Improving DLBRM's Capabilities to Forecast Hydrological and Water Quality Impacts of Land Use Changes

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Overview

Detailed mathematical models of watershed hydrology and water quality are fundamental for integrated ecological and physical forecasting as well as for developing environmental management strategies in the Great Lakes basin. To address this need, GLERL developed the Distributed Large Basin Runoff Model (DLBRM, Croley and He 2005), a distributed-parameter hydrological model that is currently being expanded to simulate sediment generation and transport (Croley and He 2006; He and Croley 2006). Performances of DLBRM in replicating present hydrological responses of watersheds are more than satisfying (correlation with observed daily streamflow better than 0.80 for most watersheds in the Great Lakes for the validation period – DeMarchi et al. 2009). However, the present version of the DLBRM is not very sensitive to land use changes and does not represent the relation between land use and hydrology/non-point pollution with sufficient detail, thus limiting its capability to evaluate different land use and climate change scenarios (Cowden et al. 2006). The research proposed herein maintains the simple, but conceptually sound and proven, structure of the DLBRM, while increasing the detail of the interception, infiltration, and evapo-transpiration processes. These modifications will increase sensitivity to land use of the overall hydrologic model. Additionally, a simplified representation of river network characteristics will be included to improve sediment transport and pollutant load simulation. The proposed modifications will enhance GLERL's ecosystem forecasting capabilities with immediate relevance to other efforts: the GLERL Lake Erie Integrated Effort, NOAA's Center of Excellence for Great Lakes and Human Health at GLERL, the EcoFor ecological forecasting project for predicting Lake Erie hypoxia and impacts, and two proposed projects looking at multi-stressors effects on fish and at watershed phosphorus loading effects on algal growth, both in the Saginaw Bay watersheds.

Proposed Work

GLERL transformed its lumped-parameter large basin runoff model LBRM (Croley and He 2002) into a two-dimensional, spatially-distributed model (DLBRM), applied to every 1 square kilometer cell of a watershed. The DBLRM adopts a spatial distribution of model parameters based on terrain elevation, soil characteristics, and land use to better represent the hydrologic response of the watershed (Croley and He 2005; Croley and He 2006). Further, it includes the spatial distribution of meteorological forcing as well as simulation of flows between adjacent cells' surface zones, upper soil zones, lower soil zones, and groundwater zones. In 2007 GLERL and CILER calibrated DLBRM for 18 Great Lakes watersheds (Figure 1 and Table 1) for the period 1950-1964 (Table 2), applied it to the period 1999-2006 (Table 3), and recalibrated it for the 1999-2006 (Table 4) (DeMarchi et al, 2009).

