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REMOTE MONITORING OF THE GRAVELLY RUN THERMAL PLUME AT HOPEWELL AND THE THERMAL PLUME AT THE SURRY NUCLEAR POWER PLANT ON THE JAMES RIVER

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SUMMARY

Remote sensing of thermal discharges entering rivers and estuaries provides synoptic spatial and temporal distributions not readily available by other means. These data form a basis for analytical investigations into the dynamics of the discharge patterns.

On May 17, 1977, a remote-sensing experiment was conducted by the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) on the James River, Virginia, whereby thermal spectrometer and near-infrared photography data of thermal discharges at Hopewell and the Surry nuclear power plant were obtained by an aircraft for one tidal cycle. These data were used in subsequent investigations into the near-field discharge trajectories.

For the Gravelly Run thermal plume at Hopewell, several empirical expressions for the plume centerline were evaluated by comparisons of the computed trajectories and those observed in the remote sensing images. Results ranged from good to poor with bathymetry and flow interference considered causes for the areas of nonagreement. A separate study of the Surry nuclear power plant plume near Hog Island used a vector composition of the tidal river flow and the discharge velocity of the thermal source. This solution to the plume centerline trajectory provided good comparisons with the observed remote-sensing images.

INTRODUCTION

NASA is investigating the potential of remote sensing for monitoring various parameters in the marine environment in cooperation with the Environmental Protection Agency (EPA). One aspect of this effort is a research program aimed at developing remote-sensing strategies for the monitoring of industrial outfalls including thermal discharges. Aircraft-mounted multispectral scanners and photographic systems have demonstrated the ability to provide synoptic coverages of point discharges into rivers, estuaries, and coastal zone waters. Repetitive overflights with such sensors also yield temporal distributions that provide for insight into the dynamics of the discharge patterns.

This paper discusses a remote-sensing experiment conducted over the James River on May 17, 1977, which included repetitive overflights of two thermal discharges, one at Gravelly Run near Hopewell, and the other from the Surry nuclear power plant near Hog Island. Several empirical and analytical techniques for calculating the near-field thermal discharge trajectories are presented and compared with near-infrared photographic data from the experiment.

Experiment

On May 17, 1977, a remote-sensing experiment was conducted by NASA LaRC on the James River, Virginia, as a cooperative effort involving NASA, the Virginia State Water Control Board, the U.S. Army Corps of Engineers, and Old Dominion University. Figure 1 summarizes the operational aspects of the experiment. The area overflown by the main aircraft platform (P3-A) ranged from Newport News to Hopewell, and included the thermal discharge plumes from Gravelly Run near Hopewell (fig. 2), and the Surry nuclear power plant near Hog Island (fig. 3). Twenty-four overflights of the Gravelly Run thermal discharge were made at 3300 meters starting at 1.7 hours before low tide and ending at 1.5 hours after high tide at Hopewell. Sixteen overflights of the Surry thermal discharge at the same altitude were made starting at 2.0 hours after low tide to 0.9 hour before the following low tide at Hog Island. A considerable portion of one tidal cycle was, thus, observed in the overflights of both thermal discharges.

Sensors onboard the P3-A aircraft included an 11-band Modular Multispectral Scanner (M2S) and a Zeiss aerial mapping camera loaded with near-infrared color film and a haze-reduction filter. Details of the aerial photographic system are presented in reference 1. The aerial photographs were the primary data source for the analysis. The mapping camera images showed good contrast between the thermal discharge waters and the background James River waters. Figures 4a and 4b show, respectively, the Gravelly Run and Surry power plant plumes at two distinctly different stages in the tidal cycle as noted on the figures.

ANALYSIS

Tracings of the near-field flow patterns for both the Gravelly Run and Surry power plant plumes were made directly from the aerial mapping photographs, examples of which have been presented in figure 4. Centerline trajectories were estimated from the tracings. Separate research efforts evaluated both empirical and analytical techniques for modeling jet discharges into crossflows.

Gravelly Run

Gravelly Run, located adjacent to Bailey Creek (see fig. 2), is a receiving body for wastes from several industries in the Hopewell area. Thermal discharges form almost the entire flow in the Run, and water temperatures of 10°C above ambient James River waters at the mouth of the Run are not uncommon. When this heated flow enters the James River, the resultant plume remains near the surface and is influenced by the cross-flow of the river.

Certain hydraulic data are necessary to model the plume dynamics. The discharge velocity of the Run, U_j, was 0.21 m/sec. and the effective discharge width, d_o, was estimated to be 37.5 m. Tidal velocities in the James River, U_R, in the immediate area of Gravelly Run are shown in figure 5. In this geographic area, the tides are asymmetric. The river flow on the day of the experiment was abnormally low and the tidal velocity curve was taken to represent the total crossflow velocity at the mouth of the Run. As indicated in figure 2, a coordinate system was set up with the origin at the mouth of Gravelly Run and + x measured alongshore towards Bailey Creek and + y measured offshore normal to the coastline.

When Gravelly Run enters the James River, ambient river waters are entrained into the sides of the jet, eroding the potential core. However, for some distance offshore, the centerline velocity of the jet is unaffected. This is the zone of flow establishment and, spatially, the offshore distance, y_{FE}, is given by

$$y_{FE} = 6.2\ d_o \qquad (1)$$

under conditions of a jet discharging into a quiescent ambient fluid. Under cross-flow conditions, however, entrainment of the surrounding fluid into the jet occurs at a higher rate and has been shown in reference 2 to depend on the ratio of jet velocity to crossflow velocity, U_j/U_R. For most of the overpasses in this experiment, this ratio was of the order of one, and reference 3 shows that for these conditions

$$y_{FE} \Rightarrow d_o \quad ; \qquad (2)$$

that is, the length of the flow establishment zone approaches the jet discharge width itself. Furthermore, this distance was generally small compared to the curvature and centerline trajectory overall distances in the near-field and, to a good approximation, was neglected in the subsequent analysis.

The subsequent approach was to examine a number of empirical and analytical expressions that have been used to describe the centerline trajectory of jets discharging into crossflows. Certain dimensionless ratios or parameters recur, namely,

$$\frac{y}{d_o} = f\left(\frac{x}{d_o}, \frac{U_j}{U_R}, C_d\right) \tag{3}$$

where x,y are alongshore and offshore coordinate distances as noted on figure 2, and C_d is a drag coefficient for the jet. The other quantities have been previously defined. Three expressions were examined in this analysis. The first was derived analytically by Volinsky and Abramovich and demonstrated by Gordier (ref. 2):

$$\frac{y}{d_o} = K_1\left(\frac{U_j}{U_R}\right)\left(\frac{x}{d_o}\right)^{0.50} \tag{4}$$

An alternative empirical form was proposed by Williams (ref. 2):

$$\frac{y}{d_o} = K_2\left(\frac{U_j}{U_R}\right)\left(\frac{x}{d_o}\right)^{0.33} \tag{5}$$

A third empirical form proposed by Shandorov and Abramovich (ref.2) was:

$$\frac{y}{d_o} = K_3\left(\frac{U_j}{U_R}\right)^{0.79}\left(\frac{x}{d_o}\right)^{0.39} \tag{6}$$

The coefficients K_1, K_2, K_3 are functions of the particular experiment and may be related to the drag coefficient, C_d. The procedure was to use the hydraulic data given previously and perform a boundary condition analysis such that the computed trajectories passed through the origin of the jet and approached the far-field conditions actually observed. From this analysis average values of K_1, K_2, K_3 were calculated as

$$K_1 = 2.76;\ K_2 = 3.73;\ K_3 = 3.53 \tag{7}$$

Equations (4), (5), (6), and (7) were then used to compute complete centerline trajectories for all the cases which were then compared with the trajectories observed in the photographs. Several representative examples are presented in figure 6 for widely variant tidal conditions.

