A SIMPLIFIED HYDRODYNAMIC FORMULA FOR ESTIMATING THE WIND-DRIVEN FLOODING IN THE LAKE PONTCHARTRAIN-AMITE RIVER BASIN

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Abstract

On the basis of approximate balance between the kinetic energy or wind stress input and the water level increase in output, a simplified hydrodynamic formula is proposed which shows that $\Delta S = KV^2$ where ΔS is the difference in water level before and after the floods, K is the set-up coefficient, and V is the upstream wind speed.

During the period of 5 - 8 October 1996, a wind-driven flooding event occurred in the Lake Pontchartrain-Amite River system of Louisiana that provides a case study to verify this equation. Results show that if the unit of S is in feet and V in mph, K is found to be 0.0056 for this coastal lake-river system.

1. Introduction

During the period of 5 - 8 October 1996, the combination of a high pressure system over the Carolinas and Tropical Storm "Josephine" over the Gulf of Mexico produced steady and moderate to strong easterly winds (Fig. 1) over Lake Pontchartrain and the Amite River system in Louisiana (Fig. 2), resulting in widespread wind-driven flooding over southern Louisiana. Measurements obtained from several water level and weather stations in the affected area enabled us to verify a simplified hydrodynamic formula that could estimate the water level induced by this wind-driven flooding phenomenon.

2. The Formula

The generic differential equations appropriate for tropical or extra-tropical storm surge problems on the open coast and in enclosed and semi-enclosed basins are provided in the Appendix. Under predominant wind-driven surge conditions when the surface slope is approximately balanced by the wind stress, these equations may be simplified with the aid of wind-stress parameterization given in Hsu (1988, p. 112, Eq. 6.41) as follows:

$$g D \frac{\partial S}{\partial X} = \frac{\tau_{SX}}{\rho_w} = \frac{\rho_a C_d V^2}{\rho_w} \tag{1}$$

In practice,

$$\Delta S = \left(\frac{\rho_a C_d V^2}{\rho_w g D} \right) \Delta X$$

$$S - S_0 = \frac{\rho_a C_d V^2 F}{\rho_w g D} \tag{2}$$

where S is water level or set-up; S_0 is the initial sea level; C_d is the wind-stress drag coefficient; V is the wind speed; F is the fetch along the wind direction; g is the gravitational acceleration; D is the average water depth along F; τ_{SX} is the wind-stress along the wind; X is the distance downwind; and ρ_a and ρ_w are the air and water density, respectively.

At a given location downwind in a lake environment, the most important variable for S is V. In other words, Eqs. (1) and (2) state that if potential energy for water level increase is approximately in balance with the kinetic energy from wind stress input, we have

$$S - S_0 \approx K V^2 \tag{3}$$

where K (= C_dF/gD) from Eq. (2) is designated as the set-up coefficient, which may be treated as a constant if F is known and g, D, and C_d can be estimated.

At time t_1

$$\left(S - S_0\right)_{t1} = KV_{t1}^2 \tag{4}$$

At a later time t_2

$$\left(S - S_0\right)_{t2} = K V_{t2}^2 \tag{5}$$

Subtracting Eq. (5) - Eq. (4) and solving for K

$$K = \frac{\left(S_{t2} - S_{t1}\right)}{\left(V_{t2}^2 - V_{t1}^2\right)} \tag{6}$$

If simultaneous measurements of wind speed at an upwind site and water level at a downward location are available as in our case, the flooding due to increase in water level can be estimated from Eqs. (3) and (6).

3. Verification

From the measurements made simultaneously at the Pontchartrain Causeway for V and Fernier, Louisiana for S on 3 - 6 October 1996 (see Table 1), we have from Eq. (6),

$$K = (4.43 - 2.10) / (24.9^2 - 14.2^2)$$

$$= 0.0056$$

$$\therefore \Delta S_{westlake} = 0.0056\, V_{midlake}^2 \tag{7}$$

For $V = 15$ mph, $\Delta S = 1.3$ ft

$V = 20$ mph, $\Delta S = 2.2$ ft

$V = 25$ mph, $\Delta S = 3.5$ ft

$V = 30$ mph, $\Delta S = 5.0$ ft

Between 1 and 9 October 1996, the rainfall amount at Baton Rouge Airport and Bayou Manchac Point near Port Vincent was less than 1 inch (Figs. 3 and 4). Therefore, the effect of runoff on the increase of the river stage was negligible. In other words, approximately 2 feet of water level increase along the Amite River (see Fig. 1) at French Settlement, Port Vincent (Fig. 3) and Bayou Manchac Point (Fig. 4) was due at first to the surge over the western side of Lake Pontchartrain which later flooded the wetland; the water then overwashed to Lake Maurepas and propagated further upstream.