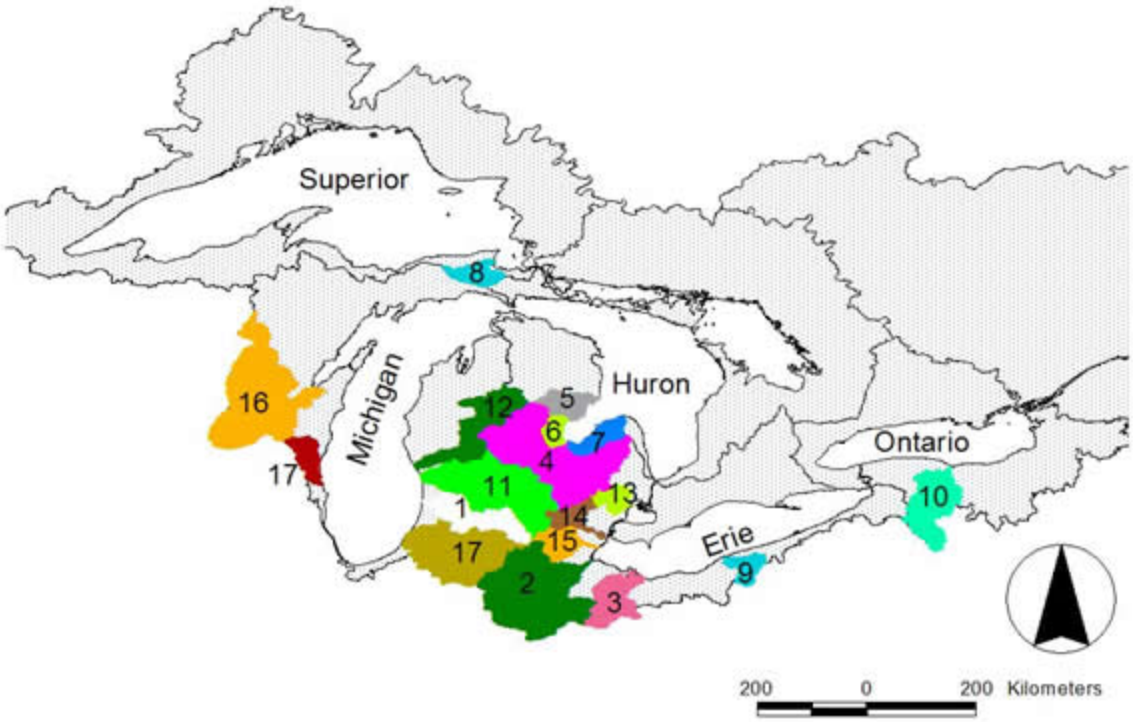

Figure 1: *Applications of the DLBRM in the Great Lakes Basin. Watersheds are described in Table 1.*

Table 1: Land use and hydrologic characteristics of the 18 watersheds.

#	Name	Size	Watershed Coverage				Hydrology (1950-64)			
			Crops	Forest	Urban	Water & Wetland	Avg. Temp.	Avg. Precip.	Avg Flow	Flow Var. Coef*
		(km^2)	(%)	(%)	(%)	(%)	( )	(cm/d)	(cm/d)	
1	Kalamazoo	5612	81.9	9.0	6.1	2.9	9.1	0.22	0.078	0.53
2	Maumee	17541	91.6	3.3	4.2	0.7	10.2	0.22	0.072	1.80
3	Sandusky	5012	91.3	2.2	4.0	2.2	10.4	0.24	0.069	2.29
4	Saginaw	16680	66.3	20.4	6.1	6.7	8.3	0.20	0.056	1.42
5	AuGres	2777	34.4	46.7	14.7	14.7	7.1	0.20	0.079	1.09
6	Kawkawlin	1409	63.7	18.9	12.4	12.4	8.1	0.20	0.048	2.44
7	Pigeon	2425	90.3	2.6	1.8	1.8	8.2	0.23	0.072	2.02
8	Tahquamenon	2307	1.9	62.9	34.9	34.9	5.1	0.22	0.099	1.11
9	Grand (Ohio)	2008	76.8	13.4	6.5	6.5	9.6	0.27	0.113	1.95
10	Genesee	6874	58.5	31.2	1.1	1.1	8.3	0.23	0.102	1.22

11	Grand (Mich.)	14879	81.3	9.7	2.5	2.5	8.9	0.21	0.062	1.01
12	Muskegon	7504	38.9	45.7	10.9	10.9	7.3	0.21	0.077	0.58
13	Clinton	2062	63.9	6.1	2.2	2.2	9.3	0.20	0.060	1.51
14	Huron	2596	72.7	10.5	5.6	5.6	9.3	0.21	0.058	0.90
15	Raisin	3015	93.1	2.4	1.5	1.5	9.3	0.23	0.060	1.54
16	Fox	17123	56.9	25.0	16.2	16.2	6.9	0.22	0.059	0.75
17	St. Joseph	12545	87.6	4.0	2.0	2.0	9.6	0.24	0.083	0.64
18	Milwaukee	2420	72.3	3.8	2.2	2.2	8.0	0.21	0.049	1.77
*Flow variation coefficient equals flow standard deviation divided by average flow										

Table 2: DLBRM calibration performances for the 1950-64 period.

