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Outfall Siting with Dye-Buoy Remote Sensing of Coastal Circulation

Siting of sewage outfalls was based on coastal circulation determined from sequential aerial photographic coverage of dye buoys.

Abstract: *A dye-buoy remote sensing technique has been applied to estuarine siting problems that involve fine-scale circulation. Small hard cakes of sodium fluorescein and polyvinyl alcohol, in anchored buoys and low-windage current followers, dissolve to produce dye marks resolvable in 1:60,000 scale color and color infrared imagery. Lagrangian current vectors are determined from sequential photo coverage. Careful buoy placement reveals surface currents and submergence near fronts and convergence zones. Inexpensive and simple, the technique has been used in siting two sewage outfalls in Hampton Roads, Virginia. In case one, the outfall region during flood tide gathered floating materials in a convergence zone, which then acted as a secondary source during ebb; for better dispersion during ebb, the proposed outfall site was moved further offshore. In case two, flow during late flood was found to divide, with one half passing over shellfish beds; the proposed outfall site was consequently moved to keep effluent in the other half.*

Introduction

Coastal Circulation and Siting Problems

Because coastal water quality is under increasing pressure from rapid population growth, coastal zone planning and management agencies have a high priority concern in wise site selection for new coastal facilities. In order to answer a siting question properly, it is necessary to assess the relative merits of alternate proposed sites by a careful study of the regional water circulation. Circulation ideally should be studied at all alternate sites; however, the study of alternate sites is often omitted due to cost, size of the effort required, and/or lack of historical circulation data for the various sites. Remote sensing, however, provides a cost-effective method of obtaining the needed circulation data. With a dye-buoy/remote-sensing technique, we have studied alternate sites simultaneously in two cases of sewage outfall siting. The data obtained were pivotal in leading the regional sanitation commission to siting decisions.

Historical Methods of Circulation Study for Siting Problems

Siting studies in estuarine waters have generally consisted of two stages of circulation study. The first stage, concerned with absolute limits on pollution loading for the entire estuarine basin, involves the question: Will the addition of a proposed facility produce an overload on the ability of the entire basin to assimilate pollutants, provide clean water, or absorb heat? In short, should the facility even be considered? If the an-

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swer is encouraging, the second stage involves selection of a specific site with the question: Will a facility at a site overload or seriously interfere with any of the other activities in its immediate vicinity? If not, construction of the facility can be given environmental approval.

The most appropriate tools for basin-wide circulation study are basin-wide physical hydraulic models and numerical models. Both types of models are constructed by using data obtained in a costly hydrographic survey, which involves vertical strings of current meters emplaced in a grid pattern, with simultaneous profiling of temperature and salinity. Models are extremely valuable for the first stage of siting studies because they provide a consistent basis for evaluating siting problems on a basin-wide scale. They do this job well at the expense of resolution of fine-scale phenomena.

When a specific site has been proposed, a fine-scale study is then appropriate for determining the impact the proposed facility will have locally. In order to obtain this information, a dye-dispersion study has generally been the most popular technique (e.g., Okubo, 1971, and for remote sensing methods, Burgess and James, 1971). The dye-dispersion study, however, gives little information about nearby alternative sites. Simultaneous study at alternative sites is needed, but a study with simultaneous release of two or more dyes is too complex and too expensive for general use. A second limitation, when the study region contains fronts and convergence zones, is that the dye may be prevented from dispersing in a simple (e.g., ellipsoidal) manner. Calculations which presume simple dispersion will in this case yield an inaccurate dispersion coefficient.

REMOTE SENSING OF CIRCULATION, FRONTS, AND CONVERGENCE ZONES

Fronts and convergence zones are generally neglected when the above methods are used to study small area circulation dynamics. This is a major drawback in studies within the Chesapeake Bay system where tidal fronts are a regular and prominent feature. It is sometimes better to use current-following tracers to resolve siting questions. This Lagrangian approach is desirable because it produces direct evidence of water displacement.