Generally, the comparisons for all the profiles examined ranged from good (figures 6a, 6c) to poor (figures 6d, 6e). No single empirical or analytical expression used in the computations appeared to have an advantage over the others. A number of factors may be proposed to explain some of the poor comparisons in figure 6 (and other cases not shown). These are related to the modeling approach and also to the particular topography and bathymetry around Gravelly Run. First, the expressions (4), (5), and (6) were derived under steady-state flow conditions. The time-dependent nature of the tidal crossflow in the actual situation results in an unsteady-flow condition. This is evident in figure 6d (and other profiles not presented) where the actual trajectories lagged behind the computed trajectories. Thus, an indeterminate degree of error results by approximating an unsteady flow situation with a succession of assumed steady states.

Obvious interactions with upstream nearshore manmade stuctures and with shallow areas are evident in the photographs (fig. 4a-right, for example). No attempts were made to account for this behavior. Also, as low-tide conditions are approached, the discharge from Bailey Creek increases. Located adjacent and downstream of Gravelly Run, this flow disrupts the tidal crossflow by adding an offshore component to the total river velocity. This is most evident in figure 6e where the actual centerline trajectory of Gravelly Run shows an opposite downstream curvature to that computed providing strong evidence to the influence of the Bailey Creek discharge.

Finally, under a range of low-tide conditions, the flow of Gravelly Run appeared to be confined to a channel for some distance offshore (with the surrounding areas appearing as exposed mudflats). This required a shift of the origin of the axis system to match the new position of the mouth of the Run. Because of the buoyant nature of the heated discharge, James River waters may flow beneath the plume at other stages of the tidal cycle with a shear effect on the plume. The effects of this shear on the position of the plume are not known.

Even with the complexities of the flow situation just described, it is interesting that the simple expressions presented did describe the general directional behavior of the Gravelly Run discharge under a tidal crossflow.

Surry Power Plant Thermal Plume

The area around the Surry power plant thermal discharge (fig. 3) does not exhibit the flow complexities observed in the case of Gravelly Run. Generally, the water remains deep under low tide conditions, and there are no other discharges directly adjacent to the Surry discharge to disrupt the crossflow field.

The necessary hydraulic parameters included: initial jet velocity, U_{j_o}, at 1.5 m/sec. and a jet discharge width, d_o, of 30.5 m. The tidal velocities in the James River near Hog Island, U_R, are shown in figure 7. For this analysis a sinusoid approximation was used

$$U_R(t) = -U_{R_o} \sin \left(\frac{2\pi}{12.3} t \right) \qquad (8)$$

where U_{R_o} = 0.62 m/sec., and t is time in hours measured from high water slack. Again, due to an extremely low river discharge, the tidal velocity was assumed to represent the total crossflow.

The length of the zone of flow establishment was calculated by equation (1). At this distance, y_{FE} , from the discharge mouth begins the zone of established flow. Beyond this point, the centerline jet velocity, U_j , was considered to decay exponentially. Thus,

$$U_j = U_{j_o} \qquad y \leq y_{FE}$$
$$U_j = U_{j_o} e^{-Ky} \qquad y > y_{FE} \tag{9}$$

where K was to be determined. Vector composition yields a total resultant centerline velocity, U_T , given by

$$U_T = \left(U_R^2 + U_j^2\right)^{1/2} \tag{10}$$

Figure 8a shows

$$\theta = \tan^{-1}\left(U_j/U_R\right) \tag{11}$$

This may be related to the trajectory of the centerline as shown in figure 8b

$$\Delta x = \Delta y/\tan\theta \tag{12}$$

By incrementing y by Δy , and using equations (1), (8), (9), (10), (11), and (12) the plot of the centerline can be drawn for any particular ambient current velocity. A value of $K = 0.0082\ m^{-1}$ gave the results shown in figure 9 for four stages of the tidal cycle. It can be seen that good results may be obtained using this simplified approach.

CONCLUDING REMARKS

Remote sensing of thermal discharges entering rivers and estuaries provides synoptic coverages not readily available by other means. Such data may be used to evaluate techniques for modeling the near-field discharge trajectories. In the case of the Surry nuclear power plant thermal discharge, the model jet trajectories matched the observed jet trajectories well, with no particular abnormalities observed in the flow field images. For the case of Gravelly Run, however, the model jet trajectories, in some instances, did not match the observed jet trajectories. For these cases, the remote sensing images show the probable problem areas, namely, flow interference effects and bathymetric, and nearshore interactions, which may not have been immediately evident without extensive in situ sampling and observations. Thus, monitoring by remote sensing may provide added insight into physical flow processes.

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2. Rajaratnam, N.: Turbulent Jets. American Elsevier Publishing Company, New York, 1976.