Basin	Bias (%)	Correlation	RMSE/Flow (%)	Nash Sutcliffe
Kalamazoo	-0.1	0.88	25.2	0.70
Maumee	7.0	0.90	78.5	0.73
Sandusky	14.0	0.85	121.9	0.55
Saginaw	-1.9	0.90	60.9	0.76
AuGres	-1.7	0.86	54.5	0.66
Kawkawlin	9.7	0.79	147.9	0.25
Pigeon	6.9	0.79	125.0	0.30
Tahquamenon	-3.3	0.95	35.9	0.89
Grand (Ohio)	5.6	0.85	103.1	0.55
Genesee	-4.5	0.87	60.9	0.64
Grand (Mich.)	-1.9	0.92	40.6	0.80
Muskegon	-1.0	0.87	27.9	0.70
Clinton	-2.1	0.87	75.4	0.65
Huron	-0.8	0.89	40.6	0.74
Raisin	1.4	0.90	66.1	0.76
Fox	0.8	0.80	45.1	0.44
St. Joseph	-0.1	0.93	24.2	0.82
Milwaukee	-2.7	0.84	94.8	0.58

Table 3: Changes in hydrology between 1950-1964 and 1999-2006 and DLBRM robustness test performances for 1999-2006.

Basin	Size (km^2)	Temp. Change (C)	Precip. Change (%)	Flow Change (%)	Bias (%)	Corr.	RMSE/Flow (%)	Nash Sutcliffe
Kalamazoo	5612	0.13	16.35	26.45	-6.9	0.86	27.0	0.43
Maumee	17541	0.18	9.67	19.28	-5.4	0.89	70.1	0.67
Sandusky	5012	0.06	11.19	28.88	-8.0	0.82	107.9	0.31
Saginaw	16680	0.25	10.49	10.30	-0.2	0.79	72.8	0.60
AuGres	2777	0.50	5.96	12.01	0.2	0.85	50.3	0.69
Tahquamenon	2307	0.74	2.61	0.18	13.4	0.93	43.1	0.85
Grand (Ohio)	2008	-0.09	14.58	18.65	-2.1	0.82	90.3	0.55
Genesee	6874	0.19	16.53	10.29	-1.2	0.80	54.9	0.59
Grand (Mich.)	14879	0.25	13.85	15.37	-1.9	0.83	46.6	0.66

Muskegon	7504	0.38	10.64	1.14	11.9	0.91	26.7	0.77
Clinton	2062	0.21	15.76	30.65	-14.4	0.79	71.2	0.43
Huron	2596	0.29	12.76	1.63	5.5	0.83	42.7	0.64
Raisin	3015	0.36	0.54	17.66	-9.0	0.84	68.8	0.53
Fox	17123	0.53	9.10	10.12	2.1	0.76	44.0	0.36
St. Joseph	12545	0.20	8.87	7.26	-8.6	0.91	22.3	0.78
Milwaukee	2420	0.57	14.54	38.53	-16.2	0.82	75.0	0.51

Table 4: DLBRM re-calibration performances for the 1999-2006 period.

Basin	Bias (%)	Correlation	RMSE/Flow (%)	Nash Sutcliffe
Kalamazoo	0.7	0.91	20.8	0.77
Maumee	6.2	0.91	66.3	0.77
Sandusky	12.8	0.84	102.3	0.49
Saginaw	2.1	0.84	60.0	0.51
AuGres	-1.7	0.89	36.6	0.72
Tahquamenon	-1.1	0.94	35.5	0.87
Grand (Ohio)	5.1	0.86	81.9	0.57
Genesee	1.8	0.85	47.9	0.50
Grand (Mich.)	0.2	0.90	35.4	0.76
Muskegon	0.0	0.92	21.4	0.82
Clinton	1.3	0.88	53.2	0.70
Huron	2.6	0.88	36.3	0.64
Raisin	5.1	0.88	61.0	0.65
Fox	-0.1	0.85	35.7	0.61
St. Joseph	-0.4	0.94	18.6	0.85
Milwaukee	3.4	0.90	56.5	0.77

In 2008, GLERL and CILER extended the application of DLBRM to additional 16 watersheds (Figure 2 and Table 5).

