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NOTE
WIND STRESS EFFECTS ON DETROIT RIVER DISCHARGES[1]

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ABSTRACT. Dynamic flow models are currently used to compute Detroit River discharges for hourly, daily, and monthly time scales. These models include the complete one-dimensional equations of continuity and motion, but neglect the effects of wind stress and ice. The effects of wind stress upon calculated daily and monthly Detroit River discharges are analyzed. The wind effects of several storms with wind setups and surges on Lake Erie were evaluated on an hourly time scale. Inclusion of wind stress terms into the Detroit River models was found to have no significant effect on the monthly flow calculations and on the majority of the daily flow calculations. However, the average monthly effect of $-47\ m^3\ s^{-1}$ *is equivalent to 111 mm depth of water per month on Lake St. Clair, which may be significant for some Lake St. Clair water balance studies. The effect on Lake Erie is on the order of 5 mm of depth per month, which is not significant for water balance studies. The wind stress was found to be important for daily and hourly flow computations when wind velocities were in excess of about* $6\ m\ s^{-1}$.

INTRODUCTION

Detroit River discharges are currently computed for hourly, daily, and monthly time scales from the upper and total Detroit River dynamic flow models developed by Quinn and Wylie (1972) and Quinn and Hagman (1977). These models include the complete one-dimensional equations of continuity and motion, but neglect the effects of wind stress and ice. Since the output from these models is used in many Great Lakes studies (Quinn 1976), it was desired to analyze the effects of wind stress upon calculated daily and monthly Detroit River discharges. In addition, wind effects of several storms with wind setups and surges on Lake Erie were evaluated on an hourly time scale.

MODEL CONFIGURATION

The Detroit River transient models presently include the equations of continuity and momentum expressed in terms of flow Q and stage Z above fixed datum as

$$\frac{\partial Z}{\partial t} + \frac{1}{T}\frac{\partial Q}{\partial X} = 0 \qquad (1)$$

and

$$\left(\frac{1}{A}\frac{\partial Q}{\partial t}\right) - \left(2\frac{QT}{A^2}\frac{\partial Z}{\partial t}\right) + \left(g - \frac{Q^2T}{A^3}\right)\frac{\partial Z}{\partial X} + \frac{gn^2Q|Q|}{2.208A^2R^{4/3}} = 0 \qquad (2)$$

where Q = flow rate
X = distance in the positive flow direction
t = time
A = channel cross-sectional area
T = water surface top width of the channel
g = acceleration due to gravity
R = hydraulic radius
n = Manning's roughness coefficient.

For this study equation (2) was modified to include the surface wind stress term, τ_W, using the common drag coefficient approach

$$\tau_W = \rho_a C_D U^2 \qquad (3)$$

where ρ_a = the air density ($1.25 \cdot 10^3$ gm m^{-3})
C_D = drag coefficient
U = the wind velocity

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[1] GLERL Contribution No. 187.

becoming

$$\frac{1}{A}\frac{\partial Q}{\partial t}-\frac{2QT}{A^2}\frac{\partial Z}{\partial t}+\left(g-\frac{Q^2T}{A^3}\right)\frac{\partial Z}{\partial X}+\frac{gn^2Q|Q|}{2.208A^2R^{4/3}}$$

$$-\frac{\rho_a}{\rho_w}\,\frac{U^2\cos(\phi-\alpha)\,|\cos(\phi-\alpha)|\,C_DT}{}=0 \qquad (4)$$

where ϕ = the channel azimuth
α = the wind direction
ρ_w = the water density ($1.0\cdot 10^6$ gm m^{-3}).

A value of C_D for 1.2×10^{-3} was used in the calculations as per Holland *et al.* (1979). The upper Detroit River flow model is composed of two equivalent channels. The upper channel, between Lake St. Clair and Fort Wayne, has an azimuth, ϕ, of 67° while the lower channel from Fort Wayne to Wyandotte has a corresponding azimuth of 19°. For the total Detroit River model, the upper reach between Lake St. Clair and Wyandotte has an azimuth, ϕ, of 43° while the lower reaches between Wyandotte and Lake Erie have an azimuth of 0°. The resultant wind speeds and directions used in the analysis were the 3-hour synoptic measurements at the Detroit City Airport. The flow rates used in the study are those computed at the Fort Wayne section for the upper river model and at the Wyandotte section for the total river model.

RESULTS

Potential wind effects are illustrated by applying constant winds from 0 to 6 m s^{-1} from a direction of 250°, which is the annual resultant wind direction as measured at the Detroit City Airport. The wind is therefore opposite the flow direction, which results in a flow reduction (Figure 1). For perspective, the maximum daily resultant wind speed from the years 1976 and 1977 corresponds to a 7.6% flow reduction in the upper river model and a 4.3% reduction in the total river model. The flow reduction is higher in the upper river model because its channel configuration aligns more closely with the prevailing wind direction than does the channel configuration in the total river model.