Because the average wind speed from 3 to 7 October 1996 between the Causeway and Frenier was about 20 mph (Table 1), a two foot water level increase from the mouth of the Amite River to an inland location at Port Vincent (along the Amite) is a reasonable estimate.

Table 1.
Daily measurements of rainfall, resultant wind speed and direction, and water level from mid-lake (on Pontchartrain Causeway) and west-lake at Frenier in October 1996.

Daily Measurements from Mid-lake (Causeway)

Date	Precip. (in.)	Resultant Direction (°)	Wind Speed (mph)	Water Level (ft.)
3	0	41	14.2	2.15
4	0	56	17.7	2.40
5	0	60	25.1	3.38
6	0.01	46	24.9	4.15
7	0	21	17.6	3.93
8	0	322	7.9	2.94

Daily Measurements from West-lake (Frenier)

Date	Precip. (in.)	Resultant Direction (°)	Wind Speed (mph)	Water Level (ft.)
3	0	57	12.8	2.10
4	0	72	15.5	2.41
5	0	79	21.9	3.66
6	0.16	48	23.3	4.43
7	0	26	15.2	3.91
8	0	313	1.6	2.73

4. Conclusions

When persistent and strong easterly winds prevail over the Lake Pontchartrain-Amite River system in Louisiana, wind-driven flooding occurs. In order to estimate the increase in water level on the western shores of Lake Pontchartrain and the propagation of flow along the Amite River further inland, a simplified hydrodynamic formula is proposed. The equation relates the water level or river stage to the wind-stress forcing; if one knows the wind speed and direction upwind, the water level downwind can be estimated. A case study of wind-driven flooding in October 1996 provides a reasonable verification. Certainly more cases are needed to further refine this highly simplified analytical method.

Acknowledgments

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Authors

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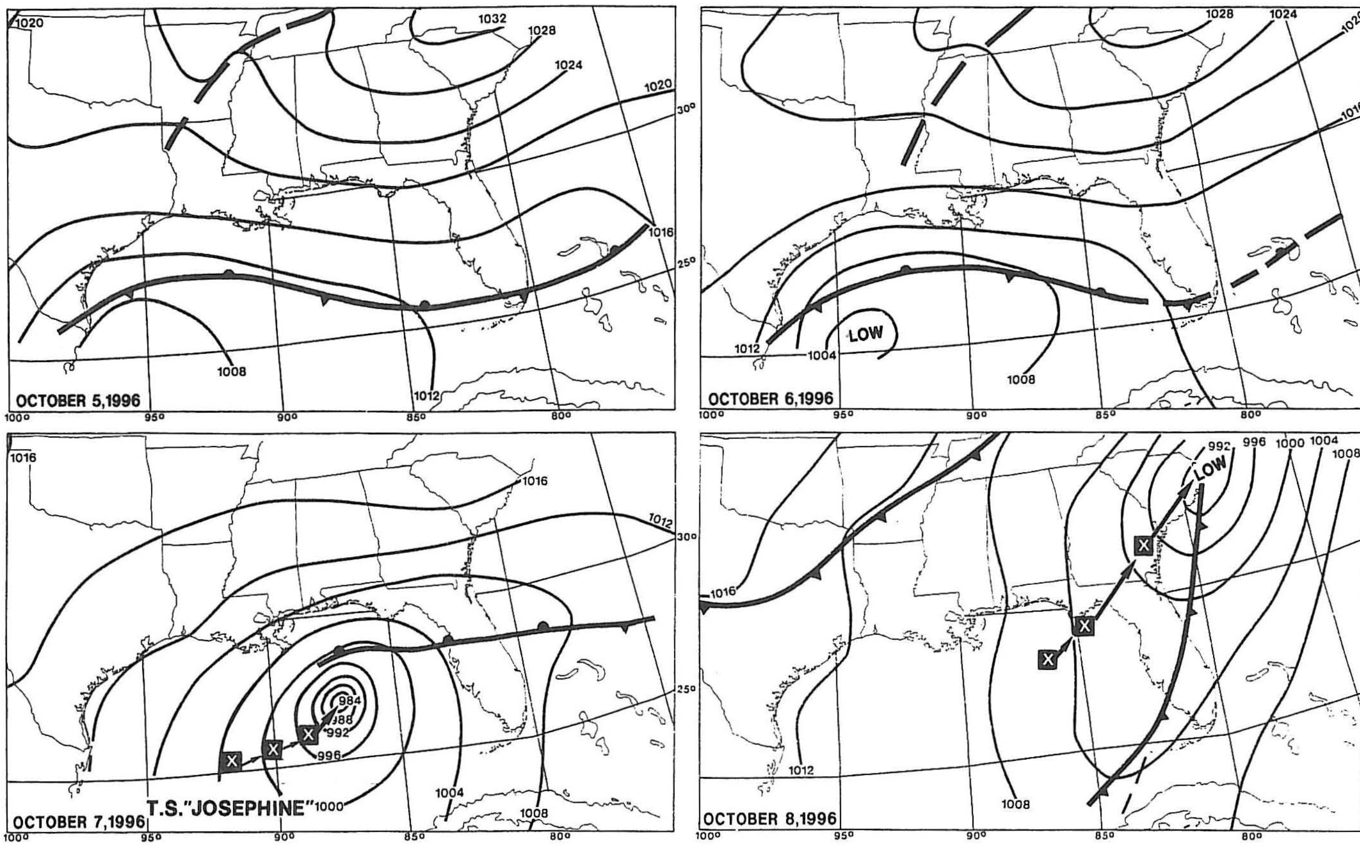