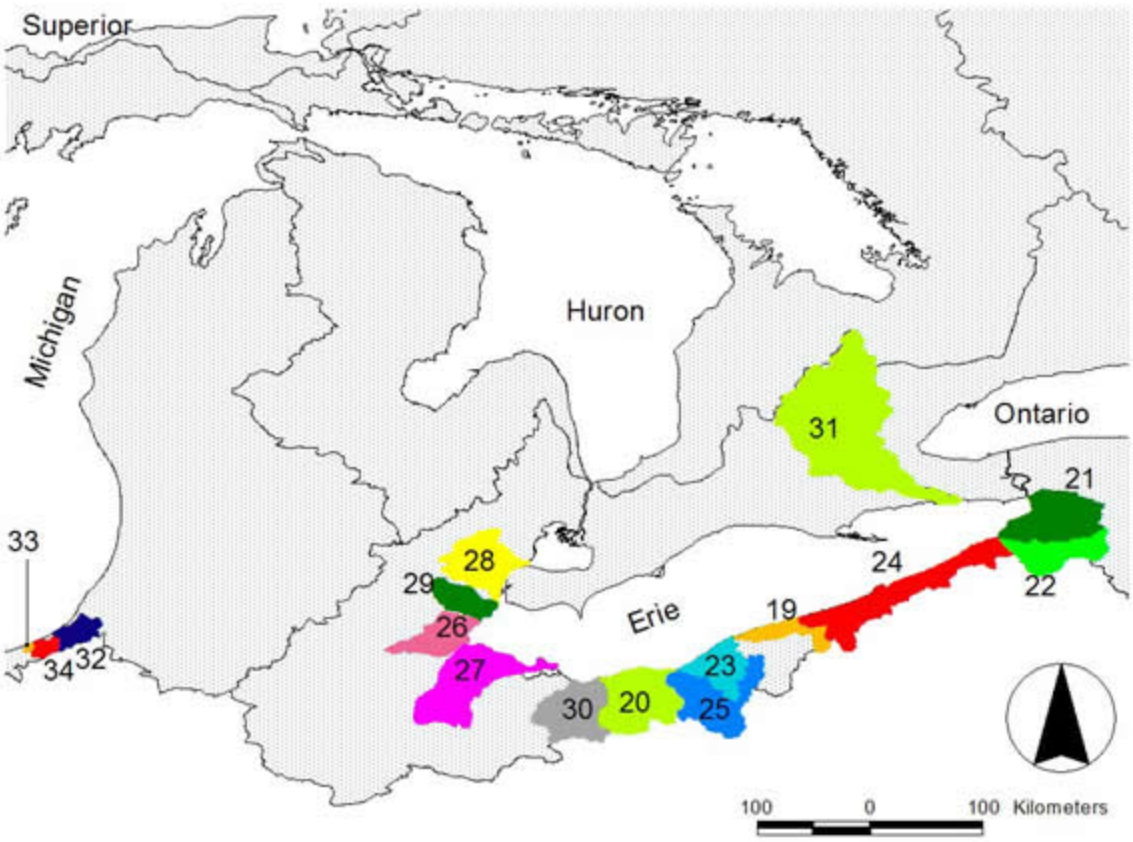

Figure 2: *Additional applications of the DLBRM in the Great Lakes basin. Watersheds are described in Table 2.*

