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Effects of warmer world scenarios on hydrologic inputs to Lake Mälaren, Sweden and implications for nutrient loads

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Abstract A simple, rapid, and flexible modelling approach was applied to explore the impacts of climate change on hydrologic inputs and consequent implications for nutrient loading to Lake Mälaren, Sweden using a loading function model (GWLF). The first step in the process was to adapt the model for use in a large and complex Swedish catchment. We focused on the Galten basin with four rivers draining into the western region of Mälaren. The catchment model was calibrated and tested using long-term historical data for river discharge and dissolved nutrients (N, P). Then multiple regional climate model simulation results were downscaled to the local catchment level, and used to simulate possible hydrological and nutrient loading responses to warmer world scenarios. Climate change projections for the rivers of Galten basin show profound changes in the timing of discharge and nutrient delivery due to increased winter precipitation and earlier snow melt. Impacts on total annual discharge and load are minimal, but the alteration in river flow regime and the timing of nutrient delivery for future climate scenarios is strikingly different from historical conditions.

Keywords Catchment modeling · Hydrologic transport · Nutrient loading · Climate impact assessment

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European Large Lakes—Ecosystem changes and their ecological and socioeconomic impacts

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Introduction

One challenge for climate change impact assessment of large lakes is to consider changes in hydrologic and nutrient inputs from large catchment areas with diverse land cover and land use. Changes in the magnitude and timing of river flows are possible consequences of climate warming (Schindler, 2001). Increased nitrogen and phosphorus loadings from rivers are among the effects projected for areas where precipitation increases are anticipated (Murdoch et al., 2000). For Sweden, regional increases in air temperature and precipitation are expected, with the largest increases occurring in the winter months (Räisänen et al., 2003). What response in river flow and nutrient transport might accompany such changes? How would projected changes be compared with the levels of enrichment from cultural eutrophication observed in the past? We explored these questions for Lake Mälaren, the third largest lake in Sweden. The objective of this article is to use existing data and simulation models to estimate the hydrologic inputs and associated dissolved inorganic nitrogen and phosphorus loads (assuming simple loading functions) in rivers flowing into one basin of Lake Mälaren, Sweden for historical conditions and under future climate scenarios. Many model choices with varying degrees of complexity are currently available (Silgram & Schoumans, 2004). We used GWLF, the Generalized Watershed Loading Functions model (Haith et al., 1992), a simple hydrologic and nutrient transport model, to first estimate stream flow and nutrient export from large catchments with mixed land uses under present day conditions. We then use state-of-the-art climate models for future scenarios to assess the pattern and magnitude of change in river water quantity and quality for major inflows to this vitally important large lake.

The study area

Lake Mälaren is the water supply for the City of Stockholm and is the dominant freshwater source to the Stockholm Archipelago, with a mean outflow averaging about 165 $m^3 s^{-1}$ (Boesch et al., 2006). Our study focused on the western basin (Galten) and its four river inflows: Arbogaån, Hedströmmen, Köpingsån and Kolbäcksån. Galten is a rapidly flushed basin with a short water retention time of 0.07 $year^{-1}$ on average (Willén, 2001) with a large catchment to lake area ratio (8,508 km^2: 61.2 km^2), and consequently, external nutrient loading exerts a strong influence on lake water quality. Historically, inputs of nitrogen and phosphorus from wastewater treatment plants have been dramatically reduced, but nutrient inputs to the Stockholm Archipelago from land-based sources are still considerable (Boesch et al., 2006). Land cover characteristics and stream gauge units for hydrological modelling of the Galten inflows are shown in Table 1. Ungauged areas were modelled using coefficients and parameters developed for areas with river discharge gauges.

Materials and methods

Overall approach

The general procedure for evaluating impacts of hypothetical climate change on hydrological behaviour and nutrient loads was to:

(1) Parameterise the GWLF hydrologic model and nutrient loading functions for the historical period using observed data for river discharge and nutrient concentration for model calibration and validation.
(2) Apply a simple statistical downscaling method to transfer the climate signal from regional climate model output to hydrological and nutrient transport models.
(3) Run GWLF simulations for multiple realisations of observed and future scenario weather sequences to get a picture of seasonal pattern and range of variability.