Aerial photography is an obvious choice for tracking a set of Lagrangian tracers, and photogrammetric analysis yields accurate average current velocities. Such remote sensing has been a tool for circulation analysis for over two decades (e. g. Cameron, 1952, 1962; Keller, 1963; Zdanovich, 1964; Yeske *et al.*, 1975). A strong advantage of remote sensing is that the spatial density of sampling points can be extremely high, and the temporal density is limited only by the number of data-collecting aerial overflights. Moreover, remote sensing also permits mapping of the movement of fronts, as shown by Mairs and Clark (1973), Klemas *et al.* (1974), Klemas and Polis (1977), and Munday and Gordon (1977).

A direct attack on the dynamics of fronts and convergence zones can be made with remote sensing by the proper choice and placement of tracers. Small dye-emitting buoys, for example, have several advantages. Dye-emitting buoys for remote sensing of currents were discussed in an early treatise by Zdanovich (1964). They are resolvable in aerial imagery at a scale up to 1:60,000, and have negligible wind drag Gordon and Munday, 1977). The buoys are deployed near fronts observed from the air. The dye streams from anchored buoys (in particular) reveal the short-term history of current directions near boundaries. The abrupt disappearance of dye streams pinpoints submergence zones and shows the link between submergence zones and water color boundaries.

In our experience, dye-buoy remote sensing is a very practical technique for mapping a flow field in the presence of fronts and convergence zones. This technique provides a high density of data points in convenient format, and it is fast and inexpensive.

METHODS

DYE BUOYS

Dye buoys are advantageous because they are very small with low wind drag and their cost is low, yet they produce dye patches which image well on small-scale aerial photography.

The dye buoys consist of uranine dye cakes incorporated into a variety of buoy designs. Uranine (sodium fluorescein, i.e., spiro [isobenzofuran-1 (3H), 9′-[9H]xanthen] -3-one, 3′, 6′-dihydroxy-disodium salt [518-47-8] (C.I. Acid Yellow 73, uranin)) produces in water a highly visible green plume (excitation λ_{max} = 494 nm, fluorescence λ_{max} = 550 nm) which is readily imaged on color and color-infrared film. The dye cakes are fabricated by dissolving polyvinyl alcohol (PVA) in a minimum volume of hot water, then adding uranine powder to fix the concentration of PVA between 3 and 15 percent non-aqueous weight. The volume of water is critical for the best viscosity (pancake batter) for easy pouring and fast drying. Biodegradable 8-ounce (30 ml) paper cups are used as casting vessels. Each cup requires 300 g of uranine. The percentage of PVA controls rate of dissolution and visibility: 3-6 percent cakes are easily imaged at 1:60,000 scale and last 2 to 2.5 hours; 10-15 percent cakes are limited to 1:30,000 and last 3.5 to 5 hours. Note: take precautions in handling uranine, because it appears that the carcinogenic potential of repeated lung or skin exposure to pure uranine has not been adequately determined (however, uranine is considered safe enough to have wide medical use).

Similar dye markers for sea-surface marking were invented by Arai and Yamade (1966) and Garrett and Barger (1972). Both groups used surfactants to establish a surface slick to promote oblique visibility. It might be useful for some studies to complex the dye to the surfactant to hold the dye at the surface, because its density promotes slow sinking. However, in our work, it is inadvisable to use a surfactant because the resulting surface film might alter the dynamics of the near surface flow.

We use three types of dye buoys (Munday *et al.*, 1975). One is a surface-current follower, biodegradable and free-floating. It consists of a dye cup hung upright through a hole centered in a 1 × 8 × 8 inches (about 2 × 20 × 20 cm) wooden float. Small vanes (20 × 20 cm deep) on the float increase water drag, without making weight and size impractical for large numbers of buoys. The freeboard is about 5 mm. This buoy produces a dye patch roughly 5 m in diameter. Another type has an anchor and a 15 cm diameter spherical plastic float. It produces a 2 meter-wide linear plume in the direction of flow. The third type uses a window shade Chesapeake Bay drogue (Terhune, 1968; Vachon, 1973) which allows remote sensing of currents at depth. The shade consists of 1 m^2 of unbleached muslin, weighted and extended by ½ in. reinforcing rod glued at the bottom, and 1 × 2 in. wood glued and stapled at the top. It is suspended at the desired depth by nylon twine beneath a 3.5 in. diameter octagonal wooden float, 6 in. long with a 2 in. diameter dye chamber open from the top. The shape of the float, its size, and 2 to 5 cm freeboard (adjusted by trimming the length of the reinforcing rod) combine to minimize wind drag. All wood surfaces are sealed with varnish to prevent sinking due to water uptake. Our unit cost is $10.00. Most parts are biodegradable.