Table 5: Land use and hydrologic characteristics of the additional 16 watersheds

#	Name	Size	Watershed Coverage				Hydrology (1950-64)			
			Crops	Forest	Urban	Water & Wetland	Avg. Temp.	Avg. Precip.	Avg. Flow	Flow Var. Coef.*
	(km^2)	(%)	(%)	(%)	(%)	(%)	(C)	(cm/d)	(cm/d)	
19	Ashtabula	677	29.3	52.6	8.6	5.1	9.6	0.27	0.115	2.46
20	Black-Rock	2294	48.9	22.8	18.2	2.4	10.1	0.25	0.081	2.64
21	Buffalo	1874	38.5	42.6	12.6	3.6	8.3	0.26	0.131	2.19
22	Cattaraugus	1427	43.8	55.0	0.3	0.4	8.1	0.27	0.149	1.64
23	Chagrin	962	4.4	40.1	31.9	3.1	9.9	0.26	0.131	2.04
24	Conneaut-Girard	2262	35.4	48.6	5.8	8.9	9.2	0.28	0.138	2.16
25	Cuyahoga	2070	19.8	37.4	28.2	1.5	9.9	0.26	0.110	1.39
26	Ottawa[2]	1015	64.1	5.4	19.7	4.0	10.0	0.23	0.074	1.88
27	Portage	2482	87.0	0.5	4.2	6.7	10.4	0.23	0.072	2.45
28	Rouge	1070	5.4	4.4	77.5	3.3	9.7	0.21	0.056	1.93
29	Stony[3]	723	70.3	12.2	6.3	5.1	9.1	0.23	0.064	1.67
30	Vermilion	1946	87.1	8.6	1.7	1.2	10.1	0.24	0.073	2.62

31	Grand (Ont)	6693	68.0	7.8	5.0	1.6	7.2	0.23	0.083	1.61
32	Galien [4, 5]	496	54.5	37.6	2.3	1.9	9.8	0.27	0.140	0.79
33	Kintzele Ditch[4 5]	42	8.9	56.8	30.2	1.8	9.8	0.27	0.127	1.00
34	Trail Creek	176	23.0	56.0	14.0	0.1	9.8	0.27	0.127	1.00

[1]Flow variation coefficient equals flow standard deviation divided by average flow.
[2]1988-1996
[3]1970-1981
[4]1970-1984
[5]500 m resolution

Parallel to the calibration/validation of this hydrologic component of the DLBRM, GLERL and CILER began adding a water quality component into it by including land erosion based on an adaptation of the revised universal soil loss equation (RUSLE), and sediment and pollutant routing capabilities (Croley and He 2006; Croley et al. 2006). Further, ginaw Bay (He et al., 2008) watersheds and transformed into GIS layers compatible with the DBLRM (He and Croley 2006) and water quality sample data for these rivers are being collected from USGS, Michigan Department of Environmental Quality, Ohio EPA, and other databases for future calibration and validation of the model (Croley et al. 2006). Similar watershed and in-stream data will be developed for additional watersheds (Muskegon, Rouge, Huron, Stony Creek, Raisin, Ottawa, Portage, Sandusky, and Vermillion) in 2007 (Croley et al. 2006).

As part of the CY07-DeMarchi-04 project, a Summer fellow did a survey of models and model parameters relating land use to interception and infiltration. He also acquired cross section and velocity measurements for the Maumee River, Grand River (Michigan), Kalamazoo River, Muskegon River, and Saginaw River and developed relations relating cross section parameters to drainage area.

First, the inclusion of sediment erosion and pollutant transport in the present DLBRM version will be completed and tested in the Maumee, Grand (Michigan), Kalamazoo, and the four tributaries of Saginaw Bay watersheds according to the procedure described in Croley et al. (2006). The sediment generation and the transport model will be calibrated to match the seasonal/annual loads assessed directly from measurements for the periods in which water quality samples are abundant and by using watershed specific sediment-rating curves when sampling is infrequent. A first order decay will be added to the transport model to describe the dynamics of nutrients, bacteria, and water temperature in the watersheds. Such models will be calibrated to match the seasonal pollutant load or average water temperature derived directly from measurements when possible or from using rating curves, when water quality samples are sparse.

The hydrology of the modified DLBRM will be modified by including a new storage variable representing the fraction of precipitation intercepted by canopy and surface depressions, by making the rate with which precipitation infiltrates in the soils dependent also on the land use in addition to its present dependence on moisture deficit, and by determining land-use specific potential evapotranspiration.