GWLF was chosen because it can be applied to catchments with mixed land uses ranging several orders of magnitude in size, and the minimal data requirements make it relatively simple and rapid to use.

GWLF model description

The Generalized Watershed Loading Functions (GWLF) model dynamically simulates the hydrologic components of runoff from different land uses and baseflow; nutrient loads associated with these flow paths are estimated by empirically derived, source-specific nutrient concentrations that are input to the model (Haith & Shoemaker, 1987; Schneiderman, 2006). Although chemical transformation processes are not simulated, the implications of hydrological changes due to climate change on nutrient loading are of major importance given the dominant role that hydrology plays as the primary mechanism for nutrient transport. To evaluate the effects of climate change on hydrology and consequent implications for nutrient loading, it was assumed that land use and management remained constant. We used a version of GWLF that was written in the Vensim (Ventana Systems, Inc.) visual modelling software (Schneiderman et al., 2002; Schneiderman, 2006).

Table 1 Drainage area description

Drainage basin characteristics				Land cover characteristics (km^2)							
River sub-catchment*	Gauged (km^2)	Ungauged (km^2)	Total area (km^2)	Conifer forest	Other forest	Water bodies	Transition woodland shrub	Pasture	Arable land	Peat bog	Other
Arbogaån			3808	1744	386	264	665	68	446	141	94
Hammarby	891	171	1062								
Dalkarlshyttan	1183	128	1311								
Kåfalla	413	80	494								
Fellingsbro	298	1	299								
Direct drainage		642	642								
Hedströmmen			1050	528	72	85	191	19	85	58	12
Dömsta	998	52									
Köpingsån			287	137	19	14	48	6	43	9	11
Odensvibron	110	177									
Kolbäcksån			3119	1623	277	272	552	40	129	116	110
Ramnäs Krv	2849	156	3005								
Berg	36	17	54								
Direct drainage		60	60								

* Sub-catchment name corresponds to river gauge name in SMHI (1994)

GWLF is driven by daily temperature and precipitation data, and water balances are calculated on a daily interval. Streamflow consists of runoff from different land uses and baseflow. Runoff is calculated using the SCS curve number method (Ogrosky & Mockus, 1964). Swedish curve numbers were estimated from soil and landuse data available for the Mälaren catchment. Dissolved nutrient loads are derived by multiplying runoff by a land use-specific nutrient concentration. There are also watershed-wide nutrient concentrations associated with baseflow. The contributions of nutrients from septic systems were estimated from literature values. Point source loadings from treated sewage and industrial effluents are also input and accounted for in the overall estimates of nutrient flux. Dissolved nutrient loads can be summed by month, season or year. Sediment and particulate nutrient loss were not included in our analysis, so only dissolved nutrient estimates were modelled.

Data requirements and data sources

Land use data from the Swedish Land Survey (Lantmäteriet) were based on the CORINE (European Commission Coordination of Information on the Environment) level 3 classification scheme. Soil data from the Swedish Geological Survey (SGU) map (1: 1,000,000) were used for runoff curve number calculation. Meteorological data (daily precipitation and air temperature) from a 4 × 4 km grid interpolation of local stations (Johansson, 2002) were used for calibration of the hydrological model for the period of 1980–1991. The fit of the model was optimised using measured stream discharge. Both meteorological and hydrological data were from the Swedish Meteorological and Hydrological Institute (SMHI). Simulations for the historical period were based on a 30-year period (1961–1990).

Point sources of nutrients from wastewater treatment plants and industry were based on published data from the TRK (Transport–Retention–Källfördelning) study (Brandt & Ejhed, 2002). Nutrients from septic systems were reported as an annual estimate for the TRK study, and these loadings were converted to fixed daily rates when used as inputs to the model.