Fig. 1. Weather systems producing the wind-driven flooding over southern Louisiana.

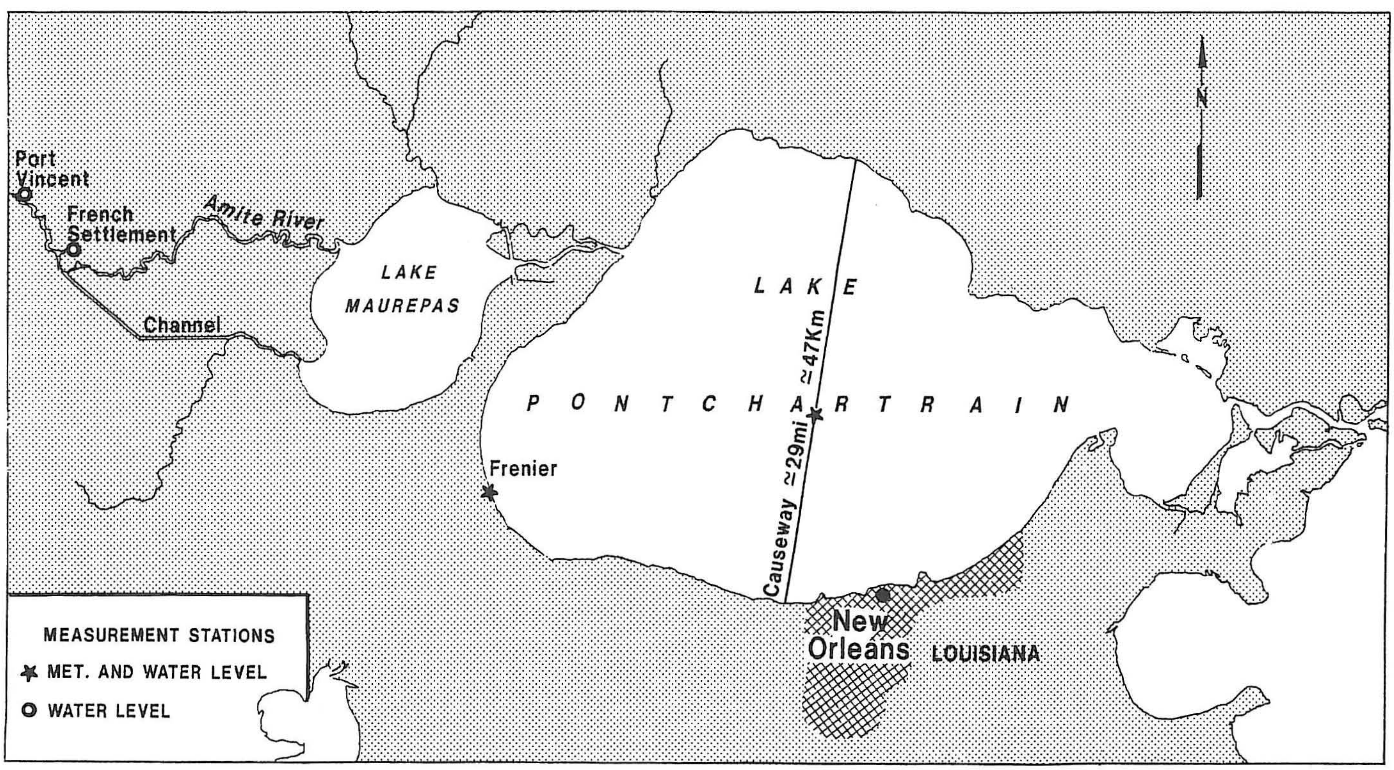

Fig. 2. The study area with locations of meteorological and water-level measurement stations.