3. Parker, F. L.; and Krenkel, P. A.: Physical and Engineering Aspects of Thermal Pollution. CRC Press, Ohio, 1970.

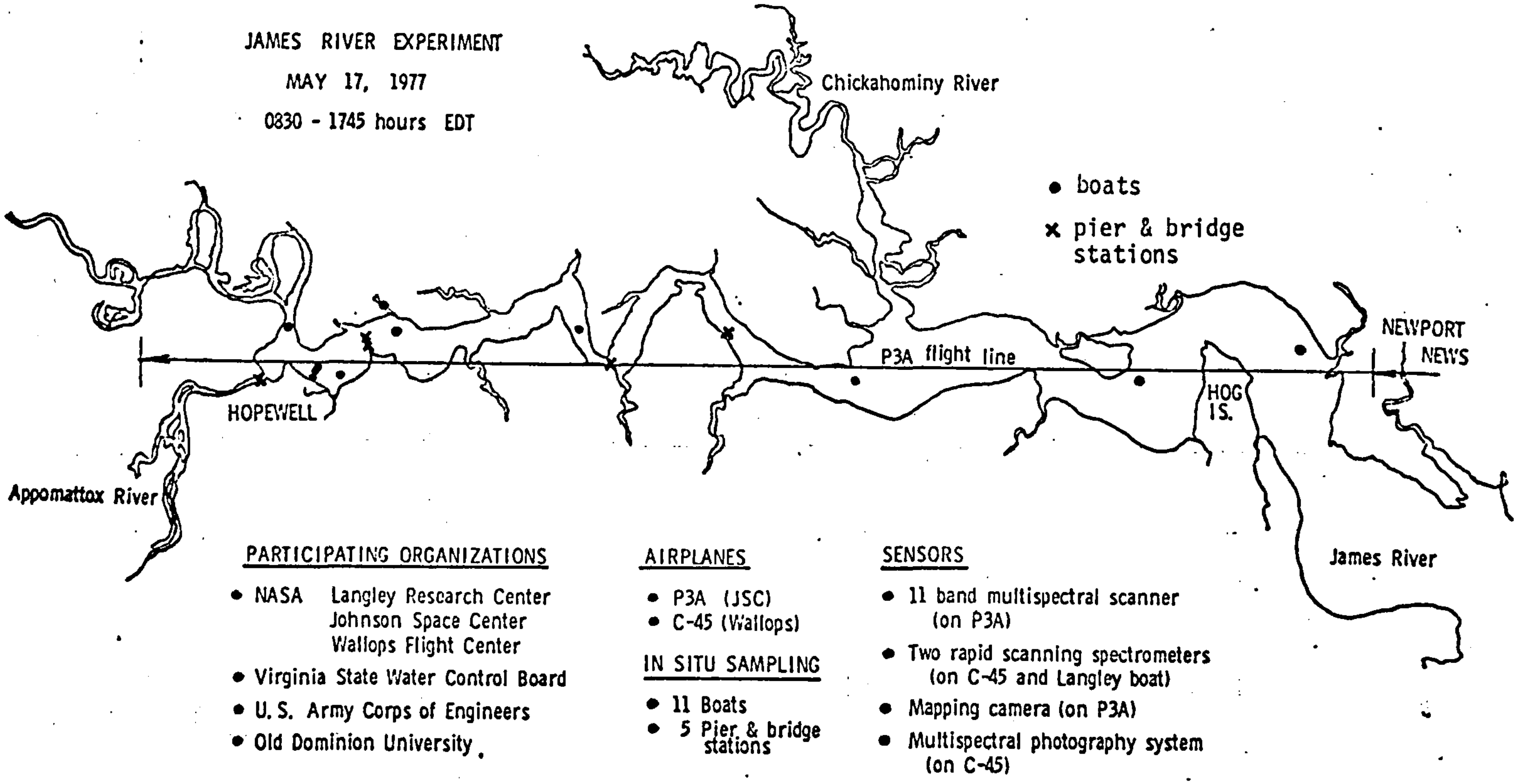


Figure 1.- Summary of James River experiment operations, May 17, 1977.

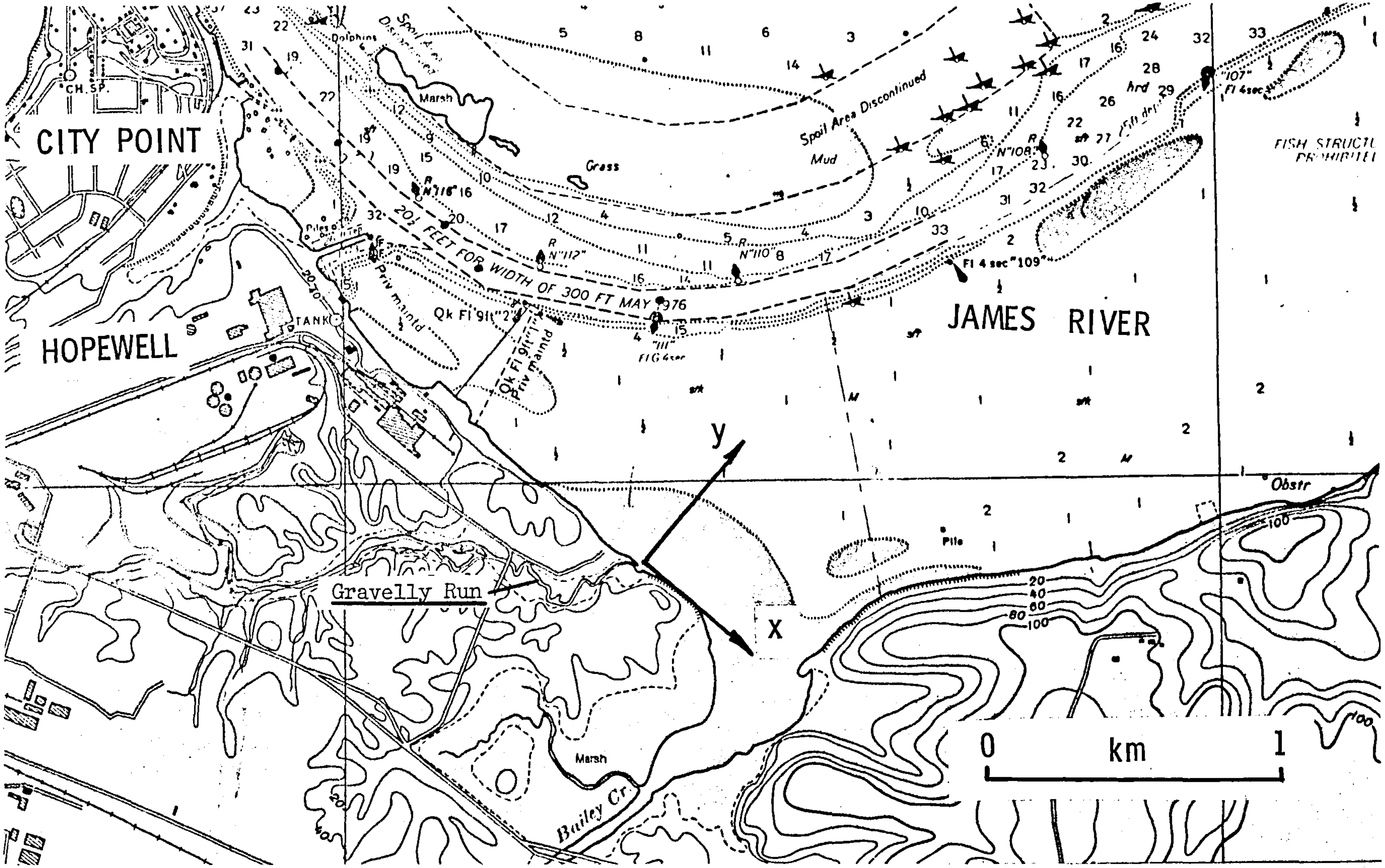


Figure 2. - Map of area around Gravelly Run near Hopewell, Virginia.

