The water balance equation developed by Mason *et al.* (1994) provided the basis for modelling discharge and lake level in Ontario. Given these quantities:

V = the lake volume (m^3)
R = the basin surface runoff rate ($m \cdot year^{-1}$)
D = the lake discharge rate ($m^3 \cdot year^{-1}$)
A_L= lake surface area (m^2)
P_L= lake precipitation rate ($m \cdot year^{-1}$)
$E_{L=}$ lake evaporation rate ($m \cdot year^{-1}$)
A_D = drainage basin area (m^2)

the differential equation of water balance for an open lake may be written as:

[1] $$\frac{dV}{dt} = R \cdot A_D + A_L P_L - A_L E_L - D$$

for lakes at equlibrium $\frac{dV}{dt} = 0$ the equation becomes:

[2] $$D_E = R \cdot A_D + A_{LE} P_L - A_{LE} E_L$$

where D_E = equilibrium discharge, A_{LE} = lake area equilibrium

equilibrium lake level is a function of the discharge rate therefore:

[3] $$L_E = f(R + A_L P_L - A_L E_L)$$

where L_E (m) = lake equilibrium level. In many open lakes lake level is dominated by runoff and discharge therefore P_L and E_L can be treated as equal and we can approximate $D_E = R \cdot A_D$ producing:

[4] $$L_E = R \cdot A_D \cdot \frac{dL}{dD} + L_0$$

where L_0 is a constant lake level (mean elevation or minimum elevation) and (dL/dD) is assumed to be linear. Equation 4 can therefore be used to predict the level of a lake under different discharge and basin surface runoff rates.

Assumption of linearity

To test the assumption of linearity between discharge and lake level, discharge and lake level (elevation in metres) data were gathered from the Ontario Ministry of Natural Resources (OMNR) and the Water Survey Division of Environment Canada (WSC). The OMNR offices for the Experimental Lakes Area (ELA) and Dorset area provided data for six and eight lakes, respectively. The HYDAT CD-ROM developed by WSC (2002) provided data for an additional three lakes in Ontario (Figure 1). The ELA data spanned 1981-1990 and were measured quarter monthly from April to October. The Dorset dataset consisted of discharges and lake levels measured daily from April 1st to October 31st from 1980-2000. The HYDAT data were daily lake levels and flows from January to December in 1995-1996.

To avoid pseudoreplication, multiple years of the lake level and discharge data were pooled for each lake. Scatterplots of the discharge versus lake level data indicated that linear or curvilinear regressions could be used to develop predictive models of lake level from discharge. Linear, exponential and third order polynomial regressions were performed to predict lake level from discharge. Logarithmic regressions were not possible since discharge often equalled zero. Analysis of variance (ANOVA's) and post hoc Tukey tests were then used to determine if significant differences existed among the predictions of the three regression models and these results were used to determine which regression type to use for the further analyses.

Results

Relationship between discharge and lake level

The linear, exponential and polynomial regressions all significantly described the relationship between discharge and lake level. Significant differences did not exist among the

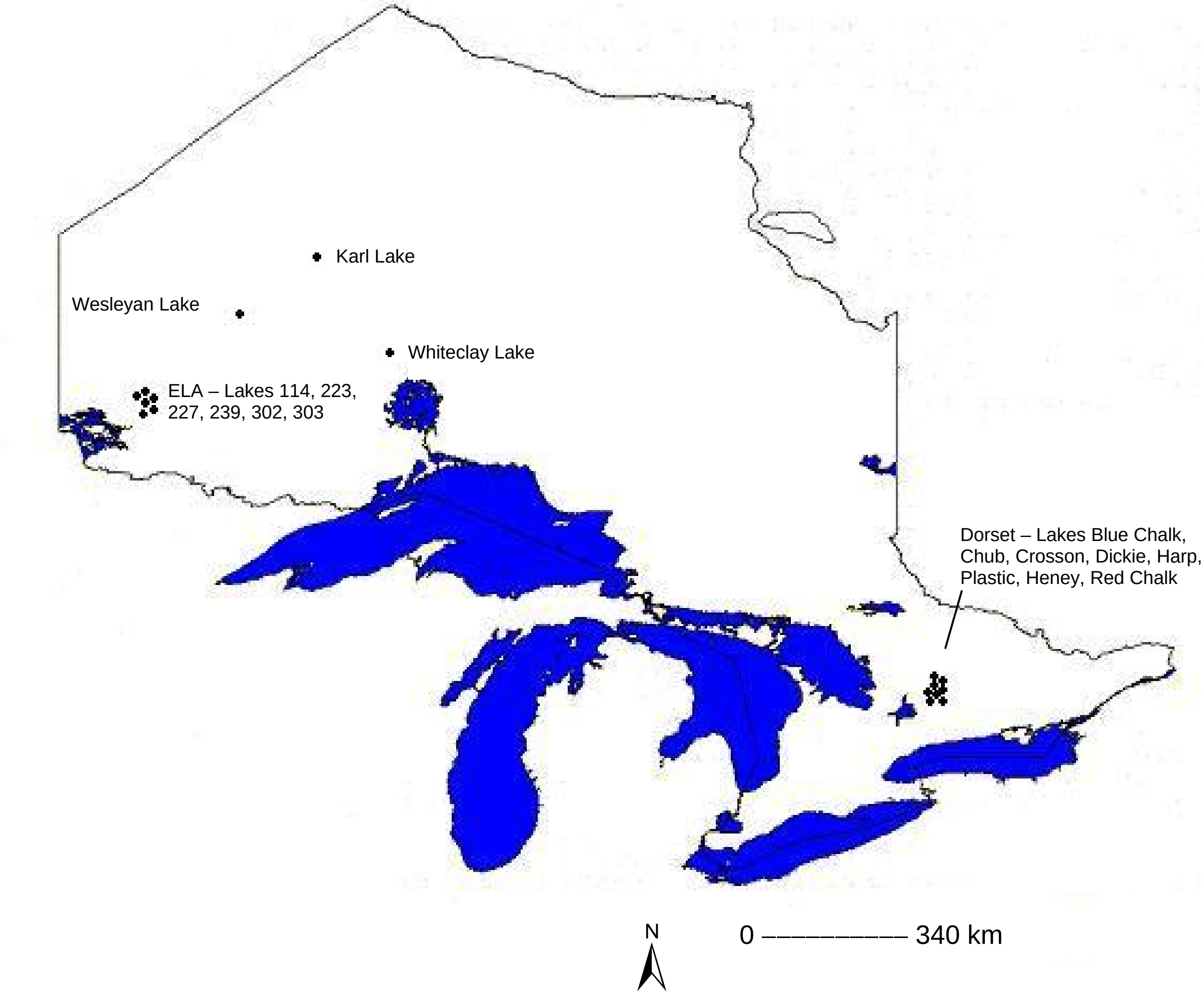


Figure 1: Seventeen lakes used to model the relationship between discharge and lake level in Ontario, (●) represents each lake.

predictions of the linear, exponential and polynomial models (Table 1). This suggested that the linear regressions effectively modelled the relationship between discharge and lake level. The slope and y-intercept values from the linear regressions were therefore used to generate lake-specific discharge-lake levels models (Table 2).