The hydrology of the modified DLBRM will be tested in the Maumee, Grand (Michigan), Kalamazoo basins and in the four Saginaw Bay watersheds. The sensitivity to land use changes will be tested also by comparing the DLBRM with observed flow and changing land uses in the Clinton River, a watershed in suburban Detroit (Cowden et al. 2006), and in the Muskegon River watershed (MREMS 2006).

Finally, several aspects of the water quality component of DLBRM will be improved by introducing a simplified representation of the river network characteristics to derive stream velocity and depth as a function of the discharge. This will allow us to better represent the erosion/deposition processes in the river network by making the sediment carrying capacity, which is presently a constant, a function of stream velocity and depth (e.g., Julien 1995; Neitsch et al. 2005). Further, we will account for the trapping of sediments by dams and reservoirs according to the procedure illustrated by Morris and Fan (1998).

The improved water quality components in the DLBRM will be coupled with the improved hydrological model and tested in the Maumee, Grand (Michigan), Kalamazoo, and the four Saginaw Bay watersheds by using the procedure described in Croley et al. (2006) and outlined previously.

DLBRM hydrologic and water quality components will be calibrated and validated also for the Muskegon River and their predictions will be compared with more detailed experimental data and with the predictions by a more complex hydrological and hydraulic model (MREMS, 2006) to assess their validity and uncertainty.

Scientific Rationale

Long-term ecological forecasting and operational water resource management in the Great Lakes basin require the use of large-scale watershed models for estimating inflow and pollutant loads. In the last thirty years several computer models have been developed for simulating watershed hydrology and water quality in great detail. However, their large data and computational requirements coupled with the substantial size of the basin, makes it impossible to use them for basin-wide applications in the Great Lakes region. The strategy adopted by GLERL to cope with this problem is to keep the complexity of models to the minimum level compatible with the desired application. Following this approach, GLERL first developed the lumped-parameter LBRM and applied it extensively to all the 121 major tributaries of the Laurentian Great Lakes. LBRM is used in the Great Lakes Advanced Hydrologic Prediction System to make extended probabilistic forecasts of many hydrological variables, including lake levels, at GLERL and at several US and Canadian agencies concerned with operational decision making. GLERL also uses it for basin-wide climate change impact assessments and management evaluations. However, the lack of spatial representation of the hydrological processes in a watershed makes the LBRM inappropriate for sensitive operational applications, such as forecasting beach closure, and for supporting nonpoint pollution estimation.

Recently, GLERL adapted the LBRM from its lumped-parameter definition for an entire watershed to a two dimensional representation of the flow cells comprising the watershed (DLBRM) and applied it to 18 watersheds in the Great Lakes region (Croley et al. 2006). This involved changes in the model structure to apply it to the micro scale, the organization of watershed cells according to flow directions, and the implementation of spatial flow routing. In the present version of DLBRM, the water in each cell is subdivided among surface water (overland flow and streams), upper soil zone water, lower soil zone water, and deep ground water. Precipitation either infiltrates into the upper soil or moves into surface water as runoff, according to the wetness of the upper soil. Water in the upper soil is subject to evaporation, vertical percolation to the lower soil zone, or lateral movement to the upper soil zone of the immediately downstream cell. Water in the lower soil zone evaporates, percolates to ground water, moves laterally to the lower soil zone of the immediately downstream cell, or exfiltrates to the surface water (interflow). Groundwater, instead, either moves laterally to the groundwater zone of the immediately downstream cell or exfiltrates to the surface water (groundwater flow). Model parameters (evaporation rates, percolation rates, and lateral movement rates) vary spatially to match the distribution of selected observable watershed characteristics, such as upper and lower soil zone permeability, upper soil zone available water capacity, and the square root of surface slope divided by Manning's roughness coefficient. Minimization of the root mean square error between observed and modeled daily watershed outflow is used to determine the watershed-wide average of the model parameters, thus limiting the calibration parameters to 15. Since meteorological forcing is spatially distributed and calibration parameters are dependent on the spatial distribution of soil properties, DLBRM simulation of present streamflow is more than satisfactory (correlation is generally higher than 0.85 for most watersheds) and allows consideration of spatial properties (Croley and He 2005).