Detailed effects of the addition of the wind stress terms on the calculated discharges were analyzed using synoptic wind and hourly water level data for 1977. Computations were conducted on hourly time scales assuming that the synoptic wind was constant between observations. The impact of the wind stress terms on monthly discharge values as computed from daily means is given in Table 1. The table shows a maximum flow reduction of 1.4% for the upper river model and 1.0% for the total river model. The corresponding absolute average monthly differences were 0.8% and 0.5%, respectively. The wind stress resulted in a flow reduction during all months except May. It should be noted that the large differences between the upper and total river models in January, February, and December are due to severe ice conditions in the river.

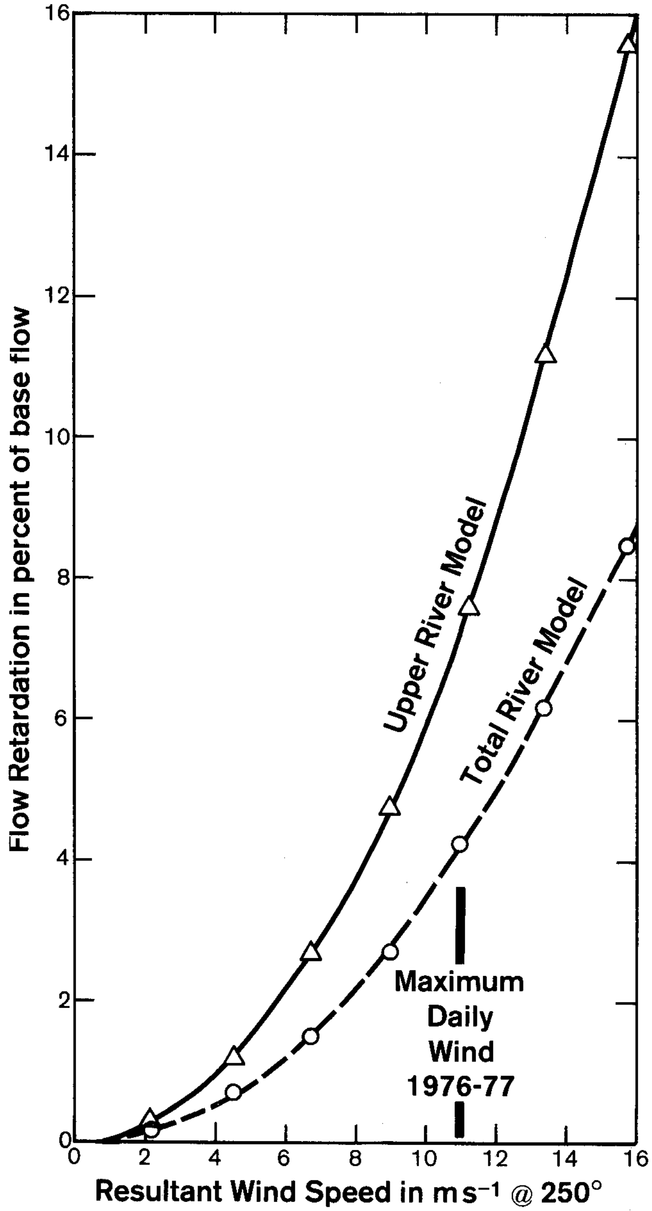

FIG. 1. Effects of constant wind stress with a base flow of 5490 m^3 s^{-1}.

The impact of the wind stress on the daily flow

TABLE 1. Wind stress effects on monthly discharge computations in $m^3\ s^{-1}$.

	Upper River Model			Total River Model		
Month	With Wind	No Wind	Percent* Difference	With Wind	No Wind	Percent Difference
Jan	6119	6206	-1.4	6029	6089	-1.0
Feb	6169	6232	-1.0	6258	6301	-0.7
Mar	5822	5874	-0.9	5718	5762	-0.8
Apr	(1)	(1)	(1)	5559	5579	-0.4
May	(1)	(1)	(1)	5364	5362	+0.0
Jun	5479	5491	-0.2	5456	5464	-0.1
Jul	5451	5488	-0.7	5456	5482	-0.5
Aug	5383	5421	-0.7	5452	5486	-0.6
Sep	5461	5486	-0.5	5525	5542	-0.3
Oct	5569	5590	-0.4	5588	5604	-0.3
Nov	5588	5616	-0.5	5569	5591	-0.4
Dec	5612	5686	-1.3	5925	5983	1.0
|Ave|			0.8			0.5

*As a percentage of the no wind discharge.

(1) Wyandotte gage out of order.

computations in the upper river model is illustrated by the histogram in Figure 2 and the cumulative frequency curves in Figure 3. The histogram for the upper river model shows a negative bias in flow computation due to the prevailing westerly winds (Figure 2). A similar, though smaller, bias was also present in the flows computed by the total river model. The cumulative frequency curve shows that for approximately 90% of the time the impact of the wind on the flow computations would be less than 140 $m^3\ s^{-1}$ for the upper river model and less than 120 $m^3\ s^{-1}$ for the total river model. This represents about 2% of the flow. The figure also shows that for 60% of the time the wind effect is less than 60 $m^3\ s^{-1}$, approximately 1% of the flow. During the 39 days when the wind effect on the upper river model was greater than 120 $m^3\ s^{-1}$, the wind was usually found to be in excess of 6 m s^{-1}, with the wind direction parallel to one of the model reaches. The maximum daily wind effect was 396 $m^3\ s^{-1}$, approximately 7% of the flow, which occurred on December 2, 1977.