In GWLF, nutrient loads from diffuse sources are partitioned by land use, and information about land use-specific nutrient concentrations were drawn from average published values from the TRK study

(Brandt & Ejhed, 2002). Information for agricultural land uses was used for selected areas in the JRK (Typområden på jordbruksmark) study (Kyllmar & Johnsson, 1998). Concentrations in groundwater were taken from long-term water quality data (SLU database, Swedish Agricultural University, http://www.info1.ma.slu.se). Groundwater concentrations were calculated as the mean of water quality samples collected at or below the 20th percentile of historical streamflow. Long-term monthly water quality data from four stations near each inflow to Galten basin were used for calibration of the nutrient model (SLU database). The model was optimised to minimise the residuals between long-term average measured and modelled N and P concentrations.

Climate change scenario application and downscaling to the catchment level

Climate forcings for this study were taken from the Rossby Centre Atmosphere-Ocean (RCAO) regional climate model and the Hadley Centre regional climate model (HadRM3p) using boundary conditions from two general circulation models: the Max Planck Institute ECHAM4/OPYC3 and the Hadley Centre HadAM3H for two IPCC emission scenarios (A2, B2) (Samuelsson, 2004; Table 2). A 30-year "time slice" was used for a control period (1961–1990) and future period (2071–2100). For both A2 and B2 scenarios, increases in population growth are projected, but the rate of increase is greater for scenario A2 (Houghton et al., 2001). The use of multiple models allows for some consideration of the range of uncertainty in model representation of the climate system.

The method used to downscale climate forcings from the regional to the local catchment scale is based on monthly average changes in precipitation and temperature, known as the "delta change" approach in its simplest form, as described by Hay et al. (2000).

The difference in average monthly temperature between control and future RCM model scenarios is added or subtracted from the observed daily temperature (Table 3). For precipitation, the ratio of the monthly total precipitation for control and future RCM scenarios is used as a multiplier that is applied to the daily record of observed precipitation (Table 3).

One limitation in this method is that the frequency of precipitation events is not varied (Andreásson et al., 2004a). To avoid this pitfall, and examine the widest range of variability in climate, we used a resampling approach to create multiple weather sequences from the control and future climate scenarios. Using this method, monthly weather records were randomly recombined to create multiple 30-year data series that could be used to drive the GWLF model. For example, a random choice of one of the 30 January records was made followed by a random choice of one of the 30 February records and so on to make up 100 30-year synthetic weather timeseries for the purpose of hydrological modelling. This approach does not account for any interdependence of monthly weather between successive months. Hydrological and nutrient yield results are presented as medians and variance of multiple model realisations.

Results

Hydrological model performance

To derive the best set of hydrological model coefficients, eight sub-catchments, where streamflow measurements were available, were modelled. Hydrologic model coefficients were optimised to obtain the

Table 2 Climate models and scenarios used for future projections of climate

Abbreviation	General Circulation Model (GCM)	Regional Climate Model (RCM)	SRES Scenario (IPCC, 2001)
E A2	ECHAM4/OPYC3	RCAO	A2
E B2	ECHAM4/OPYC3	RCAO	B2
H A2	HadAM3H	RCAO	A2
H B2	HadAM3H	RCAO	B2
Had A2	HadAM3P	Had RM3p	A2
Had B2	HadAM3P	Had RM3p	B2

Table 3 Monthly change factors applied to observed weather timeseries for future scenario (2071–2100) simulations

