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APPLICATION OF A DISTRIBUTED WATERSHED HYDROLOGY AND WATER QUALITY MODEL IN THE GREAT LAKES BASIN

CARLO DEMARCHI
School of Natural Resources & Environment, University of Michigan, 440 Church Street Ann Arbor, MI 48109-1041, United States

THOMAS E. CROLEY II, TIMOTHY S. HUNTER
National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory, 2205 Commonwealth Blvd.
Ann Arbor, MI 48105-2945

CHANSHENG HE
Department of Geography, Western Michigan University, 3234 Wood Hall
Kalamazoo, MI 49008-5424

The NOAA Great Lakes Environmental Research Laboratory, Western Michigan University, and the University of Michigan are jointly developing a Distributed Large Basin Runoff Model (DLBRM), a physically based, spatially-distributed hydrology and water quality model, to simulate spatial and temporal point and nonpoint source material distributions in Great Lakes watersheds. We automatically calibrated the DLBRM hydrology to reproduce the 1950-1964 and the 1999-2006 watershed outflows in 18 watersheds throughout the Great Lakes region with excellent results; we are extending it to an additional 16 watersheds. In this paper, we analyze the performance of the DLBRM hydrology components in space and time and its further development.

INTRODUCTION

Nonpoint source pollution (from agriculture practices, contaminated sediments, urban runoff, and atmospheric deposition, etc) has been commonly regarded as the primary source of impairment for rivers, lakes, fisheries and wildlife, and aquatic ecosystems in the United States, Europe and other countries (U.S. Environmental Protection Agency (EPA) [1]; He and Croley [2]; Bouraoui and Grizzetti [3]). During the past few decades, several simulation models have been developed to track the production and transport of both point and nonpoint source materials through a watershed by hydrological processes. Examples of such models include ANSWERS (Areal Nonpoint Source Watershed Environment Simulation), AGNPS (Agricultural Nonpoint Source Pollution Model), HSPF (Hydrologic Simulation Program in FORTRAN), and SWAT (Soil and Water Assessment Tool), to name a few (He and Croley [2]). However, these models are either empirically based, or spatially lumped or semi-distributed, or do not consider nonpoint sources from animal manure nor combined sewer overflows (CSOs). To meet this need, the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL), Western Michigan University, and the University of Michigan are jointly developing the Distributed Large Basin Runoff Model (DLBRM), a spatially-distributed, physically-based watershed-scale water quantity and quality model to estimate movement of materials through both point and nonpoint sources in both surface and subsurface waters to the Great Lakes watersheds (Croley and He [2], [4], [5]; He and Croley [6], [7], [8]).

In this paper, we first briefly describe the 18 watersheds throughout the Great Lakes region where the DLBRM was applied, the DLBRM's characteristics, and the calibration procedure. Then we analyze the performance of the DLBRM hydrology component in space and time and anticipate its future developments.

The Study Area

The watersheds where we applied the DLBRM encompass the entire Great Lakes basin (Figure 1) and cover most watershed types present in the areas, from the forested watersheds found in the Lake Superior basin, to the agricultural powerhouses of Southern Michigan and Northern Ohio, to heavily urbanized watersheds (Table 1).

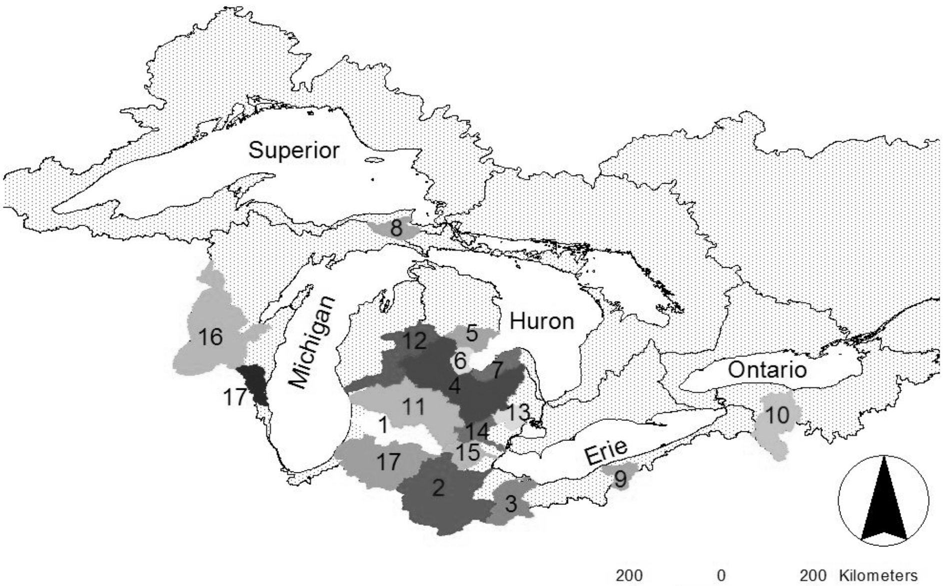

Figure 1. Applications of the DLBRM in the Great Lakes basin. Watersheds are described in Table 1.