SENSORS

We employ a Hasselblad 500 EL/M camera with 70-frame magazines and a 50 mm focal length Distagon lens. The film is Kodak 70 mm Hi-Speed Ektachrome ER 5257, ASA 160, with a resolving power of 60 line pairs per mm at a contrast of 1000:1 and 30 1p/mm at 1.6:1. The Effective Aerial Film Speed is found to be roughly 40. As an accessory camera, and to check proper exposure, we carry a Nikon F2 Photomic 35 mm with a Micro Nikkor 55 mm focal length lens, loaded with Kodak VPS color negative film.

FIELD OPERATIONS

The typical field operation requires a boat, an aircraft equipped with a nadir-viewing camera, and radio communication between the boat and aircraft. The VIMS aircraft is a DeHavilland Beaver with a metric camera port. Anchored buoys are deployed first as position markers and streamflow indicators. With radio communication, the first set of floater buoys is deployed, followed by the first aerial photorun. Communication is based on radios that use state-controlled frequencies, and on Citizens Band mobile units. Radio permits specific placement of dye buoys so as to elucidate flow in the neighborhood of foam lines and water color boundaries. The airborne cameraman employs a pocket tape recorder for record keeping.

CURRENT VECTOR PHOTOGRAMMETRY

Photographic images of dye marks are transferred to enlarged scale base maps with a Bausch & Lomb Zoom Transfer Scope ZT4-H. Coordinates obtained from these maps with an electronic digitizer are reduced by computer to scaled current vectors and manually plotted on copies of the base maps. The computer program also analyzes the density of data coverage over a specific region of interest, according to different wind and tidal conditions. Since completing the studies described in the Applications section below, we have incorporated a capability for preparing base maps and current vector maps from a digitizer output tape using a CALCOMP plotter.

ERROR ANALYSIS

A consideration of errors allowed at each step of the data handling procedure yields a possible total error of <10 m for a buoy position. This error generally contributes an error under 2 cm/sec to computed average current speeds (for a 20-minute period). We do not employ a large enough number of buoys to be able to reduce the error by least-squares adjustment as did Yeske *et al.* (1975).

In other studies involving panchromatic infrared photography and essentially the same data handling procedures as above, areas were measured with absolute errors of under 2 percent for areas of 2 hectares, for 1:30,000 scale imagery. This error figure includes the component due to camera tilt along a photorun of 10 frames. Non-tidal areas on topographic maps (scale 1:24,000) were used as the area standards.

Applications to Sewage Outfall Siting

Outline of the Planning and Design Process

For sewage treatment facilities, the focal agency in our area is the Hampton Roads Sanitation District Commission (HRSDC), which has responsibility to locate, design, construct, and operate sewage treatment facilities in the Hampton Roads region. HRSDC normally hires a consulting engineering firm to design a plant and its outfall. HRSDC then presents the design as a permit application to appropriate state and federal agencies for approval. During reviews and public hearings, questions may be raised concerning dangers and environmental impacts of the proposed facility. In Application 1 which follows, VIMS remote sensing entered the decision pathway in the early design stage. In Application 2, VIMS remote sensing entered in response to environmental questions raised by the Virginia Bureau of Shellfish Sanitation at a public hearing. In both cases there was a direct line between the remote sensing and its application, embedded strategically in the decision pathway.