Month	Temperature change factor (°C)[a]						Precipitation change factor (proportion)[b]					
	E A2	E B2	H A2	H B2	Had A2	Had B2	E A2	E B2	H A2	H B2	Had A2	Had B2
Jan	5.76	4.23	4.18	2.85	5.13	4.52	1.58	1.32	1.50	1.16	1.53	1.27
Feb	6.45	5.17	3.26	2.46	2.66	2.69	1.43	1.50	1.40	1.30	1.37	1.16
Mar	6.51	5.05	3.36	2.17	4.24	2.92	1.39	1.23	1.18	1.17	1.16	1.14
Apr	5.00	3.74	3.96	2.71	3.98	3.31	1.38	1.12	1.02	1.06	1.15	1.24
May	3.59	2.73	3.98	2.74	3.64	2.98	1.04	1.18	1.35	1.04	1.11	1.23
Jun	3.35	2.67	3.01	1.24	4.04	3.06	0.93	0.92	0.86	1.05	0.99	0.90
Jul	3.77	2.81	3.21	1.45	4.79	4.21	0.88	1.02	0.86	0.78	0.86	0.74
Aug	4.54	3.42	3.49	2.24	5.03	4.44	0.67	0.74	0.70	0.79	0.83	0.74
Sep	4.15	3.11	3.80	2.55	4.37	3.13	0.90	1.02	0.73	1.00	0.76	0.79
Oct	4.49	3.24	3.73	2.64	3.85	3.04	1.38	1.26	1.19	1.06	0.80	0.96
Nov	4.96	4.01	4.18	3.18	4.36	3.50	1.40	1.29	1.22	1.24	0.95	1.05
Dec	4.65	3.75	4.65	2.94	4.85	3.59	1.44	1.34	1.30	1.17	1.20	1.16

[a] Model (scenario—control) mean monthly temperature

[b] Proportion model (scenario: control) total monthly precipitation

best match between simulated and measured river discharge. The coefficients were then used to simulate river discharge for the total river drainage areas for each of the four inflows. Summaries and statistics for evaluating model efficiency are given in Table 4. The hydrological model calibration period was 1981–1990. The same model coefficients were tested for a 10-year validation period (1991–2000) and the Nash-Sutcliffe statistics (Nash & Sutcliffe, 1970) remained high, indicating a close correspondence between measured and modelled streamflow (Table 4).

Patterns in climate forcings

In Figs. 1–4, only results for Arbogaån, the largest river drainage in Galten basin, are shown, since the patterns in results for all other sub-basins are consistent with those for Arbogaån. The temperature factors applied in Table 2 result in a change in mean daily air temperature at the catchment scale, as shown in Fig. 1. Scenario E A2 shows the greatest overall increase in mean daily air temperature, and all scenarios show the greatest temperature increases during the winter months (Table 3).

Changes in precipitation are variable at a monthly interval between different scenario projections (Fig. 2). Overall, there is an increase in annual precipitation for all scenarios except for the Hadley Centre Had B2 results. In general, the future scenarios suggested that the increase would occur between the fall and spring, and the summers would be somewhat drier.

Impacts on modelled snowpack

In GWLF, a simple algorithm is used to estimate the partitioning of precipitation into rain and snow, and to estimate the accumulation and melting of snow. On any day when mean daily temperature drops below 0°C, precipitation is accumulated as snow. To account for snowmelt, losses from the snowpack are modelled as a function of mean daily air temperature using a simple degree-day melt factor (Haith et al., 1992). A great reduction in snowpack occurs in all future scenario simulations, due to higher winter temperatures.

Catchment response: seasonal changes in river discharge and nutrient loads

The greatest change in streamflow resulted from increased winter precipitation in the form of rain rather than snow (Fig. 2), lower snow accumulation and decreased spring snow melt. This translated to a change in the timing of peak river discharge, with a shift or disappearance of the springmelt peak (Fig. 3). A similar shift is seen in nutrient loadings as a

Table 4 Performance of GWLF hydrological sub-model for gauged sub-catchments

River	Calibration period	Validation period	Summary for calibration period (1981–1990) (mm)		
Sub-catchment*	Nash-Sutcliffe R^2 streamflow (monthly) 1981–1990	Nash-Sutcliffe R^2 streamflow (monthly) 1991–2000	Mean annual streamflow (observed)	Mean annual evapotranspiration	Mean annual precipitation
Arbogaån					
Hammarby	0.76	0.80	387 (387)	471	853
Dalkarlshyttan	0.70	0.78	436 (434)	473	905
Kåfalla	0.64	0.78	454 (453)	493	943
Fellingsbro	0.69	0.70	391 (390)	496	882
Hedströmmen					
Dömsta	0.74	0.79	395 (394)	491	880
Köpingsån					
Odensvibron	0.75	0.75	293 (293)	467	756
Kolbäcksån					
Hallstahammar	0.56	0.61	328 (326)	468	756
Berg	0.69	0.59	276 (275)	426	701