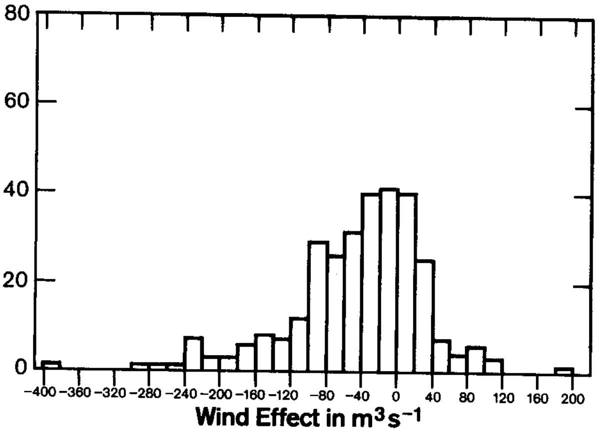

FIG. 2. Histogram of wind effects on daily discharge computations for the upper Detroit River model.

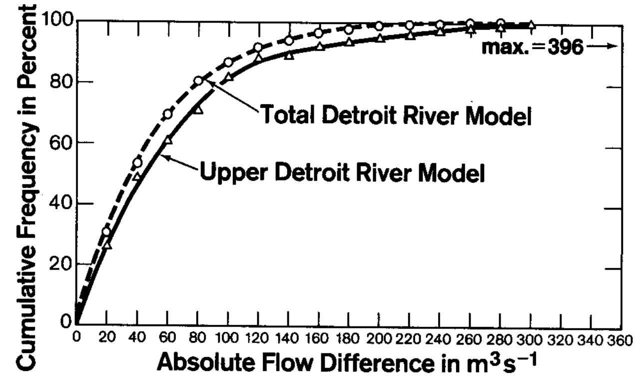

FIG. 3. Cumulative frequency curves for wind effects on daily discharge computations.

The maximum impact of wind stress on calculated hourly discharges was analyzed by examining four December 1977 storm periods during which flows fluctuated as much as 50%. These storms occurred on December 1 and 2, December 5 and 6, December 9 and 10, and December 25, 1977. The Fort Wayne flow hydrograph for the December 1 and 2 episode, as simulated by the upper river model, is shown as an example in Figure 4. The maximum observed effect was a reduction of approximately 460 $m^3\ s^{-1}$, or 9%, occurring at 1100 hours on December 1. In only one storm, December 5 and 6, did the addition of the wind stress increase the calculated flow. In all four cases the total river model showed a smaller effect due to the wind stress.

CONCLUSIONS

The inclusion of wind stress terms into the Detroit River models was found to have no significant effect on the monthly flow calculations and on the majority of the daily flow calculations. However, it should be noted that the average monthly wind effect of -47 $m^3\ s^{-1}$ is equivalent to 111 mm depth of water per month on Lake St. Clair. Thus the monthly wind effects are significant for some

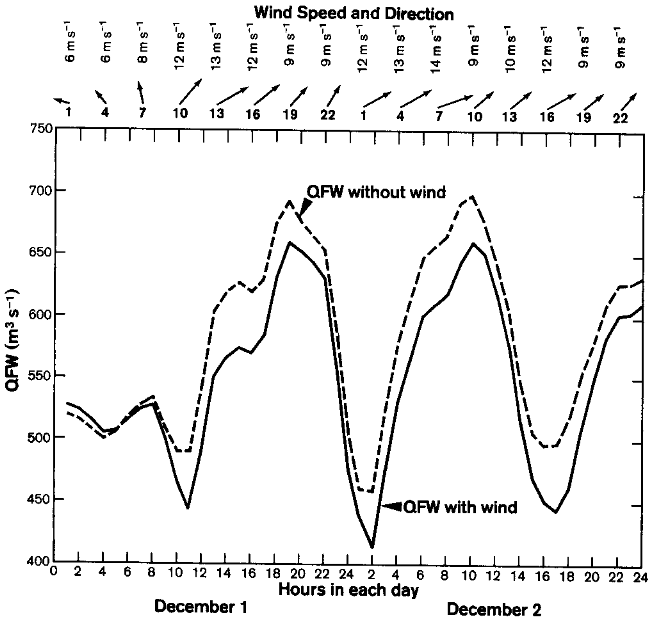

FIG. 4. Storm data: QFW with and without wind, December 1 and 2, 1977.

Lake St. Clair water balance studies. The effect on Lake Erie is on the order of 5 mm of depth per month, which is not significant for water balance studies. The wind stress was found to be important for daily and hourly flow computations when wind speeds were in excess of about 6 m s^{-1} and should be included when examining river discharges during high wind episodes.

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