Relationship to morphometric variables

The slopes and y-intercepts of the linear regressions for each lake were plotted against lake surface area, volume, mean depth and maximum depth to determine if significant relationships existed between a measure of lake morphometry, lake level and discharge.

Relationship between discharge, lake level and lake morphometry

Lake surface area was the strongest predictor of the slopes between discharge and lake levels ($F_{0.05,1,15}$=98.33, r^2=0.87, p<0.00). Slopes increased with decreasing lake size and lakes smaller than 65 ha had slopes greater than one while lakes greater than 100 ha had slopes close to zero (Figure 2). The y-intercepts were dependent upon the elevation of the lake and were not strongly related to lake surface area.

Model scenarios

The results of this study confirm that the relationship between discharges and lake levels is linear therefore the assumption of linearity between these two variables by Mason *et al.* is correct. The slope, (*dL/dD*), can be approximated from lake surface area using this equation:

$$\frac{dL}{dD} = 10^9 \cdot (A_L)^{-1.59} \qquad [5]$$

Where A_L is the lake surface area (m^2). This therefore provides a scaling coefficient whereby the magnitude of lake level change with discharge change can be adjusted based on lake size using:

$$L_E = R \cdot A_D (orD) \cdot (10^9 \cdot (A_L)^{-1.59}) + L_0 \qquad [6]$$

Table 1: Results of ANOVA's comparing the predictions of linear, exponential and polynomial regressions of discharge and lake level in Ontario's inland lakes.

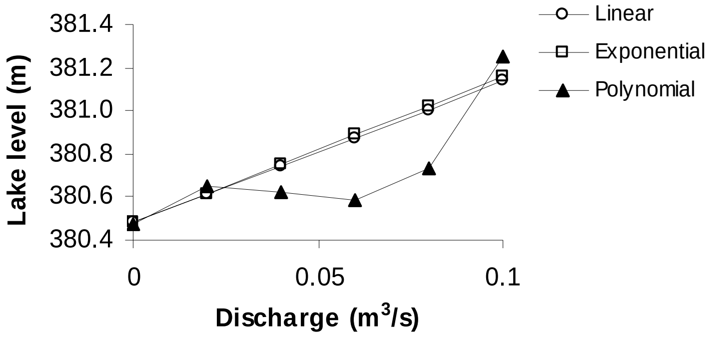
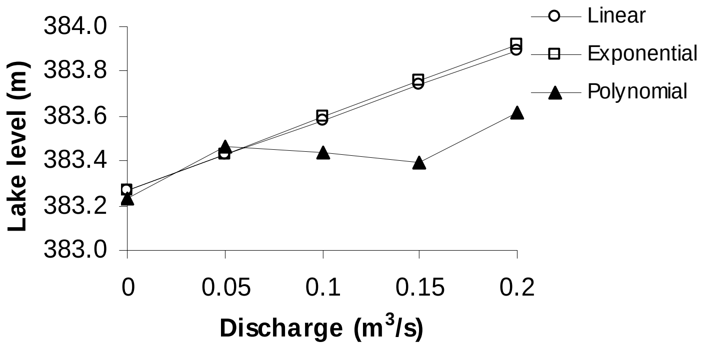
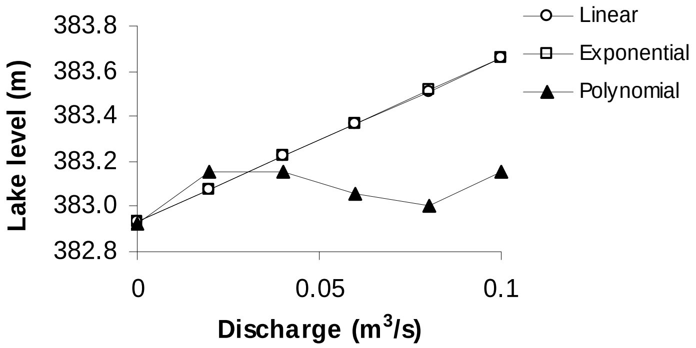
Lake	**Regression model predictions**	*F* ratio	*p*-value
L114		$F_{0.05,2,15}=0.266$	0.77
L223		$F_{0.05,2,13}=1.296$	0.30
L227		$F_{0.05,2,15}=1.849$	0.19

Table 1 (cont'd)