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)	(%)	(%)	(%)	(%)	(ºC)	(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	1.6	14.7	7.1	0.20	0.079	1.09
6	Kawkawlin	1409	63.7	18.9	2.1	12.4	8.1	0.20	0.048	2.44
7	Pigeon	2425	90.3	2.6	1.6	1.8	8.2	0.23	0.072	2.02
8	Tahquamenon	2307	1.9	62.9	0.3	34.9	5.1	0.22	0.099	1.11
9	Grand (Ohio)	2008	76.8	13.4	3.0	6.5	9.6	0.27	0.113	1.95
10	Genesee	6874	58.5	31.2	8.2	1.1	8.3	0.23	0.102	1.22
11	Grand (Mich.)	14879	81.3	9.7	6.4	2.5	8.9	0.21	0.062	1.01
12	Muskegon	7504	38.9	45.7	3.7	10.9	7.3	0.21	0.077	0.58
13	Clinton	2062	63.9	6.1	26.9	2.2	9.3	0.20	0.060	1.51
14	Huron	2596	72.7	10.5	10.6	5.6	9.3	0.21	0.058	0.90
15	Raisin	3015	93.1	2.4	2.7	1.5	9.3	0.23	0.060	1.54
16	Fox	17123	56.9	25.0	1.9	16.2	6.9	0.22	0.059	0.75
17	St.Joseph	12545	87.6	4.0	6.3	2.0	9.6	0.24	0.083	0.64
18	Milwaukee	2420	72.3	3.8	21.3	2.2	8.0	0.21	0.049	1.77

*Flow variation coefficient equals flow standard deviation divided by average flow.

Though climate is generally temperate, the northernmost watersheds (Tahquamenon and Fox) are characterized by long and frigid winters, strong, often single, springtime snowmelt, and tepid summers, while the southernmost watersheds feature milder winters with several snowmelt episodes and warmer summers with frequent convective thunderstorms. Watersheds along the eastern and southeastern shores of the lakes [e.g., Sandusky, Grand (Ohio), and Genesee] are much snowier than watersheds on the western shores of the lakes (e.g., Huron, Raisin, and Saginaw) due to the lake-effect snow.

As a result of geology, land use, and climate, the hydrology of these watersheds varies from runoff-dominated watersheds [e.g., Grand (Ohio), Sandusky, and Kawkawlin] to watersheds featuring a strong base flow component (e.g., Kalamazoo and Muskegon). In addition, the Fox River's hydrology is dominated by the large regulated Lake Winnebago.

The Distributed Large Basin Runoff Model

The watershed quality model under development evolves from GLERL's DLBRM (Croley and He [2], [4]; and He and Croley [7]). The DLBRM divides a watershed into a 1-km^2 grid network and simulates hydrologic processes for the entire watershed sequentially. Each 1-km^2 "cell" of the watershed is composed of moisture storages of upper soil zone, lower soil zone, groundwater zone, and surface, which are arranged as a serial and parallel cascade of "tanks" to coincide with the perceived basin storage structure (Figure 2). Water enters the snow pack, which supplies the basin surface (degree-day snowmelt). Infiltration is proportional to this supply and to saturation of the upper soil zone (partial-area infiltration). Excess supply is surface runoff. Flows from all tanks are proportional to their amounts (linear-reservoir flows). Mass conservation applies for the snow pack and tanks; energy conservation applies to evapotranspiration.