* Sub-catchment name corresponds to river gauge name (SMHI, 1994)

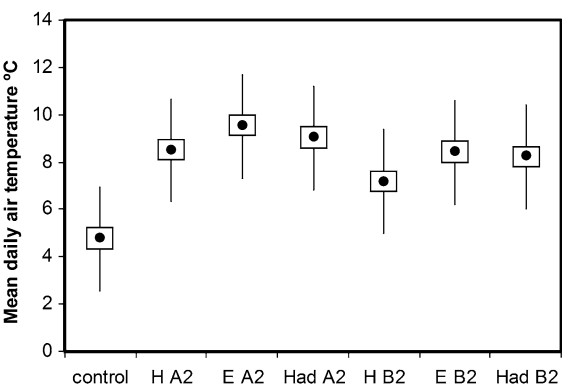

Fig. 1 Mean daily air temperature—100 30-year simulations obtained by resampling. Boxplots indicate medians and interquartile ranges, and whiskers show minimum and maximum values for 100 30-year sequences of mean daily air temperature for a control (based on observed weather) and future scenarios (based on observed weather perturbed by factors given in Table 2)

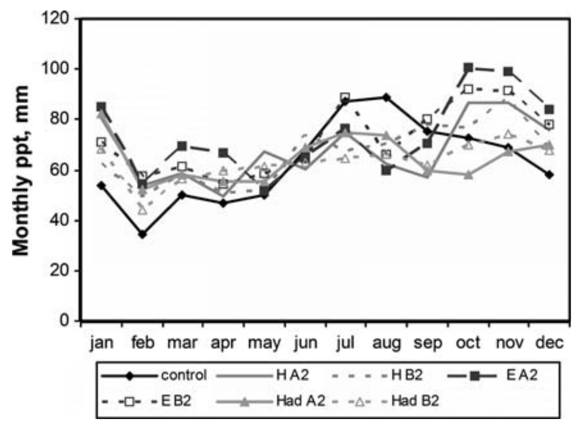

Fig. 2 Monthly precipitation (ppt) based on 100 30-year simulations obtained by resampling

consequence, with decreased loading during the period from spring to autumn and increased loading in the winter months. The pattern for dissolved inorganic nitrogen (DIN) load is shown in Fig. 4. The pattern for dissolved phosphorus load is similar, with a maximum increase of 12% in the annual load for the most extreme future scenario (E A2), with the majority of this increase occurring during the winter months. DIN and DIP loads decreased by 12–14% and 4–6%, respectively for the HadRM3p A2 and B2 scenarios due to a decrease in annual river discharge. The impact on total annual loads is shown in the range of median values for streamflow, dissolved phosphorus and dissolved inorganic nitrogen in Table 5.

Discussion

The net effect of future climate projections on changes in river flow is variable in terms of total

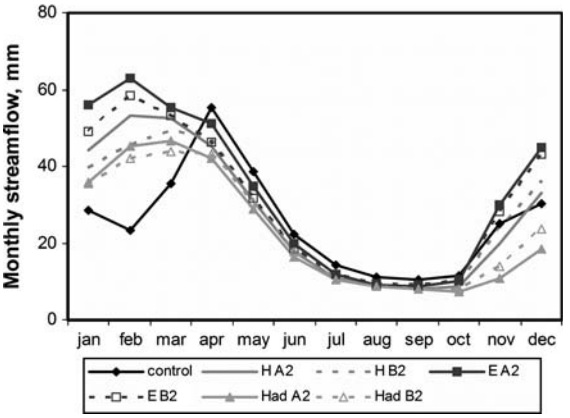

Fig. 3 Monthly streamflow based on 100 30-year simulations obtained by resampling