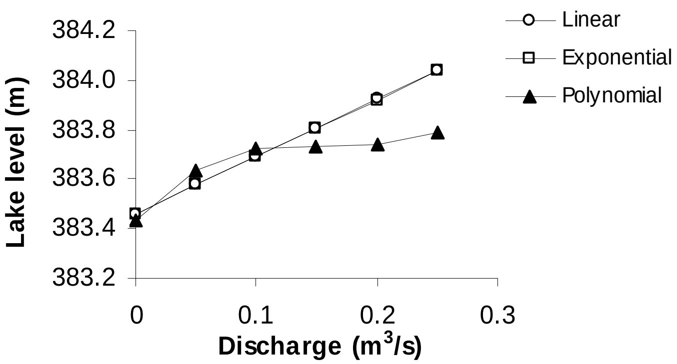
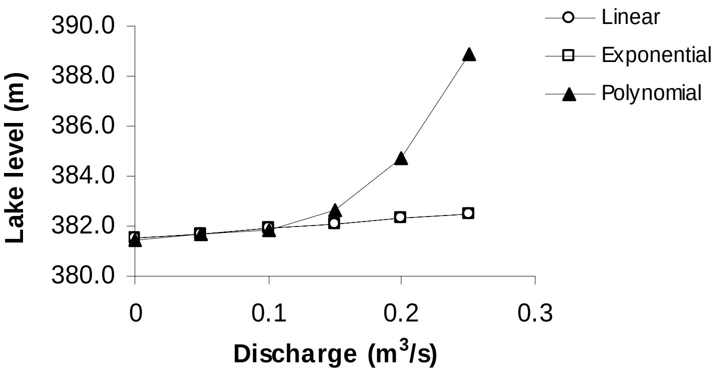
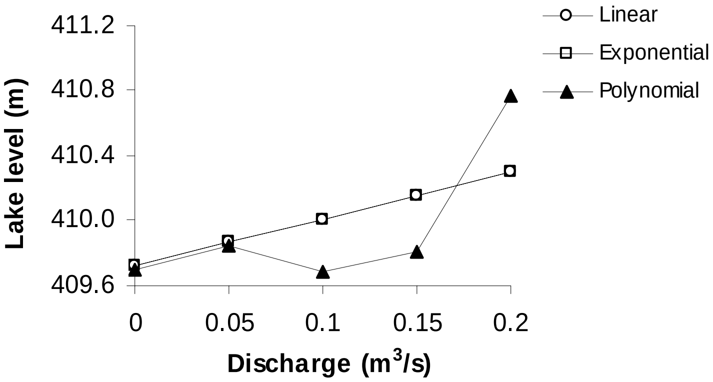
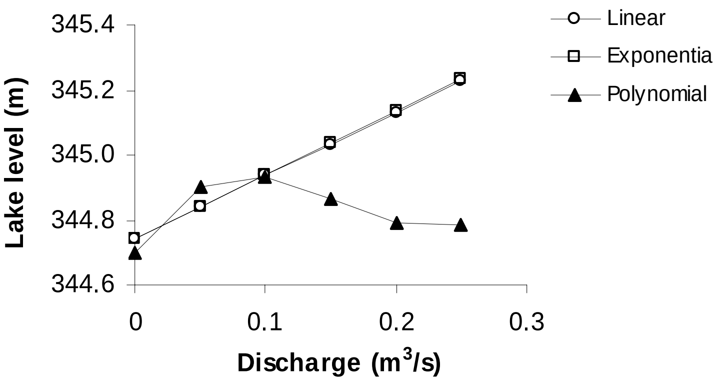
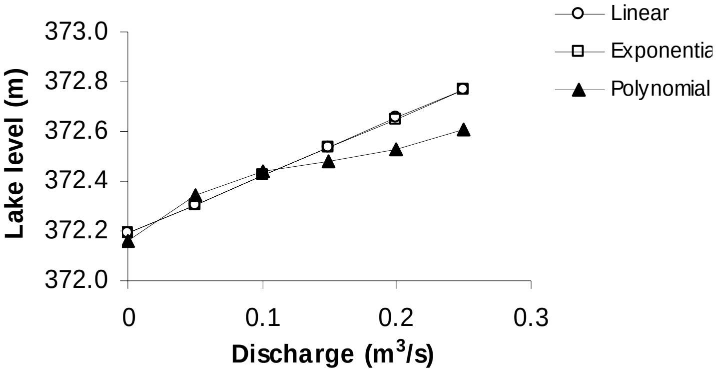
L239		$F_{0.05,2,15}$=0.472	0.63
L302		$F_{0.05,2,15}$=0.328	0.73
L303		$F_{0.05,2,15}$=0.038	0.96
Blue Chalk		$F_{0.05,2,15}$=1.946	0.18

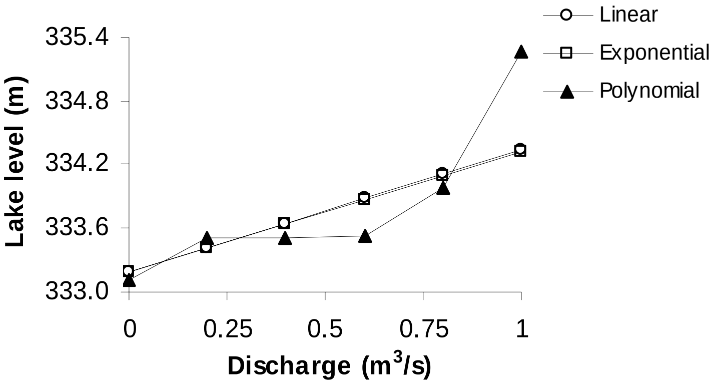
Table 1 (cont'd)

Chub



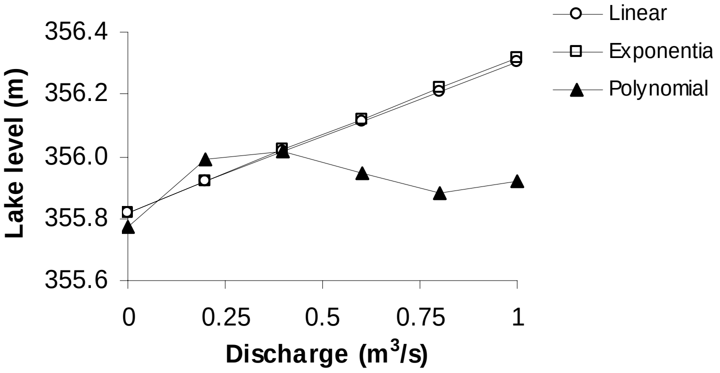
$F_{0.05,2,15}=0.140$ 0.87

Crosson



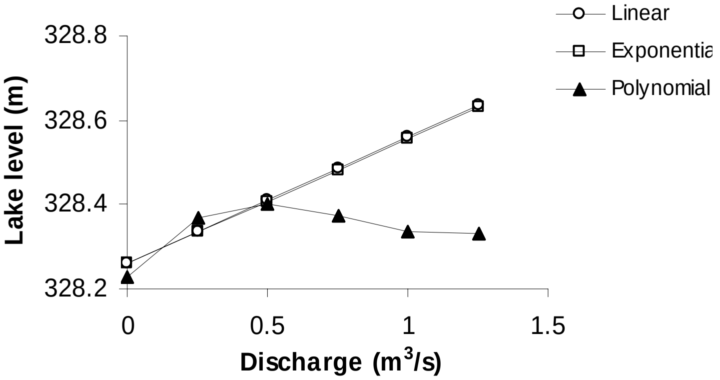
$F_{0.05,2,15}=0.022$ 0.98

Dickie



$F_{0.05,2,15}=1.660$ 0.22

Harp



$F_{0.05,2,15}=1.597$ 0.24

Table 1 (cont'd)