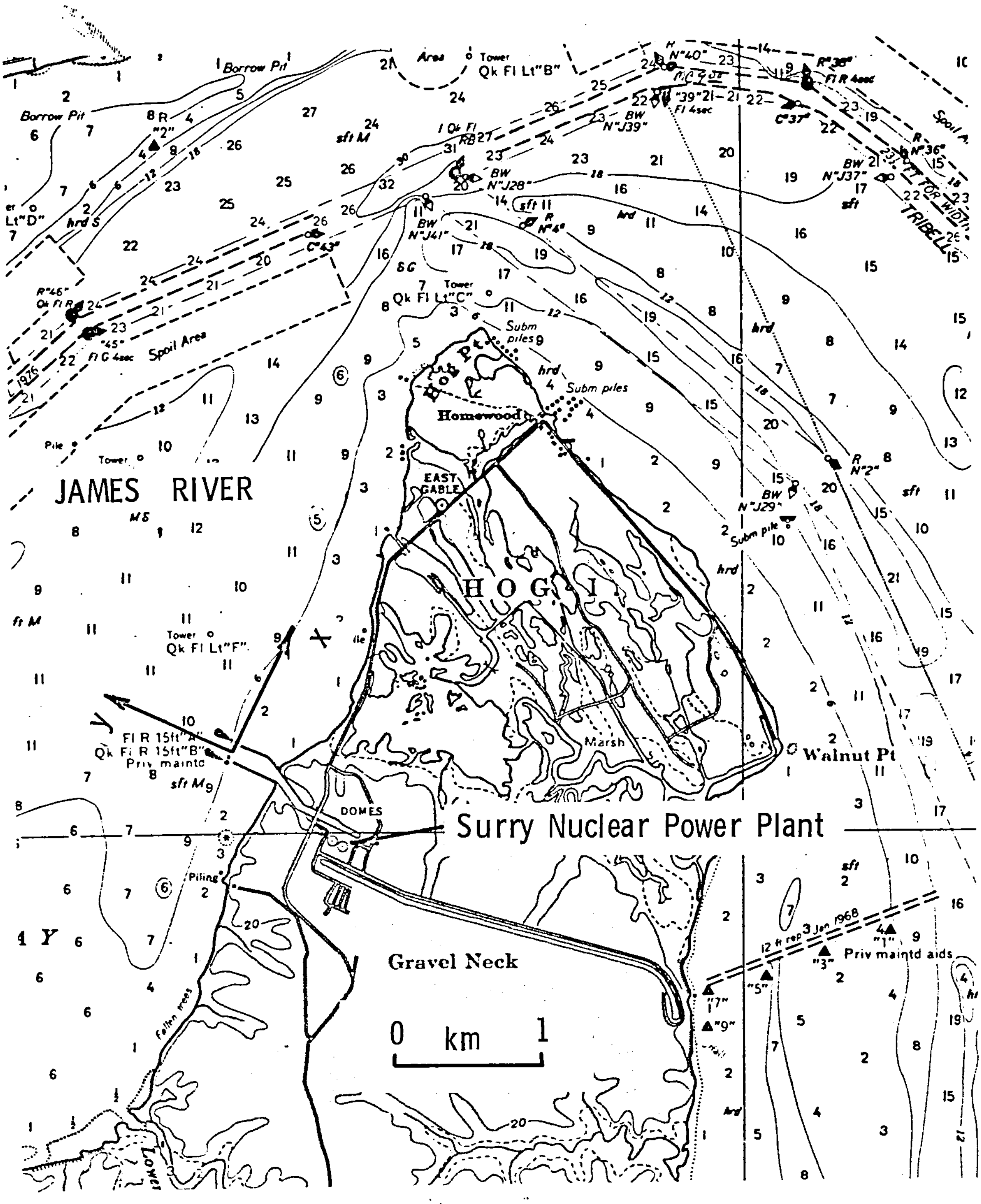


Figure 3. - Map of area around the Surry nuclear power plant near Hog Island, Virginia.

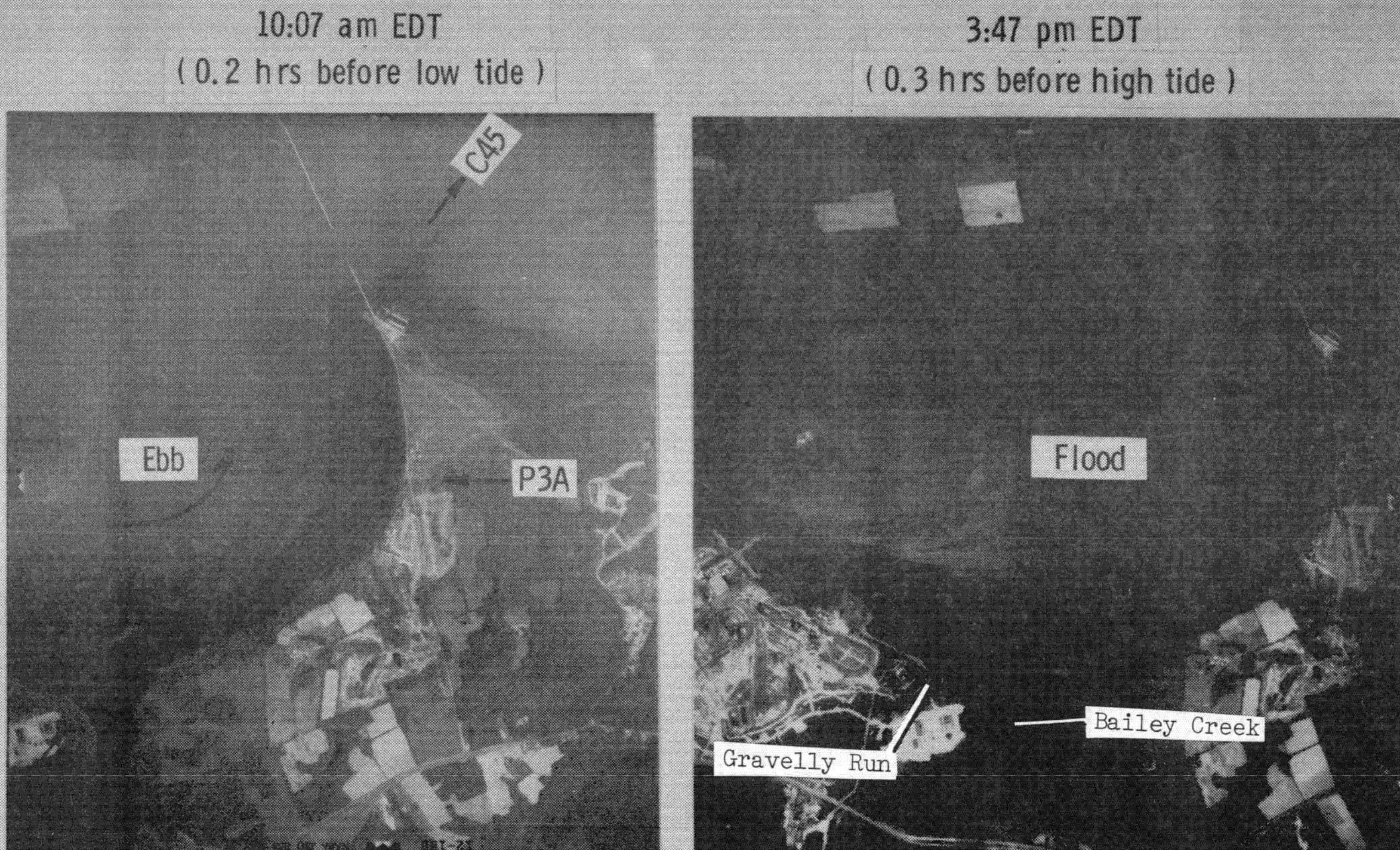


Figure 4a. - Discharges from Bailey Creek and Gravelly Run near Hopewell, May 17, 1977 (P3A mapping camera at 3300 m)

10:30 am EDT
(0.4 hrs before maximum flood current)

5:31 pm EDT
(0.25 hrs after maximum ebb current)