The present structure of the DLBRM increases GLERL capabilities to forecast flow for sensitive applications, to determine the water distribution within a watershed, and to support non-point source pollution assessment, while minimizing the number of calibration parameters and computation requirements. However, in the present version of the DLBRM, land use contributes directly only to the routing of surface flow, thus limiting the sensitivity of the model to landscape variations (Cowden et al. 2006). This reduces the ability of the DLBRM to forecast the hydrologic response of watersheds experiencing relevant changes in land use because of urbanization, agricultural practice change, or implementation of land reclamation projects.

Land Use

We will increase the influence of land use on the DLBRM by increasing the detail of three components of the model: vegetation and surface interception, infiltration, and evapotranspiration. A fraction of precipitation is intercepted by canopies and small surface depressions and does not contribute to runoff and subsurface flows. We will model interception as a storage variable that precipitation must fill before becoming available to other hydrological processes. The importance of interception depends strongly on land cover: for example, surface storage capacity is 5.0 cm for flat areas covered by mature corn plants, 0.6 – 0.8 cm for areas covered by grass, but only 0.2 cm for paved areas (Hiemstra 1958; Tholin and Kiefer 1960). In addition, we will make the infiltration rates dependent on land use and the upper soil moisture

deficit instead of only on the upper soil moisture deficit as in the present formulation. Infiltration rates vary from close to zero for heavily paved areas, to 0.2 cm/h for fallow conditions, to 0.7 cm/h for woods and forests (Holtan and Lopez 1973). Finally, we will introduce a relation between land cover and evapotranspiration, with soil covered by plants transpiring much more water than paved or fallow soils, especially during the growing season. For this purpose, we will use typical crop factors and development stages (Allen et al. 1998) to determine land use-specific potential evapotranspiration. These improvements will increase the complexity of the DLBRM, requiring the addition of one state variable, three new calibration parameters, and complex seasonally-varying functions of land use. On the other hand, this will enhance the role of land use in the hydrologic response of a watershed, allowing better accounting of the changes in runoff and peak flow resulting from urbanization or remediation measures.

Sediment

Several studies have shown that the maximum concentration of sediments supported by rivers (carrying capacity) is a function of water velocity, depth, and sediment size distribution. Concentrations of available sediments higher than the carrying capacity will cause a deposition of the sediment surplus, while concentrations lower than the carrying capacity will induce erosion of erodible materials along the stream bed and banks. The present formulation of DLBRM simulates this process, but makes the carrying capacity a function only on the season of the year. This solution was temporarily taken because more refined solutions require the determination of the stream depth and velocity along the channel network as function of the cell discharge, a complex process. In order to obtain such information without completely rewriting DLBRM, we will develop watershed-specific regression relations between drainage area or stream order and stream characteristics. These relations will allow us to derive the outflow velocity and depth for each cell as function of the discharge and, by adapting one of several formulas available, the carrying capacity (e.g., Julien 1995; Neitsch et al., 2005). The dependence of the carrying capacity on flow characteristics will improve the capability to represent the “pulsing” nature of non-point source pollution and assess the impacts of urbanization on water quality. Finally, we will introduce in the DLBRM another layer describing the average sediment trapping capacity of dams and reservoirs in the watershed, which will be computed from the ratio between reservoir volume and inflow (Morris and Fan 1998). In this way we will be able to improve the modeling of sediment transport and to widen the range of management options we can explore by including detention basins and wetlands.