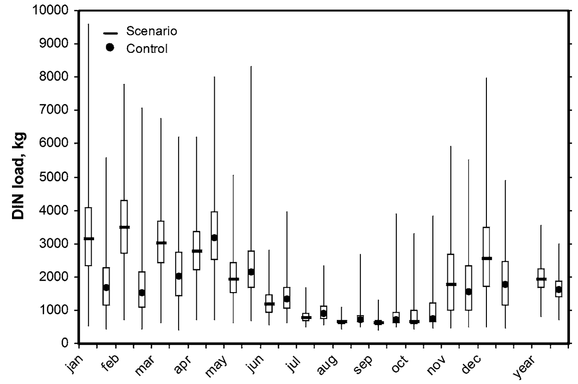

Fig. 4 Comparison of the dissolved N load for the control and E A2 climate scenario based on 100 30-year simulations obtained by resampling. Boxplots indicate medians and interquartile ranges, and whiskers show minimum and maximum values

increase (3–22%), but the change in flow regime from snowmelt-dominated spring runoff to one dominated by maximum winter discharge is the prevailing pattern for all future climate scenarios. The Hadley Center RCM results are less extreme, but show a similar pattern. Each of the climate models has its own biases, but the outcome is not markedly different when the impacts on hydrology and nutrient transport are considered with this simple modelling approach. Hydrological modelling results for the HBV model applied to a comprehensive study for the whole of Sweden showed a change in runoff ranging from +2 to −35% for the Norrström basin (Andréasson et al., 2004a, b). Our results for the same scenarios range from +3 to +22%. Andréasson et al. (2004a, b) presented results on a regional scale, and their approach differed from ours, particularly in how the climate signal was transferred to the hydrological model. However, a similar seasonal pattern in runoff was shown, for an example from southern Sweden for four future climate scenarios that matched our discharge results. The impacts of shifts in the timing of peak flows and nutrient pulses from spring to winter

Table 5 Median streamflow and dissolved nutrient loads for principal rivers of Galten basin

Parameter	Model Scenario						
	CTL	E A2	E B2	H A2	H B2	Had A2	Had B2
Streamflow (mm year^{-1})							
Arbogaån	328	398	376	339	336	285	292
Hedströmmen	339	409	387	350	347	296	299
Köpingsån	266	336	310	281	277	237	241
Kolbäcksån	270	318	303	270	270	219	226
DIP (kg km^2 year^{-1})							
Arbogaån	6.43	7.16	6.82	6.57	6.43	6.10	6.04
Hedströmmen	3.47	4.12	3.85	3.62	3.52	3.24	3.20
Köpingsån	5.61	7.07	6.48	5.88	5.70	5.05	5.46
Kolbäcksån	2.75	2.75	2.75	2.75	2.75	2.75	2.75
DIN (kg km^2 year^{-1})							
Arbogaån	148	177	166	153	150	131	132
Hedströmmen	168	205	193	175	172	147	149
Köpingsån	148	186	174	157	153	131	133
Kolbäcksån	86.0	92.8	90.7	86.3	86.3	79.8	80.7

have important implications for receiving waters. The magnitude and variability in winter discharge may increase when precipitation from individual winter storms is not stored in a snowpack (Gibson et al., 2005). This accounts for the winter increases in DIN, as shown in Fig. 4. Galten basin, with a short retention time, would experience earlier flushing at a time when light and temperature limit phytoplankton growth. So increases in dissolved nutrient loads may not result in a growth response in phytoplankton. Other basins of Lake Mälaren have much longer residence times than Galten (Willén, 2001), and as a result impacts in these areas could be greater.

Conclusions

The GWLF model was used to estimate the effects of hypothetical climate change scenarios on hydrology and the consequent implications for nutrient loading, for four rivers spanning three orders of magnitude in drainage area size. The most profound change for future scenarios was in the seasonal distribution of river flow and nutrient loads. Increases in export occur earlier in the winter, with decreases during the spring snow melt period and summer months for all future scenarios. Seasonal changes in water quantity and quality from diffuse sources projected from climate impacts are unparalleled in the historical record. A logical next step to our modelling work would be to evaluate management strategies and land use change in combination with climate projections to get a better picture of their combined effects.

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