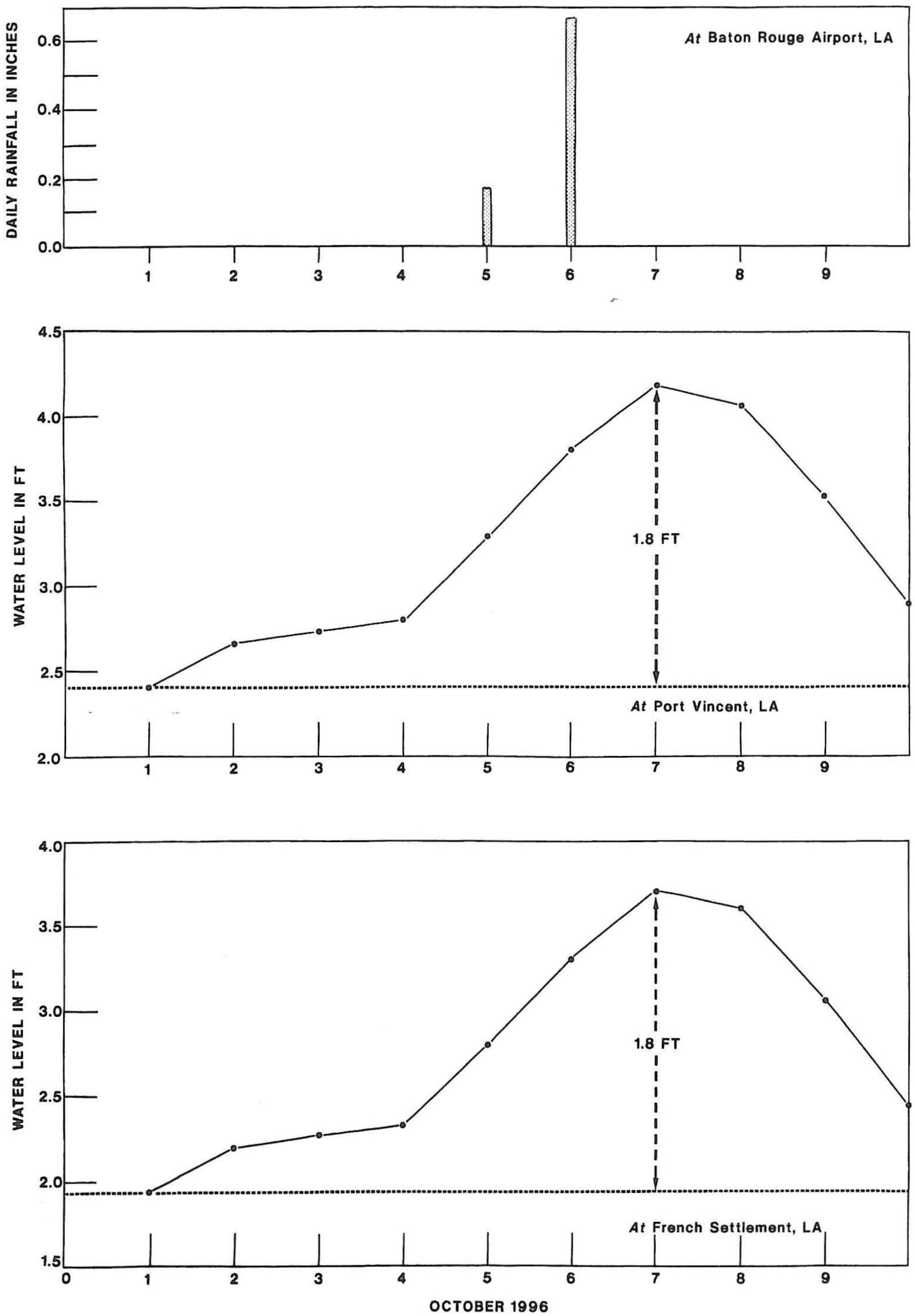

Fig. 3. Measurements of water level at French Settlement and Port Vincent as well as rainfall at Baton Rouge Airport, Louisiana in October 1996.