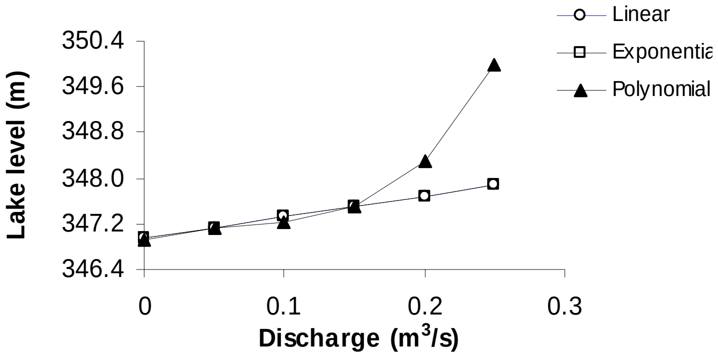
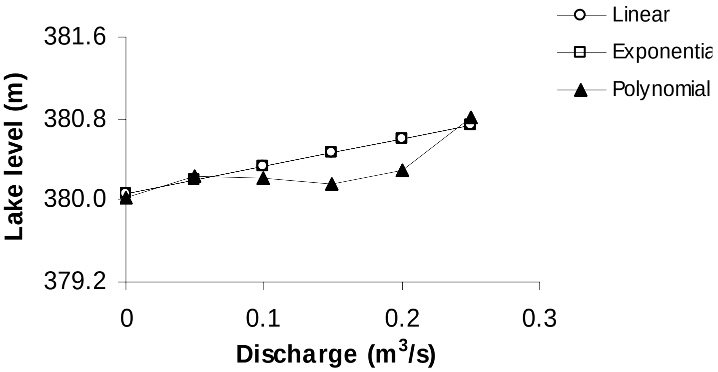
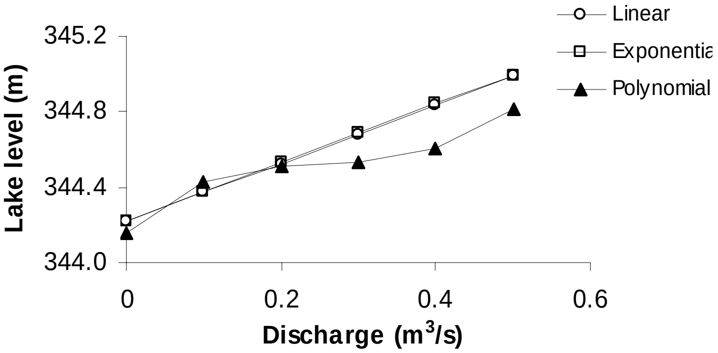
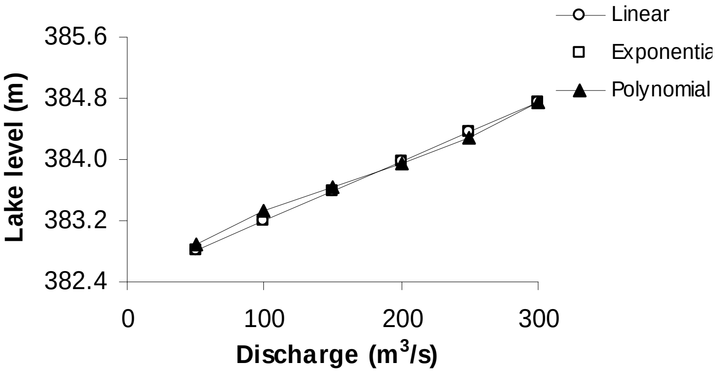
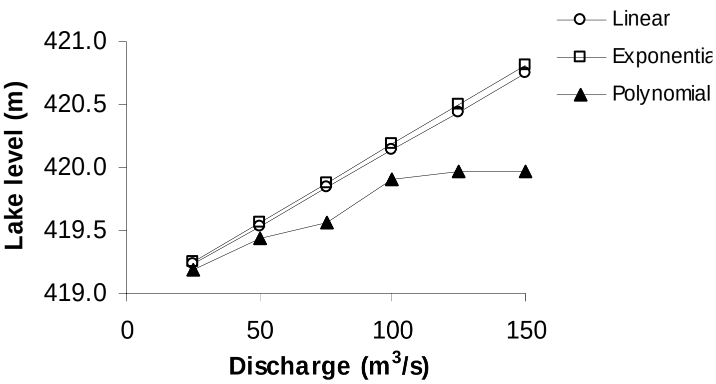
Heney		$F_{0.05,2,15}=0.723$	0.50
Plastic		$F_{0.05,2,15}=0.391$	0.68
Red Chalk		$F_{0.05,2,15}=0.275$	0.76
Karl		$F_{0.05,2,15}=0.002$	0.99

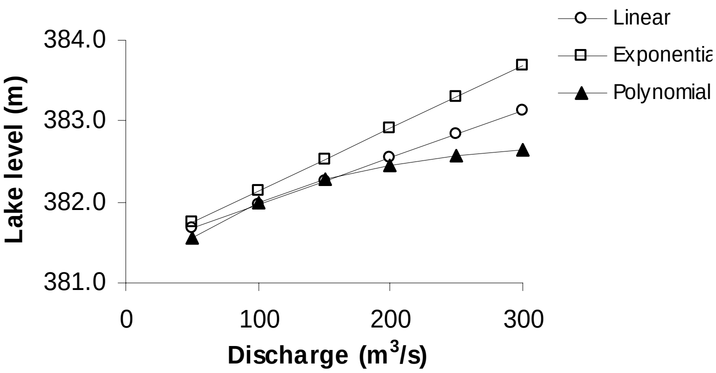
Table 1 (cont'd)

Wesleyan



$F_{0.05,2,15}=2.163$ 0.15

Whiteclay



$F_{0.05,2,15}=1.056$ 0.37

Table 2: Mean slope (*dL/dD*), y-intercept (L_0), r^2 and *p*-value of the linear regressions used to model the relationship between discharge and lake level in 17 Ontario lakes.

Lake	slope	y-intercept	r^2	*p*-value
114	6.56	380.48	0.29	<0.00
223	3.13	29.27	0.25	<0.00
227	7.27	382.94	0.29	<0.00
239	2.32	383.46	0.58	<0.00
302	4.11	381.48	0.23	<0.00
303	2.89	409.71	0.10	<0.00
Blue Chalk	1.96	344.74	0.13	<0.00
Chub	2.31	372.19	0.50	<0.00
Crosson	1.15	333.19	0.31	<0.00
Dickie	0.49	355.82	0.18	<0.00
Harp	0.30	328.26	0.20	<0.00
Heney	3.74	346.94	0.46	<0.00
Karl	0.01	382.44	0.96	<0.00
Plastic	2.70	380.07	0.11	<0.00
Red Chalk	1.53	344.22	0.63	<0.00
Wesleyan	0.01	418.92	0.99	<0.00
Whiteclay	0.01	381.30	0.91	<0.00