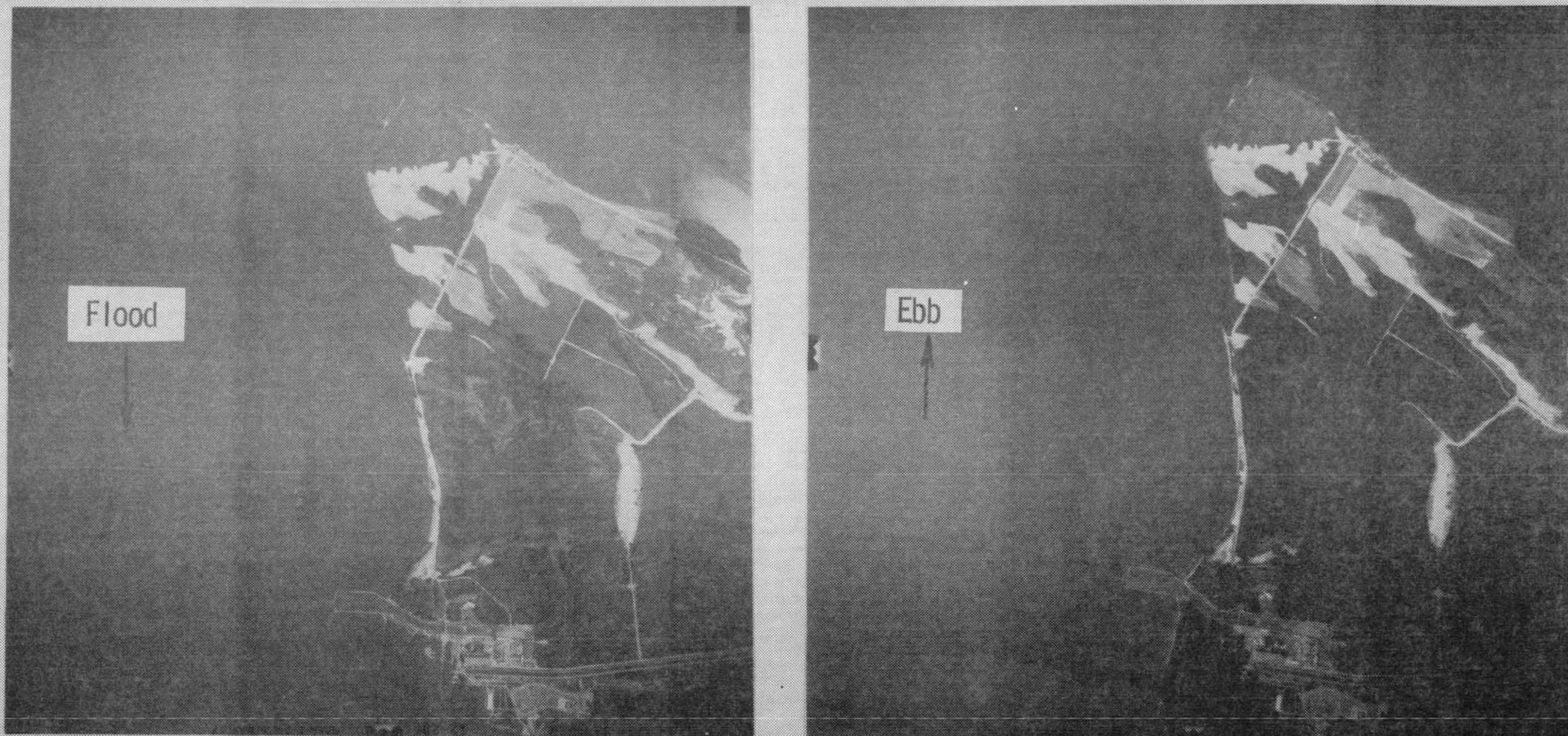


Figure 4b. - Thermal discharge flow dynamics near the Surry nuclear power plant, May 17, 1977 (P3A mapping camera at 3300 m)

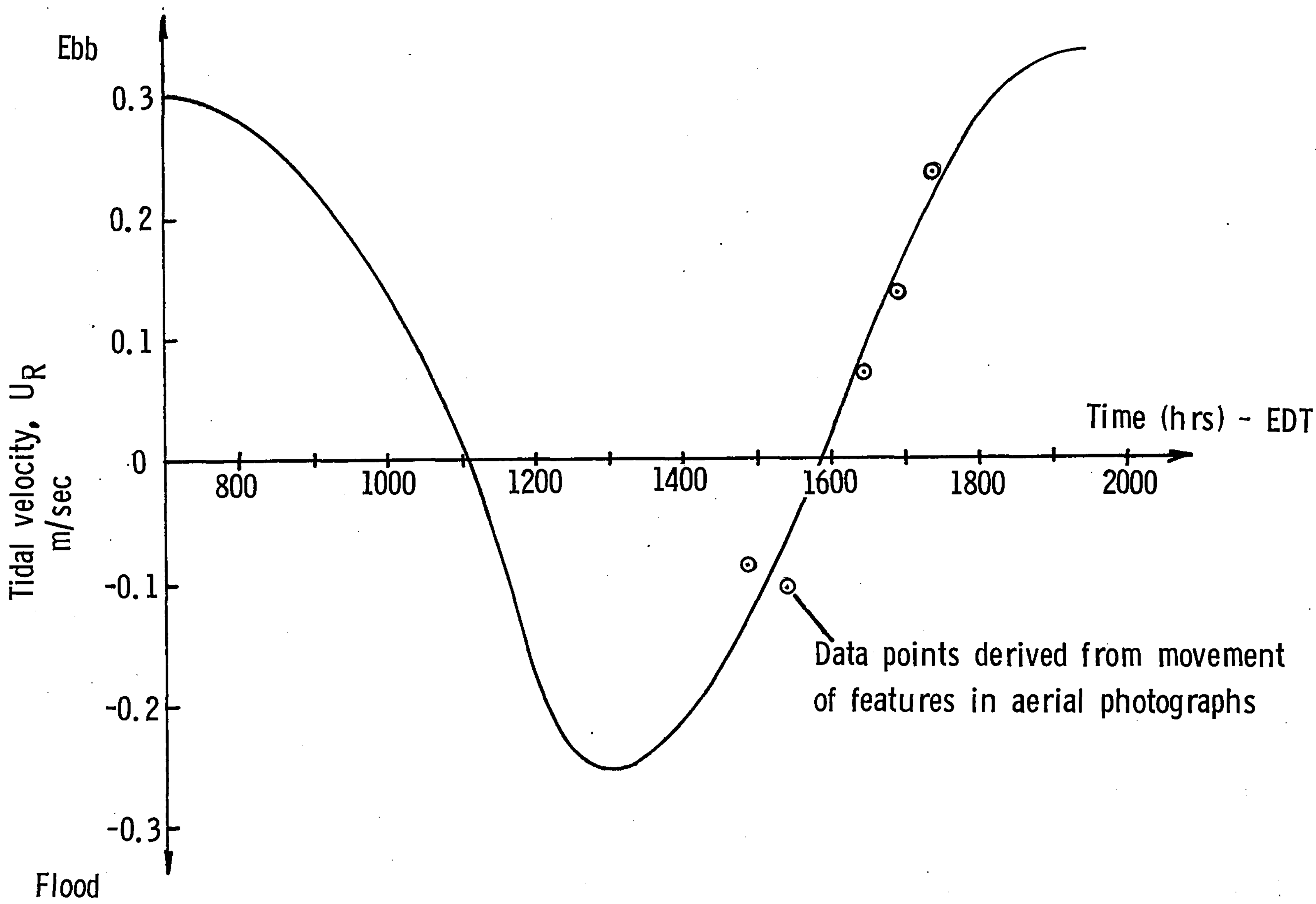


Figure 5. - Tidal velocities in the James River, U_R, near Gravelly Run, May 17, 1977.