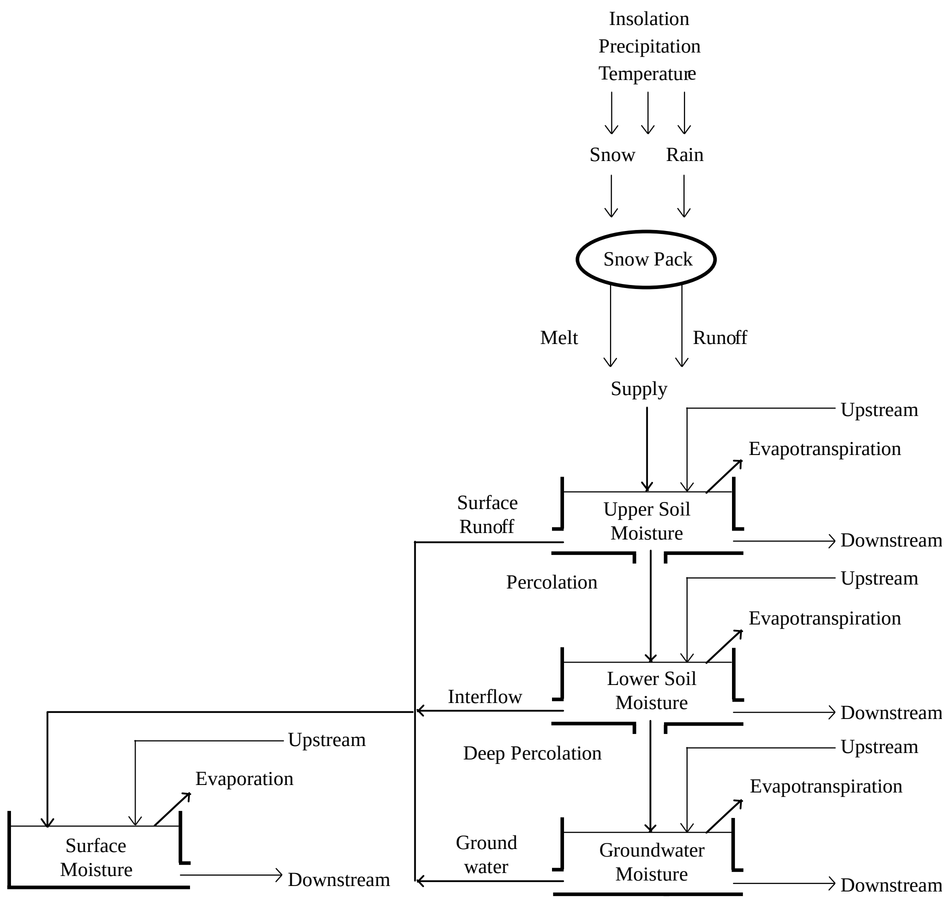

Figure 2. Schematic of Distributed Large Basin Runoff Model (DLBRM) for one cell.

The model computes potential evapotranspiration from a heat balance, indexed by daily air temperature, and calculates actual evapotranspiration as proportional to both the potential and storage. It allows surface and subsurface flows to interact both with each other and with adjacent-cell surface and subsurface storages.

The DLBRM has been applied extensively to the riverine watersheds draining into the Laurentian Great Lakes for use in both simulation and forecasting (Croley and He [2], [4], [5]; He and Croley [6], [7], [8]; Croley *et al.* [9]). Currently, the model is being modified to add materials runoff through each of the storage tanks routing from upstream to downstream.

The DLBRM hydrology component requires 16 parameters for each of the cells. In order to maintain the number of calibration parameters small and ensure a consistent representation of the spatial variation of topographic, hydrological, land use and soil properties, parameter values vary from cell to cell according to the formula:

$$\alpha_{k,i} = \overline{\alpha}\left(0.2 + 0.8\frac{x_{k,i}}{\frac{1}{N}\sum_{j=1}^{N} x_{k,j}}\right) \quad (1)$$

where $\alpha_{k,i}$ = model parameter k for cell i (e.g., percolation linear reservoir coefficient, upper soil zone capacity, etc.); $\overline{\alpha}$ = basin-wide average model parameter k; $x_{k,j}$ = observed topographic, land use or soil properties related to parameter k for cell j; and N = the number of cells in the watershed.

We automatically calibrate the DLBRM using a systematic gradient search of the 16 basin-wide average model parameters that minimize the root mean square error between model and observed flow at the watershed outlet.

METHODS

For each of the 18 watersheds we first reduced daily maximum and minimum air temperatures and precipitation at 1 km^2 resolution by inverse distance squared interpolation of gage data. Daily river discharge measurements from one or more gages operated by the United States Geological Service were weighted and prorated to project daily basin outflow at the watershed outlet. With these data, we first calibrated the DLBRM for each individual watershed for the period 1950-1964 (with the exception of the Pigeon River, which we calibrated with 1986-1993 data); then, we applied these parameter sets to the period 1999-2006 (in a *Robustness test*); and finally we recalibrated the DLBRM for this last period to reproduce the observed daily flow under more recent conditions (with the exception of the Kawkawlin and Pigeon watershed, for which no recent discharge data are available).