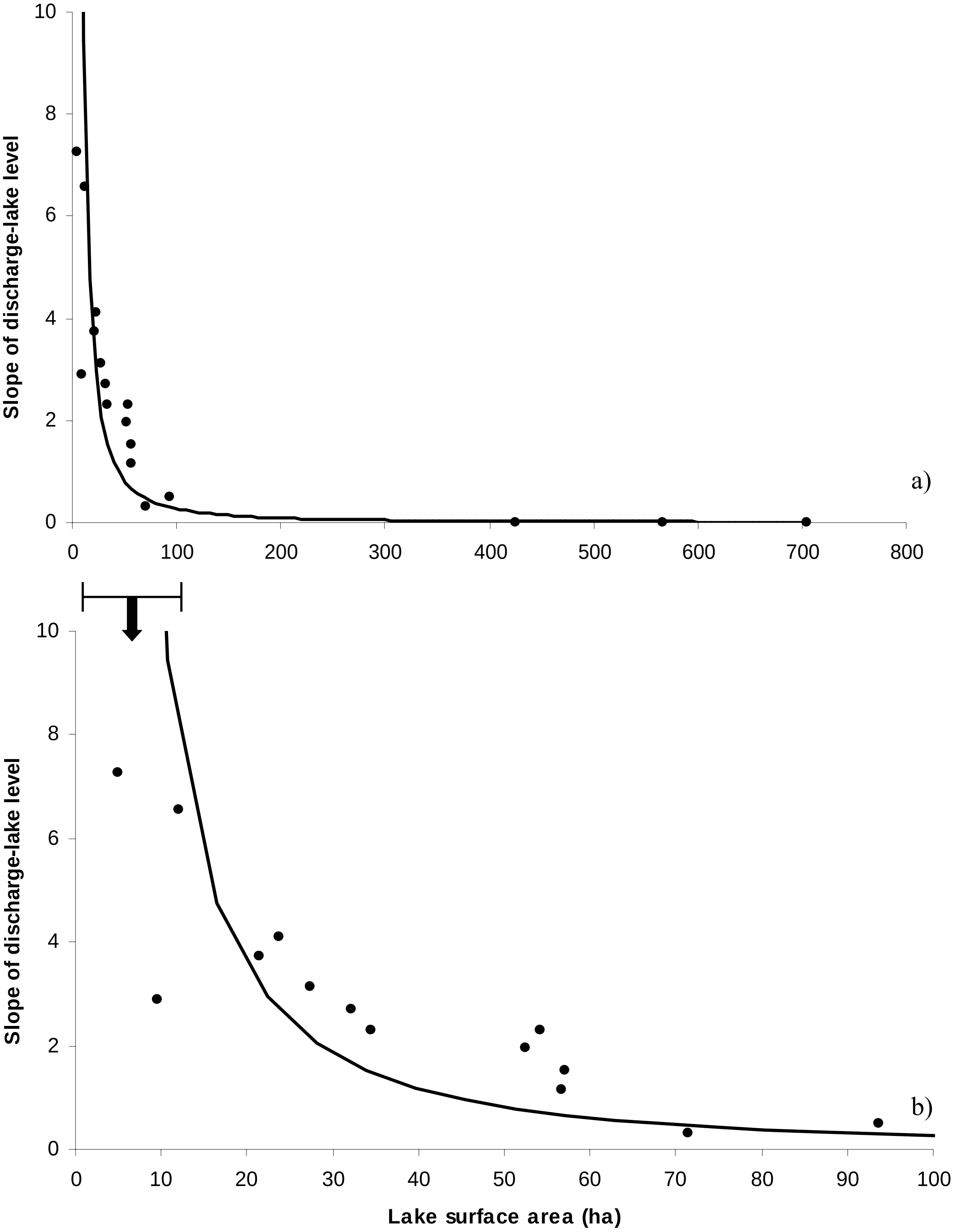


Figure 2: Slope of discharge and lake level in relation to lake surface area (ha) for 17 lakes in Ontario, (●) represents the mean slope across all years a) all seventeen lakes ($F_{0.05,1,15}$=98.33, r^2=0.87, p<0.00) b) only lakes smaller than 100 ha shown. Note: in figure lake surface area is presented in hectares, in equation 5 lake surface area is in m^2.

where D = $R \cdot A_D$, L_0 can be thought of as the lake level at which discharge equals zero but could not be predicted from lake surface area since there was no relationship between lake area and elevation. For modelling purposes we suggest using the mean elevation of the lake or if the data are available, the lake level at which discharge equals zero.

If we assume that the area and level of a lake are in equilibrium with respect to the current discharge rate, the expected change in lake level under a future climate can be estimated as follows:

$$[7] \qquad dL=(c-1)\cdot R_{base}\cdot 10^{9}\cdot[(A_L + A_D)\cdot A_L^{-1.59}]/31536000$$

where c is the scaling factor for reduced runoff due to climate change (currently 0.5 $m\cdot y^{-1}$ for 2025 and 0.25 for 2050, see *Climate scenarios*), *dL* is the lake level change (m), A_L is the lake area (m^2) and A_D is the drainage area (m^2).

Climate scenarios

Climate change is expected to increase Ontario's air temperatures by 1°C in the year 2025 and 1.5°C by 2050 (Smith *et al.* 1998; Environment Canada 2003). Runoff is predicted to decrease. Therefore if we assume for example, that the current runoff (R_{base}) = 0.5 $m\cdot y^{-1}$, and runoff is proportional to temperature, R_{2025} in 2025 might be $0.5\cdot R_{base}$ or $0.25\cdot R_{base}$ in 2050, we can predict the likely water levels for the sample lakes in our study. Drainage areas were not available for all of the lakes in our study so fourteen lakes and their associated drainage areas (Table 3) we entered into equation 7, using assumed values of $R_{base} = 0.5\ m\cdot y^{-1}$, $R_{2025} = 0.5\cdot R_{base}$, and $R_{2050} = 0.25\ R_{base}$, to predict the impact of climate change on discharge and lake levels.

Scenario results

Lake levels decreased in all lakes using the 2025 and 2050 scenarios (Table 3). Lake

Table 3: Predicted changes in lake level for fourteen lakes in Ontario after 2025 and 2050 climate change projections using assumed values of $R_{base} = 0.5$ m·y^{-1}, $R_{2025} = 0.5 \cdot R_{base}$ and $R_{2050} = 0.25\ R_{base}$. Data are listed by lake size.

Lake	Lake area (ha)	Drainage area (ha)	Lake level change 2025 (m)	Lake level change 2050 (m)
227	5	34.4	-0.106	-0.158
303	9.5	54.1	-0.061	-0.092
114	12.1	57.7	-0.046	-0.069
Heney	21.37	71.66	-0.025	-0.037
302	23.7	102.5	-0.028	-0.043
223	27.3	260	-0.052	-0.078
Plastic	32.14	95.5	-0.018	-0.027
Chub	34.41	271.84	-0.038	-0.057
Blue Chalk	52.35	105.93	-0.010	-0.015
239	54.3	393.3	-0.027	-0.041
Crosson	56.74	521.75	-0.033	-0.049
Red Chalk	57.13	480.01	-0.030	-0.045
Harp	71.38	470.66	-0.021	-0.032
Dickie	93.6	406.42	-0.013	-0.019

levels generally decreased more in the smaller lakes (<20 ha) than in the larger lakes (>50 ha) (Table 3). The assumed proportional decreases in runoff and discharge rates were greater than the proportional decrease in lake levels after climate change.

Discussion

The mean slope between discharge and lake level showed a clear increase in lakes less than 65 ha suggesting that lake levels increase at a greater rate than water discharges from these lakes. Lakes in the 65 – 100 ha size range had discharge and lake level slopes close to one which implies that their discharges are directly proportional to their lake levels. Lakes greater than 100 ha had slopes close to zero suggesting that discharge has less of an impact on lake level in larger lakes.