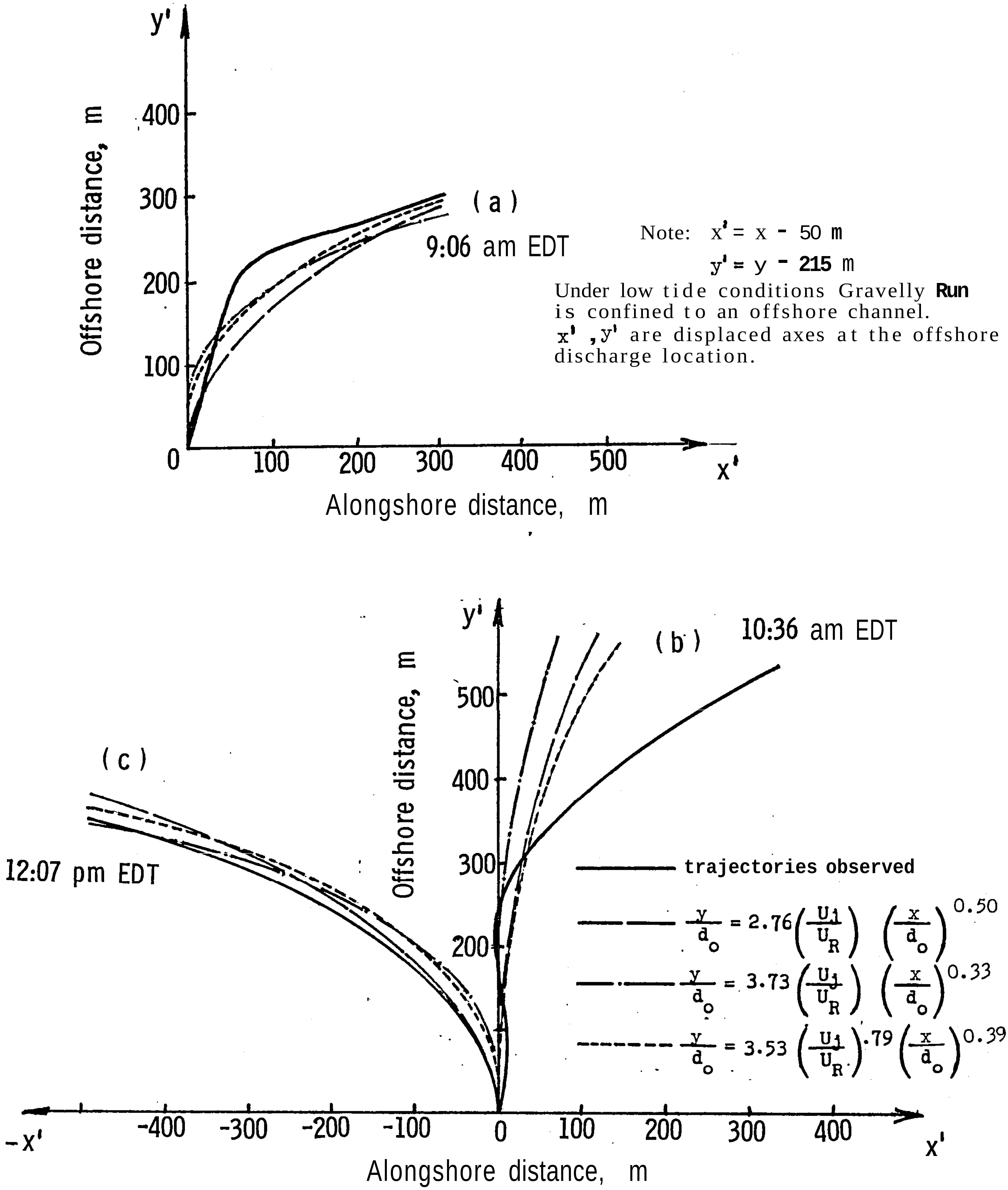


Figure 6. - Comparisons between analytical or empirical expressions and actual observed near-field discharge trajectories for Gravelly Run, May 17, 1977.