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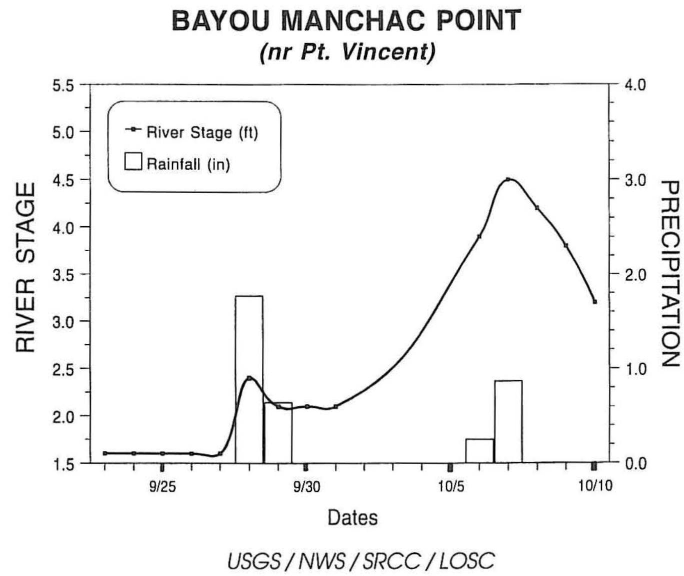

Fig. 4. River stage and rainfall at Bayou Manchac Point near Port Vincent (see Fig. 2; courtesy of Jay Grymes, Louisiana State Climatologist).

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Appendix

The differential equations appropriate for tropical or extratropical storm surge problems on the open coast and in enclosed and semienclosed basins are as follows (see Coastal Engineering Research Center 1984):

$$\frac{\partial U}{\partial t} + \underbrace{\frac{\partial M_{xx}}{\partial x} + \frac{\partial M_{xy}}{\partial y}}_{\text{Advection of Momentum}} = \underbrace{fV}_{\text{Coriolis}} \underbrace{- gD\frac{\partial S}{\partial x}}_{\text{Surface Slope}} + \underbrace{gD\frac{\partial \xi}{\partial x}}_{\text{Inverse Barometer}} + \underbrace{gD\frac{\partial \zeta}{\partial x}}_{\text{Astro. Tide Potential}} + \underbrace{\frac{\tau_{sx}}{\rho_w}}_{\text{Wind Stress}} - \underbrace{\frac{\tau_{bx}}{\rho_w}}_{\text{Bottom Stress}} + \underbrace{W_x P}_{\text{Rainfall Rate}} \quad \text{(A-1)}$$

$$\frac{\partial V}{\partial t} + \overbrace{\frac{\partial M_{yy}}{\partial y} + \frac{\partial M_{xy}}{\partial x}} = \overbrace{-fU} \overbrace{- gD\frac{\partial S}{\partial y}} + \overbrace{gD\frac{\partial \xi}{\partial y}} + \overbrace{gD\frac{\partial \zeta}{\partial y}} + \overbrace{\frac{\tau_{sy}}{\rho_w}} - \overbrace{\frac{\tau_{by}}{\rho_w}} + \overbrace{W_y P} \quad \text{(A-2)}$$

$$\frac{\partial S}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = P \quad \text{(A-3)}$$

$$\text{and} \quad D = d + S \quad \text{(A-4)}$$

$$\text{where} \quad M_{xx} = \int_{-d}^{S} u^2 dz; \quad M_{yy} = \int_{-d}^{S} v^2 dz; \quad M_{xy} = \int_{-d}^{S} uv dz$$

$$U = \int_{-d}^{S} u dz; \quad V = \int_{-d}^{S} v dz;$$

The symbols are defined as:

U, V = x and y components, respectively, of the volume transport per unit width
t = time
M_{xx}, M_{yy}, M_{xy} = momentum transport quantities
$f = 2\omega \sin \phi$ = Coriolis parameter
ω = angular velocity of earth (7.29×10^{-5} radians per second)
ϕ = geographical acceleration
g = gravitational acceleration
ξ = atmospheric pressure deficit in head of water
ζ = astronomical tide potential in head of water
τ_{sx}, τ_{sy} = x and y components of surface wind stress
τ_{bx}, τ_{by} = x and y components of bottom stress
ρ_w = mass density of water
W_x, W_y = x and y components of wind speed
u, v = x and y components, respectively, of current velocity
P = precipitation rate (depth/time)
D = the total water depth at time t
d = the undisturbed water depth
S = the height of the free surface above or below the undisturbed water depth due to surge