The future scenarios indicate that climate change will decrease runoff, discharge rates and lake levels in Ontario. Lake levels in smaller lakes (<20 ha) will decrease more than larger lakes (>50 ha). Climate change effects have already increased air temperatures, evaporation rates and decreased water renewal rates in lakes in north-western Ontario (Schindler *et al.* 1990). If these trends continue, our findings suggest that the nearshore habitats of all lakes are threatened and the threat is greater in smaller lakes.

This study presents a simple model of the impact of climate change on lake levels. For demonstration purposes we showed a proportional decrease in basin runoff with temperature. The relationship between these variables is obviously more complex therefore one avenue of future work will involve making better estimates of surface runoff and discharge from air temperatures. Once such model presented in Wanchang *et al.* (2000), examined the impact of global warming on stream flow and river runoff. Nonetheless this study extends the usefulness of the Mason *et al.* model and may prove handy for reservoir or lake management decisions.

Acknowledgements

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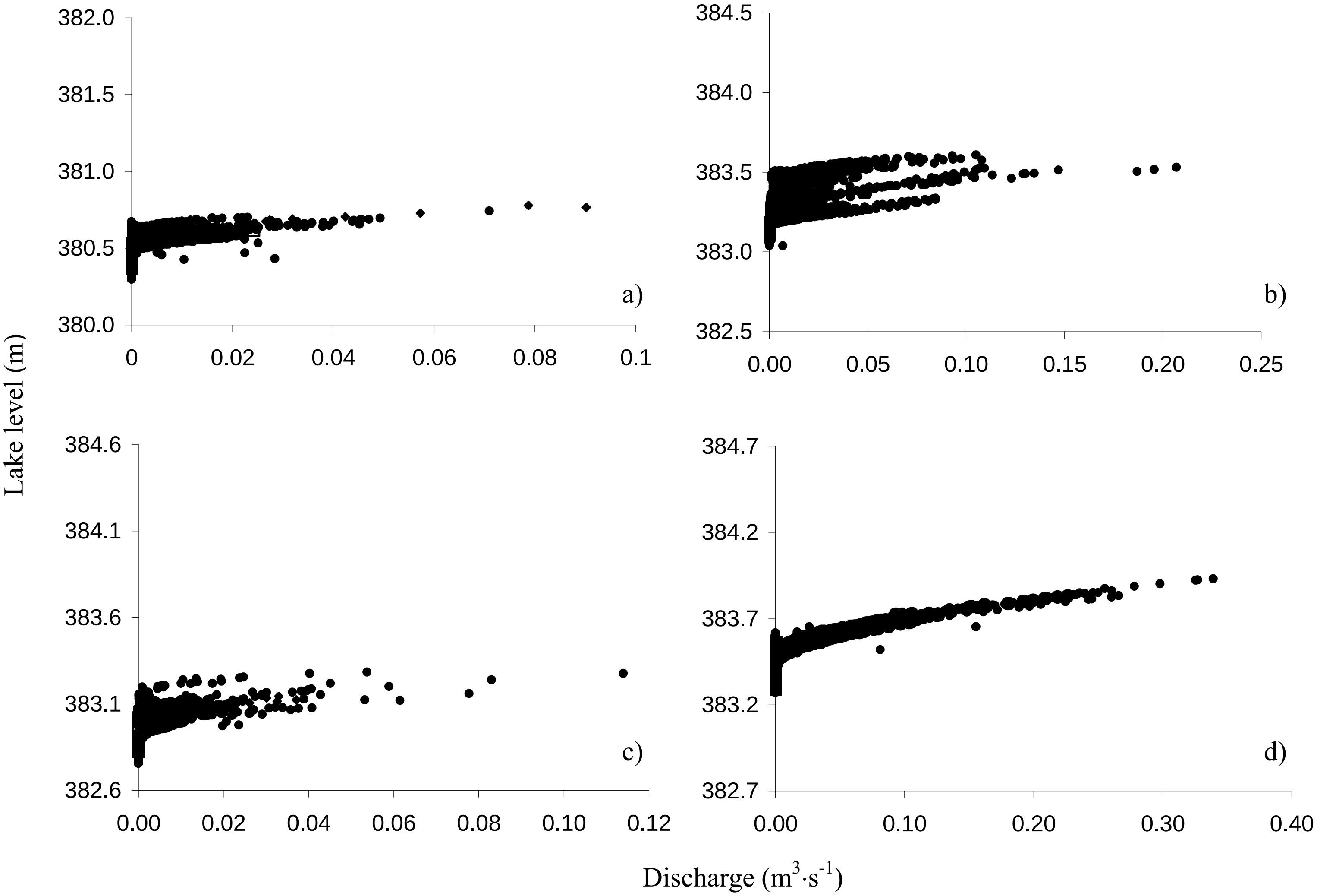
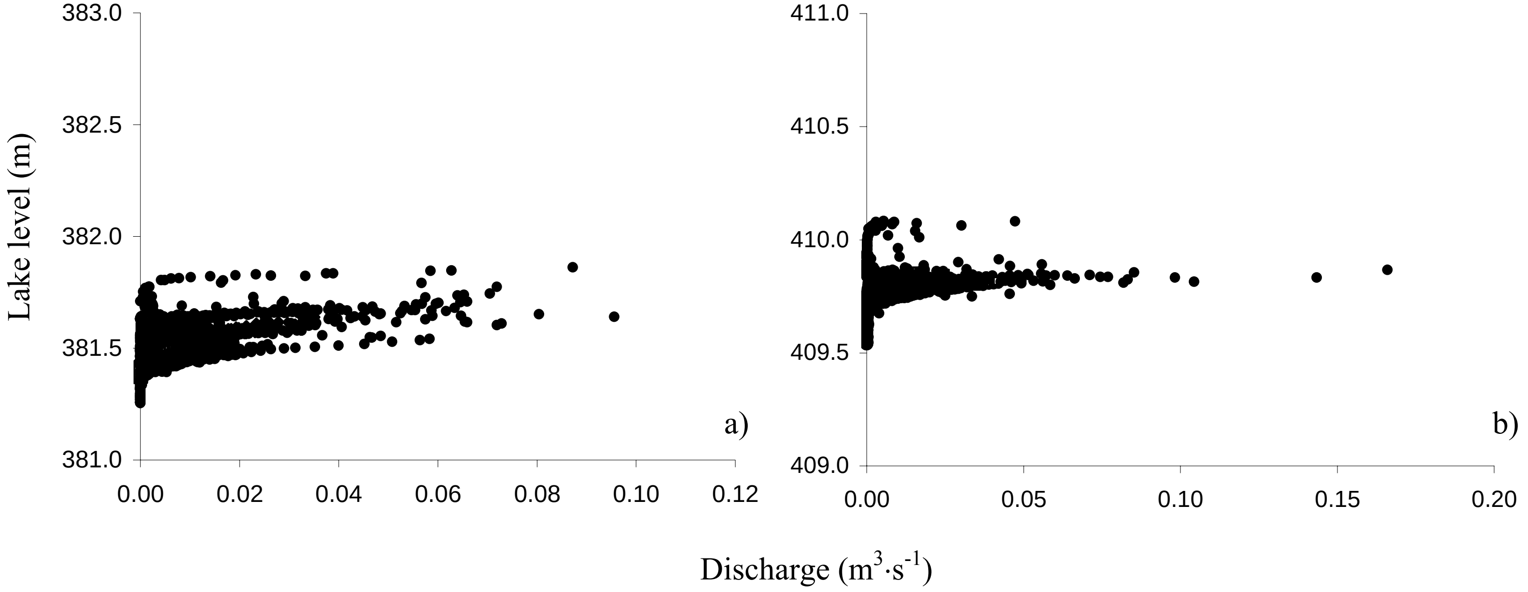
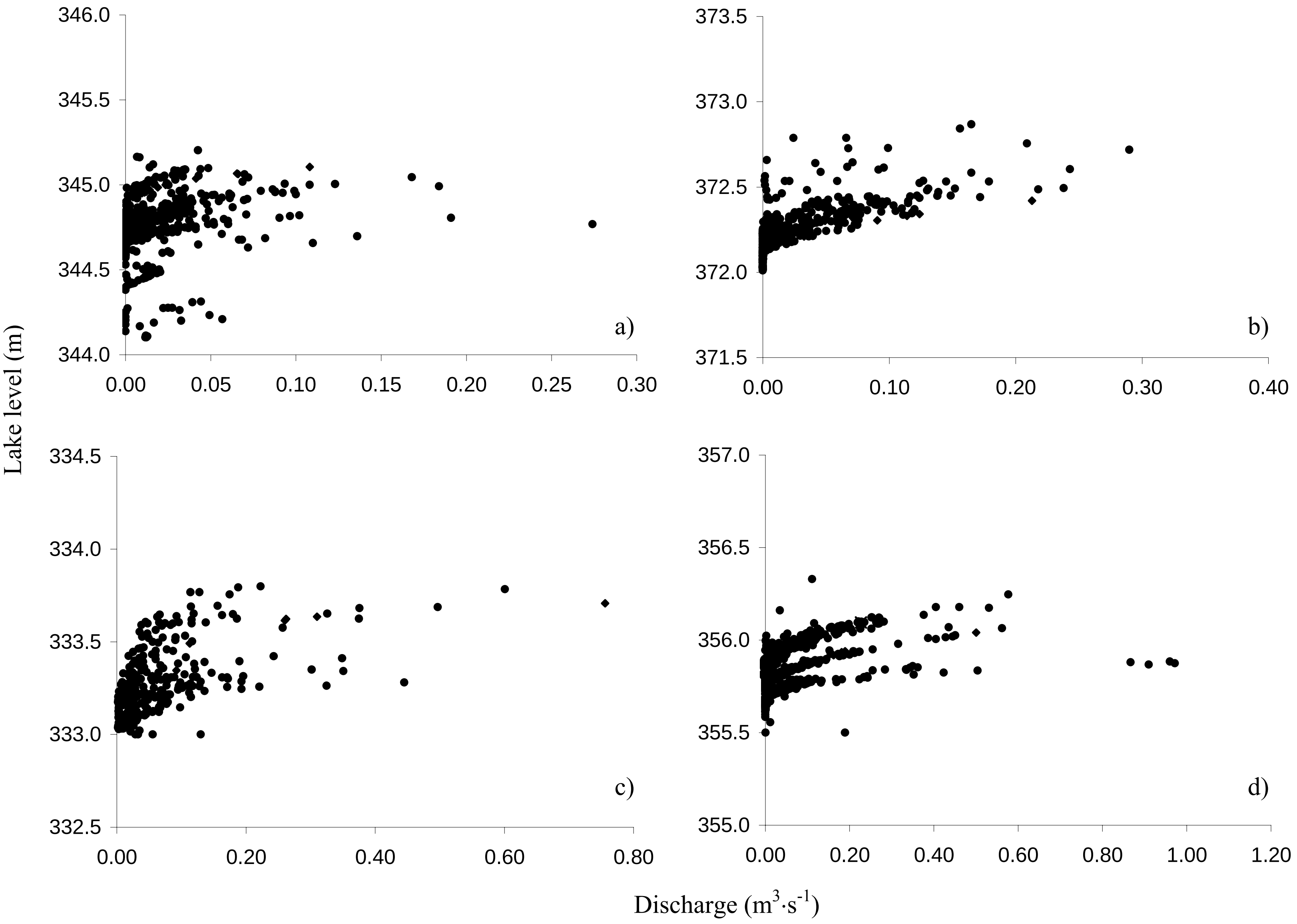
Appendix A