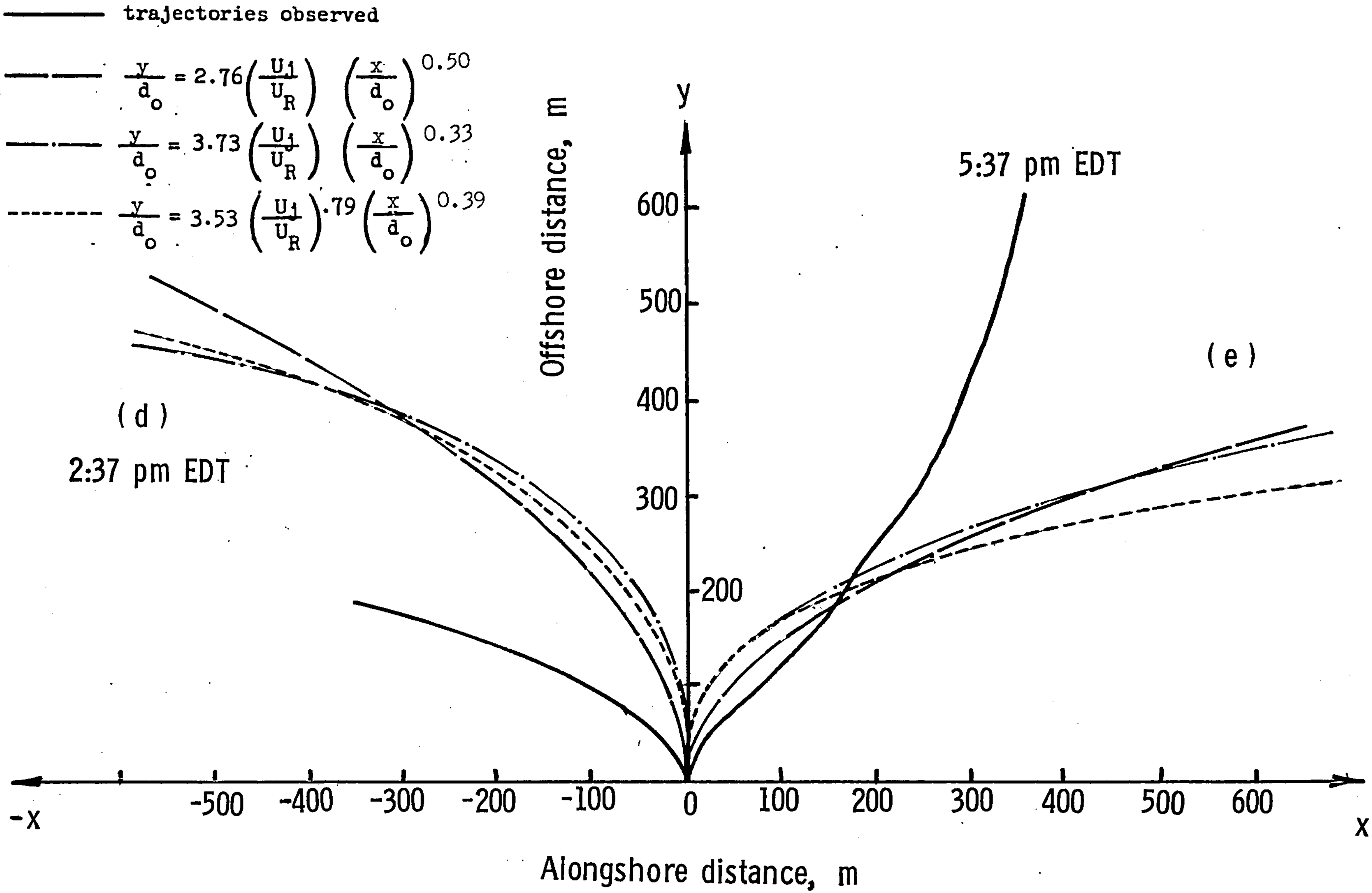


Figure 6. - Concluded.

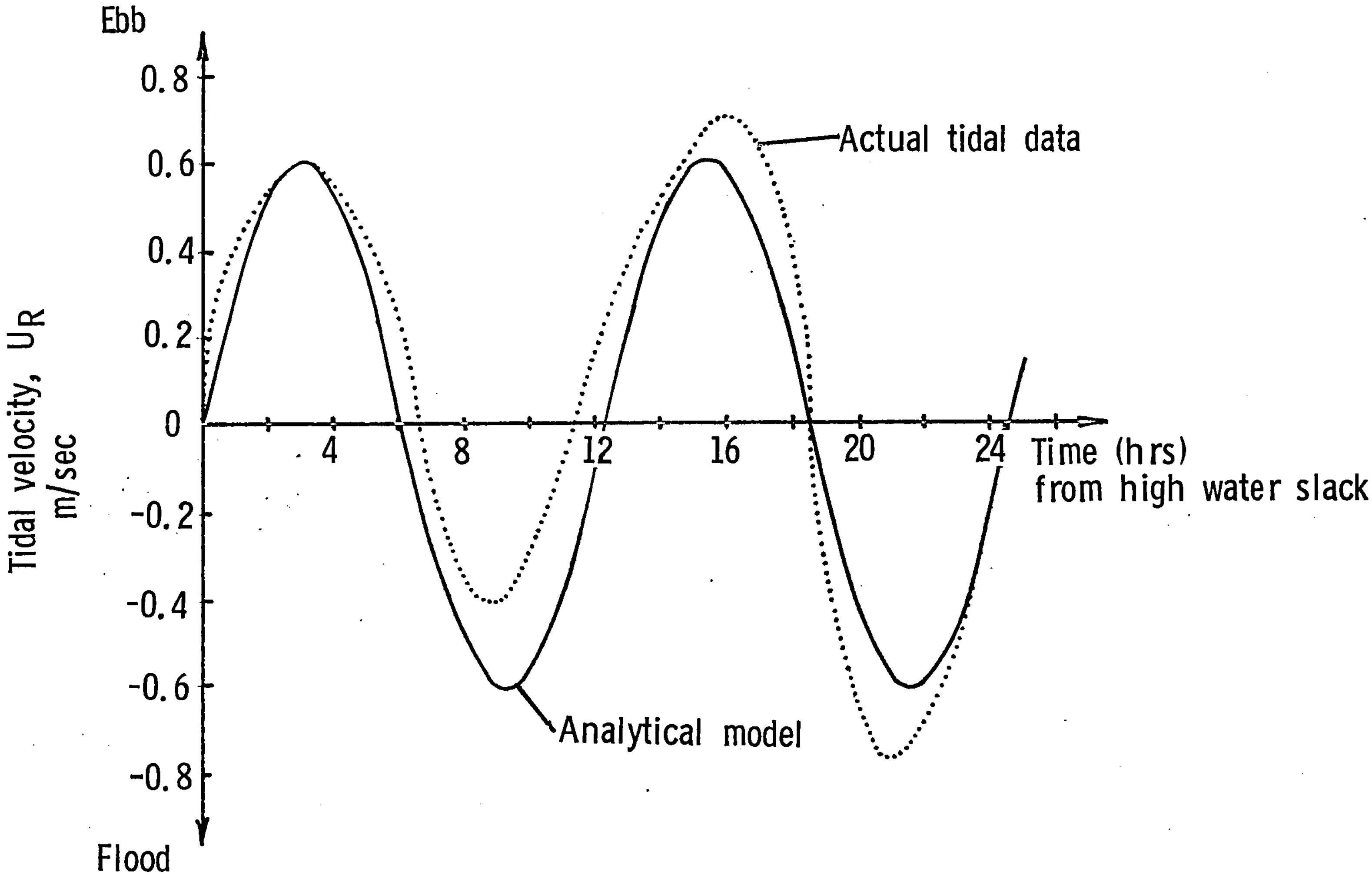
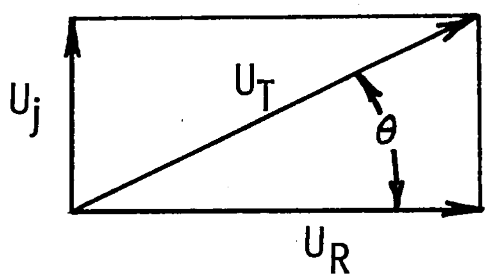
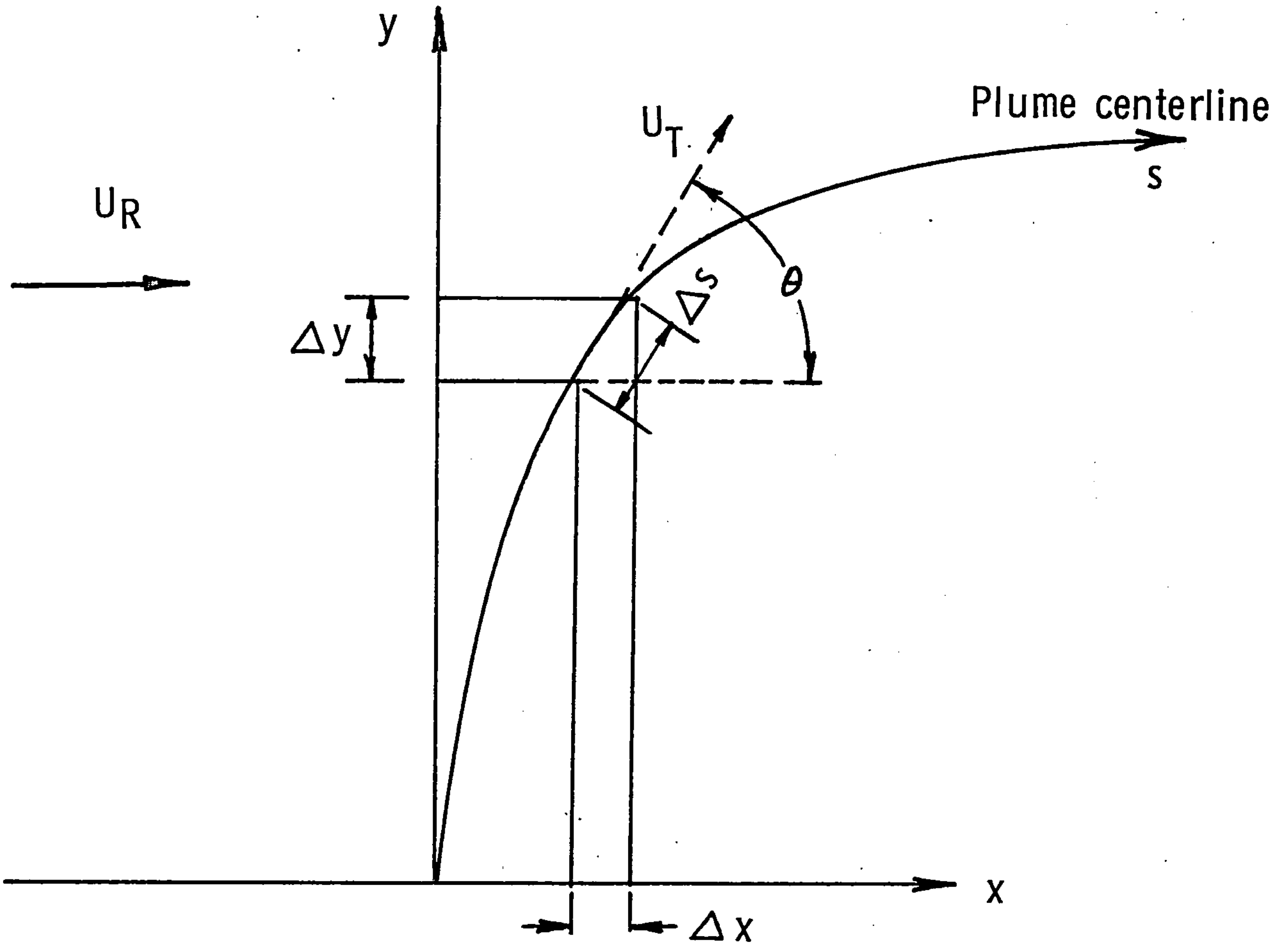