This research will considerably extend the forecast capabilities of the DLBRM, a critical tool for the achievement of GLERL’s mission (GLERL 2006) and will increase its usefulness for water resources management. This project supports other projects depending upon it, including NOAA’s Center of Excellence for Great Lakes and Human Health, projects that are part of GLERL’s internal Lake Erie integrated effort, a NOAA project between the National Severe Storms Laboratory and GLERL on using radar-observed precipitation in Great Lakes hydrological forecasting, entitled: Great Lakes-Runoff-Ecosystem Coupling, an NSF project on Understanding Sensitivity of Great Lakes Water Levels to Climatic Forcing: Closed Lake Status 8.4-6.8KA (9400-7700 CAL), a NOAA EcoFor project on Ensemble Forecasts of Hypoxia And Its Ecological Effects via an Integrated Assessment Framework, a New York Sea Grant project

on Great Lakes Resource Shed Delineation, and possibly a NSF/NASA project on Modeling Continental Hydrological and Biological Effects of Intensive Irrigation in the Yellow River Basin, a, NOAA/CSCOP/COP project on Adaptive Integrated Framework (AIF): a new methodology for managing impacts of multiple stressors in coastal ecosystems, and an EPA project on Forecasting algal bloom response to phosphorus loading in Saginaw Bay.

Governmental/Societal Relevance

Forecasting the short and long term quantity and quality of water entering the Great Lakes is fundamental to GLERL's mission and water resources management in the basin (GLERL 2006). For this reason the development and improvement of the DLBRM is a cornerstone of many research projects both inside GLERL and outside. This research will coordinate with NOAA's Center of Excellence for Great Lakes and Human Health for improving the understanding of the relationship between human health and Great Lakes health. DLBRM development is a fundamental part of a multidisciplinary effort to predict the location and severity of toxins in the water, beach closures, and water quality conditions in the Great Lakes basin through a combination of scientific understanding and models of climate, weather, circulation patterns, hydrology, land use, and biology. Such information will allow Great Lakes managers and users to rapidly respond to changes in lake conditions and inform the public of potential health risks in a timely manner. The information ultimately will aid coastal decision-makers in long-term planning to minimize human health hazards.

In addition to this project's relevance to ecosystem forecasting (described below) and hence to GLERL, small-time-and-space-scale distributed-parameter runoff models also would enable improved forecasts of Great Lakes basin riverine flooding, as well as improve existing US and Canadian probabilistic Great Lakes water level outlooks. Interested parties include both Federal governments and National Weather Service River Forecast Centers. The proposed model developments would also benefit climate and land use change impact studies by extending the level of detail possible in assessing impacts over selected areas. This has potential in the upcoming International Joint Commission study of Lake Superior Regulation. The improved distributed-parameter runoff model will be of interest to ongoing Environment Canada Great Lakes–Ottawa River –St. Lawrence River distributed modeling and GLERL's own Great Lakes Advanced Hydrologic Prediction System.

This project addresses NOAA's goal to "Protect, Restore, and Manage Use of Ocean and Coastal Resources through Ecosystem Management Approaches," relevant to the objective to "Protect Restore and Manage use of coastal, ocean and Great Lakes resources." In particular it addresses the strategy to "Assess and Predict" as measured by the "increased number and accuracy of models to understand and predict the interactions of species and their environment."

Finally, the improved DLBRM will provide the stakeholders in the basin with better predictions of the hydrological and water quality response to urban development, changes in agricultural practices, adoption of best management techniques, and land reclamation, as well as other non-point source pollution mitigation projects such as detention basins and wetland restoration.

Relevance to Ecosystem Forecasting

This project is especially relevant to GLERL's emphasis on Ecosystem Forecasting. The DLBRM's continuous-time distributed-parameter rainfall-runoff simulations complement many ongoing and future investigations. The improved DLBRM could be used to estimate flow, sediment, and pollutant loadings to a lake. When coupled with lake circulation, biology, and chemical models, impacts of land-use change or basin developments could be assessed in terms of impacts on a lake environment to which the watershed drains. This project forms part of GLERL's internal Lake Erie integrated effort, NOAA's Center of Excellence for Great Lakes and Human Health, the joint EcoFor project, Ensemble Forecasts of Hypoxia And Its Ecological Effects via an Integrated Assessment Framework, a New York Sea Grant project on Great Lakes Resource Shed Delineation, and an NSF project on Understanding Sensitivity of Great Lakes Water Levels to Climatic Forcing: Closed Lake Status 8.4-6.8KA (9400-7700 CAL). It is also instrumental to three proposed projects mentioned at the end of section 12 above.