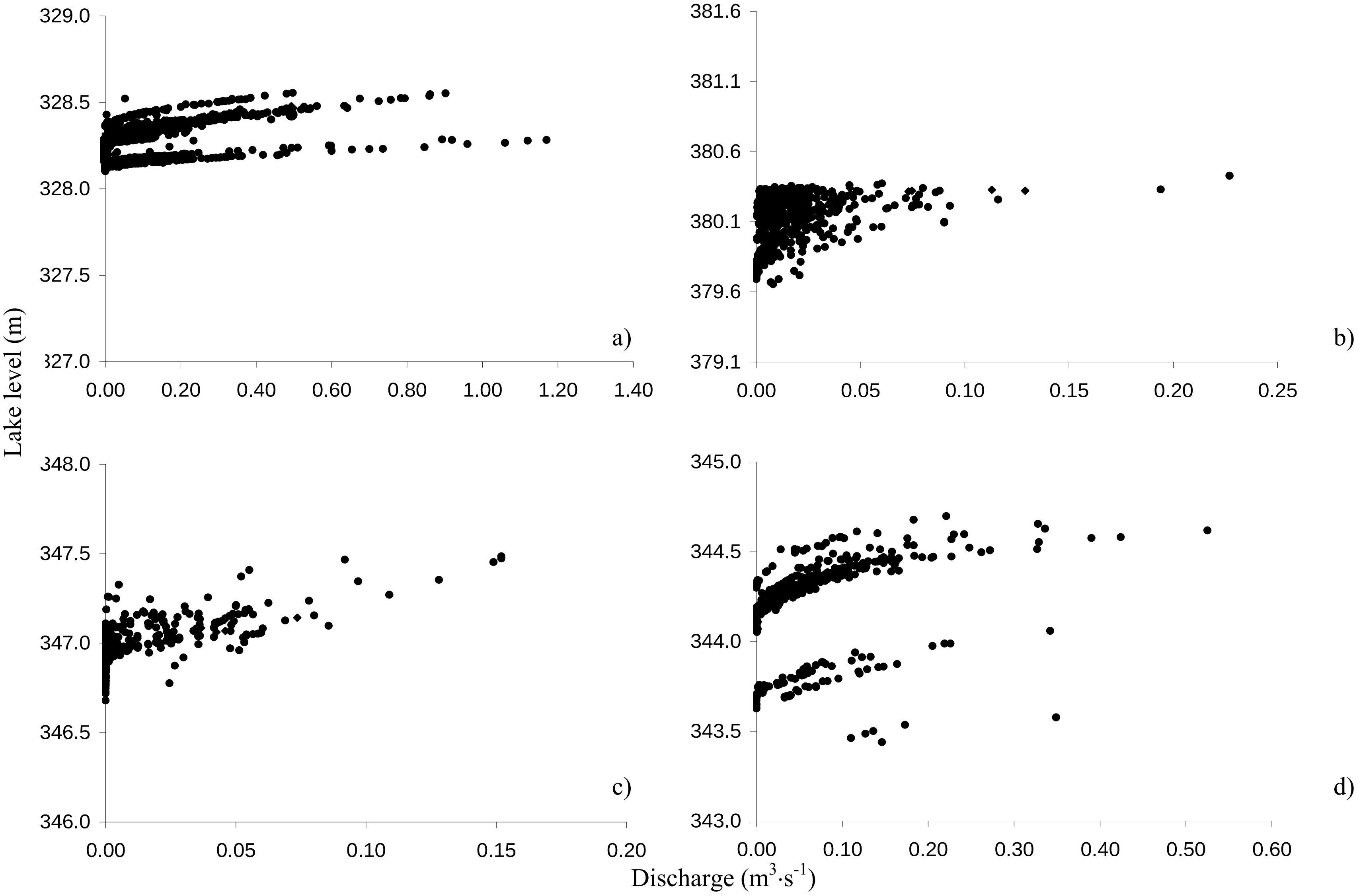
A-1: Discharge and lake level for lakes a) 114, b) 223, c) 227 and d) 239 in the Experimental Lakes Area, north-western Ontario (note different scales).