RESULTS AND DISCUSSION

1950-1964 Calibration

The calibration performance in Table 2 indicates that the model reproduces very well the flow of most rivers. Exceptions are the Sandusky, which features a high bias and RMSE, the Kawkawlin and Pigeon, which feature high RMSE and bias and low correlation and Nash index, and the Fox river, which shows low correlation and Nash index. For the Sandusky, a possible explanation is the high flow variability due to poor soil permeability and intensive use of tile drainage, aggravated by the fact that the flow gage covers only the upper 70% of the basin, and ignores the coastal area, which is strongly affected by lake-effect snow. For the Kawkawlin and Pigeon, the poor DLBRM performance is probably due to the fact that gages there cover respectively only 21% and 15% of the watershed. The Fox River's poor performance is due to the regulation of Lake Winnebago, which effectively disconnects the river discharge from precipitation and snowmelt (the DLBRM presently does not account for large reservoir operations).

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 (Michigan)	-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

Robustness test

We cannot base proper assessment of model performance solely on calibration results. Application of model parameters to an independent set of data is also necessary (validation/verification). In this case, the 35-year difference between the calibration period (1950-1964) and the verification period (1999-2006), besides validating the model calibration, makes this a more complete test of the model's robustness for long-term river discharge prediction. Further, it may reveal possible impacts on watershed hydrology of the climate and land use changes in the last half-century.

Table 3 shows that not only is there a slight general increase in temperature between 1950-1964 and 1999-2007, but also that such an increase has a positive northward gradient. Precipitation also increases substantially, in this case with a negative northward gradient. Discharge also increases substantially, mainly as result of the increase in precipitation. In many cases, however, the increase in discharge greatly exceeds the increase in precipitation, especially in urban watersheds (Milwaukee and Clinton).

DLBRM performance is worse than for the calibration period, but despite such large changes in hydroclimatological conditions, the DLBRM is able to simulate discharge very well (bias of less than 6% and Nash index above 0.5) in seven of the 16 watersheds [Maumee, Saginaw, AuGres, Grand (Ohio), Genesee, Grand (Michigan), and Huron].

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 Sutcl.
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

In addition, the DLBRM simulation for the Fox river has an excellent bias (2%), but poor correlation and Nash index. However, these values are not so different from the calibra-tion values (Table 2), making model performances in this watershed still robust. In another two cases (Raisin and St. Joseph), the DLBRM underestimates discharge by around 9%, while showing good correlation, RMSE, and Nash index. The Kalamazoo and Sandusky, on the other hand, also show bias in the 7-8% range, but their Nash index is below 0.5. Finally, the DLBRM substantially underestimates discharge in the Clinton and Milwaukee basins and substantially overestimates discharge in the Tahquamenon and Muskegon basins, although it well represents their variability. In the Clinton and Milwaukee basins, the heavy urbanization and sprawling occurring between the early 1960s and the late 1990s-2000s is probably responsible for a large part of the difference. In this respect, we need to consider that the DLBRM is not very sensitive to land use changes (Cowden *et al*. [10]). The causes of the flow overestimation for the Tahquamenon and Muskegon are less clear, but they are probably related to the larger increase in temperature and lower increase in discharge characterizing these watersheds. DLBRM seems to overestimate mainly the flow in autumn and early winter, possibly because of changes in ice cover. Changes in flow and precipitation gage location and operation, and in hydraulic structures along rivers also affect verification statistics.

1999-2006 Re-calibration

We recalibrated the DLBRM for the period 1999-2006 by using as a starting point the set of parameters obtained from the 1950-1964 calibration. Results (Table 4) were excellent for all basins, except the Sandusky, and in average superior to the 1950-1964 calibration, especially in the RMSE statistics.

CONCLUSIONS AND FUTURE DEVELOPMENTS

The excellent DLBRM calibration performance over two very long and different periods (1950-1964 and 1999-2006) and for a variety of watersheds indicates that the DLBRM may be a valuable tool for short term forecasts in applications such as beach closure forecasting and non-point reduction policy assessment in temperate climates. DLBRM performance in the robustness test demonstrates the resilience of the model in the face of substantial changes in hydroclimatological conditions. However, poor performance in the Tahquamenon and Muskegon basins seems to indicate that the DLBRM has problems in dealing with large increases in temperature, possibly due to ignoring ice cover influences. Poor performance in the Clinton and Milwaukee basin suggests that changes in land use are a more important threat to long-term forecasting than climate change. In this respect, these results are a reminder to the scientific community that changes in watershed response as results of different climate scenarios should be labeled as “potential changes” and not as “forecasts”.

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

We currently are extending the DLBRM to an additional 16 watersheds in the Great Lakes basin and to the Heihe River in the desert region of Gansu (China). Further, we are adding simple mass transport, soil erosion, and nonpoint source pollution simulation capabilities (see Croley and He [2], [4]). Planned DLBRM developments include the addition of vegetation interception and influence of land cover on infiltration rates and evapotranspiration rates. These measurements should improve DLBRM sensitivity to land use changes.

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