Figure 7. - Tidal velocities in the James River, U_R , near Hog Island, May 17, 1977.



(a) Definition of θ



(b) Defining incremental centerline distances

Figure 8. - Geometrical description of the Surry nuclear power plant discharge.

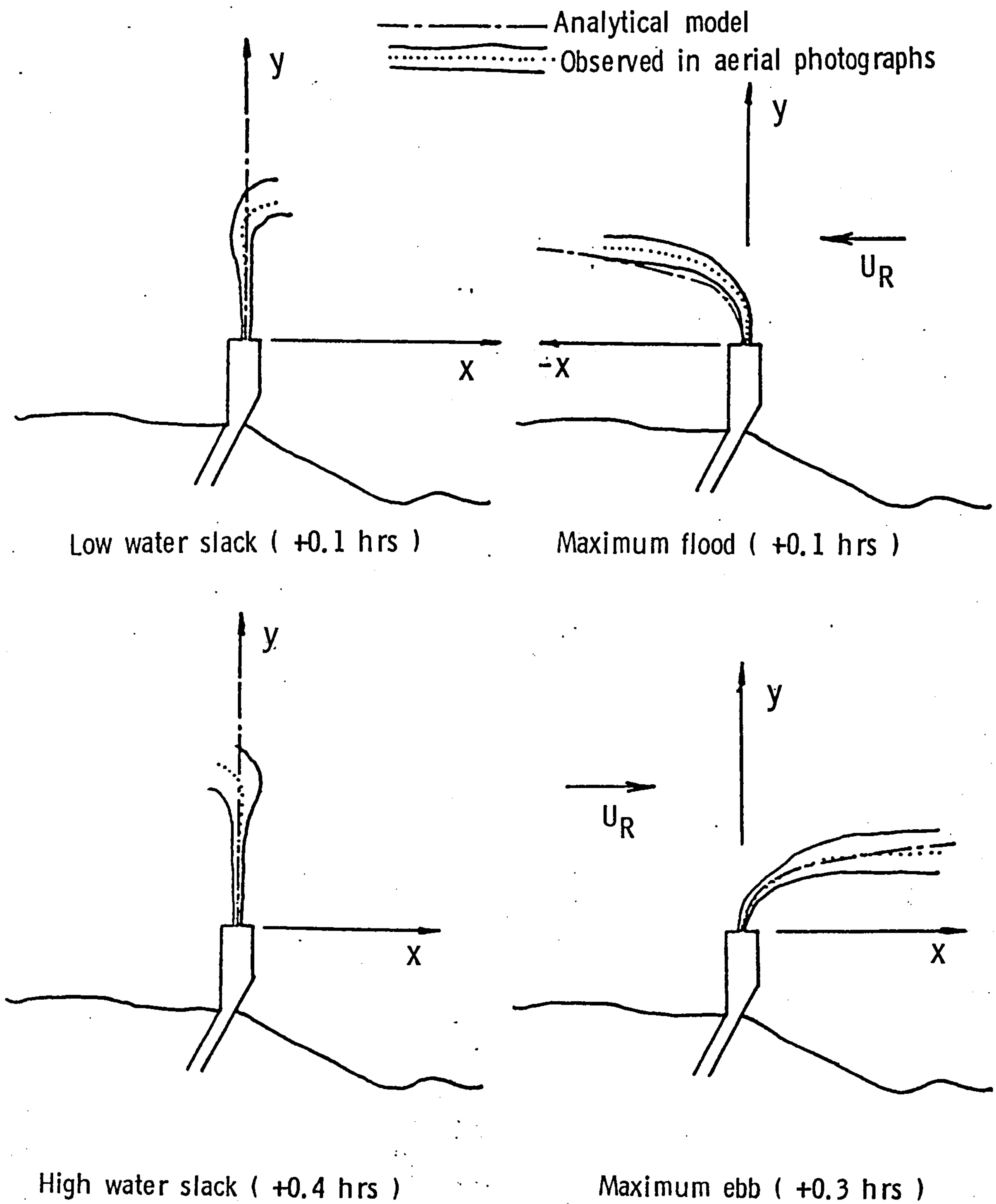


Figure 9. - Comparisons between analytical and actual observed near-field trajectories for the Surry power plant disharge, May 17, 1977.

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16. Abstract
On May 17, 1977, a remote sensing experiment was conducted by the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) on the James River, Virginia, whereby thermal spectrometer and near-infrared photography data of thermal discharges at Hopewell and the Surry nuclear power plant were obtained by an aircraft for one tidal cycle. These data were used in subsequent investigations into the near-field discharge trajectories.

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