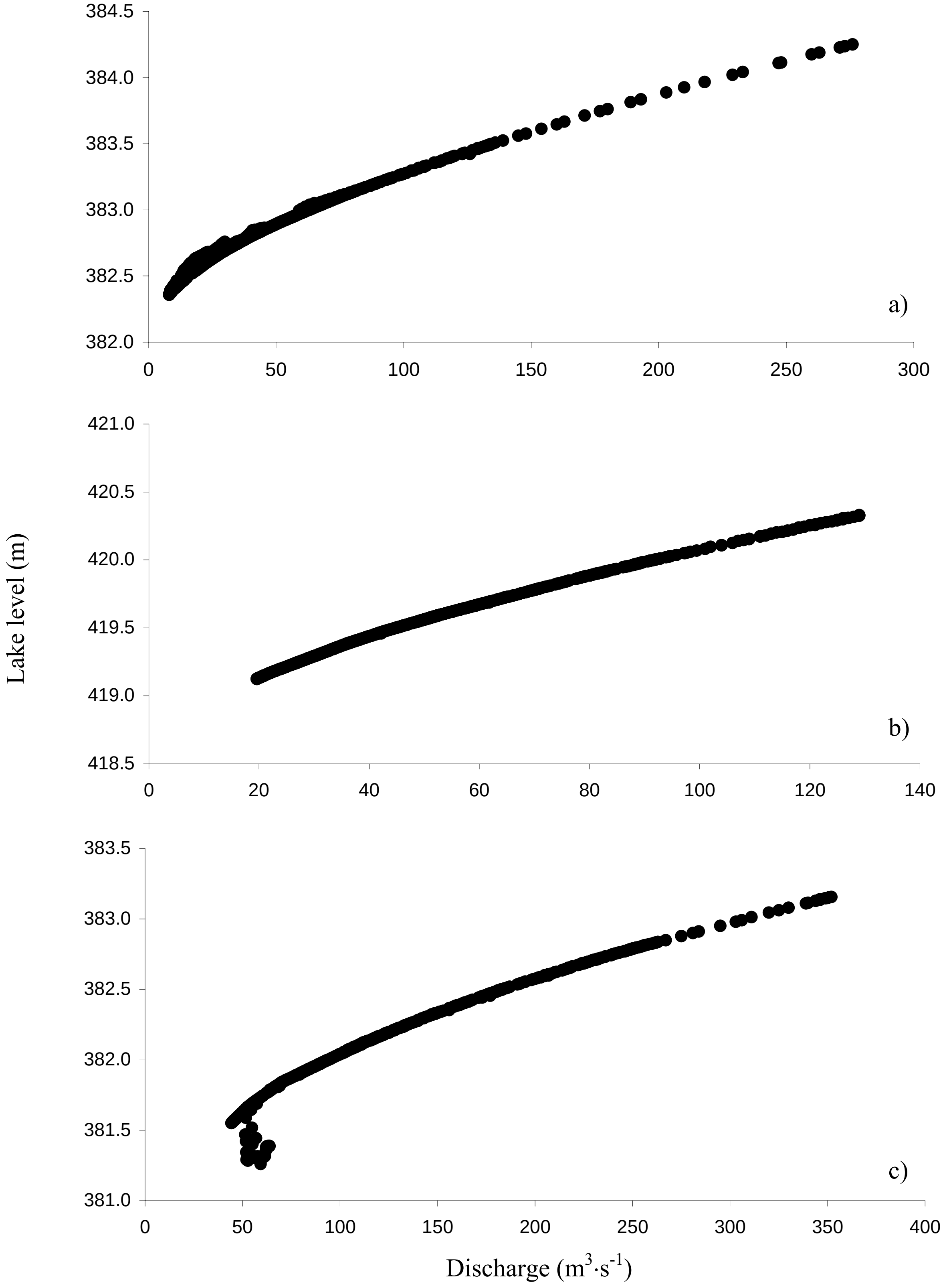
A-2: Discharge and lake level for lakes a) 302 and b) 303 in the Experimental Lakes Area, north-western Ontario (note different scales).



A-3: Discharge and lake level for lakes a) Blue Chalk, b) Chub, c) Crosson and d) Dickie in the Dorset area, south-central Ontario (note different scales).



A-4: Discharge and lake level for lakes a) Harp, b) Plastic, c) Heney and d) Red Chalk in the Dorset area, south-central Ontario (note different scales).



A-5: Discharge and lake level for lakes a) Karl, b) Wesleylan and c) Whiteclay in northwestern Ontario (note different scales).