Application 1, Newport News Point Sewage Outfall

The problem. HRSDC is upgrading and tripling the capacity of its sewage treatment plant located on the James River at the end of Newport News Point, Newport News, Virginia. A new sewage outfall will be built. HRSDC hired the firm of Hayes, Seay, Mattern and Mattern (Roanoke, Virginia) to design the new outfall. This firm asked VIMS to determine the best site among several proposed for the new outfall. The region of the proposed sites (see Figure 1) is subject to a substantial tidal flow, with speeds of two knots (1 m/sec) commonly exceeded at maximum current. It is also a major shipping corridor and anchorage area for tankers, cargo vessels, and barges.

Methods. Even though the use of dye-buoy remote sensing for circulation studies has been justified in general (see above), specific factors in this problem led to its use. First, a bridge-tunnel for the I-664 highway will be built from Newport News Point to Portsmouth in the near future. A bridge-tunnel will probably alter the flow sufficiently that the long-term dispersion patterns determined beforehand by using a dye-dilution study will no longer apply. Second, Newport News Point is a region of high dispersion because of the large maximum values of the tidal current. This high dispersion makes it a favorable location for sewage outfalls, but it drives up the expense of dye-dilution studies, because more dye is required than in low dispersion areas to maintain a given dye density. The dye alone costs several thousands of dollars. The use of current meter strings was considered inappropriate because high dispersion would have necessitated a large density of meters. Furthermore, in the heavily-used traffic zones near Newport News Point, current meters are vulnerable to damage by ship traffic or to theft and vandalism. Finally, surface circulation patterns obtained via remote sensing (in contrast to sub-surface data obtained in other methods) were considered sufficient because sewage effluent is observed to rise to the surface near the existing outfall site, due to low density relative to the receiving waters.

Two studies were performed, one for each half of the semi-diurnal tidal cycle. In addition to the use of VIMS photography, color and color-infrared NASA imagery (scale 1:49,000) was studied for indications of stream-flow around Newport News Point.

Results and discussion. The current at Newport News Point flows generally parallel to the shore for most of each half-tidal cycle. A dye-buoy deployment line normal to the shore allowed to us construct a grid diagram for each set of dye buoys which represents the history of the water past the deployment sites (cf. Figure 1).

The initial mixing of effluent from an outfall occurs at the interface between the effluent and receiving water by the process of entrainment. The rate at which a given volume of effluent mixes is proportional to the area of the interface. This area increases with velocity of the water past the outfall and with horizontal divergence of the flow. Ve-

(1) 3:35 hours into flood tide.

(2) 4:25 hours into flood tide.

(3) 4:50 hours into flood tide.

(4) 5:05 hours into flood tide.

PLATE 1. Flood tide convergence zone at Newport News Point. Photographic sequence from 9 September 1974. Hasselblad 70 mm format, 50 mm lens, altitude 1500 m (1:30,000), Hi-speed Ektachrome, f/8,1/500 sec.

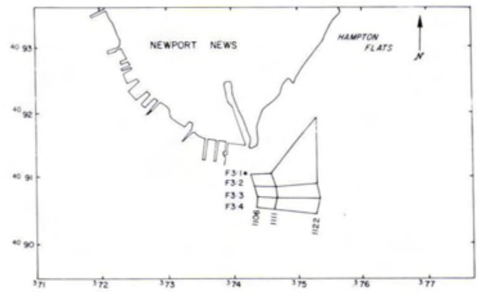


FIG. 1. Ebb tide divergence at Newport News Point, Hampton Roads, Virginia. Pathlines of floaters from set F3 deployed August 15, 1974, 2.5 hours after predicted slack water. F3:3, followed for two hours, went halfway (4 km) to Norfolk. The present outfall location is denoted*. UTM coordinates.

locity, divergence, and increase in area (the most important variable) can be evaluated directly from the constructed grid diagram.

The ebb tide analysis was based primarily on floater data from August 15, 1974. One grid diagram of Lagrangian trajectories starting at the proposed outfall sites and flowing downstream with the ebb current is shown in Figure 1 (see Neilson (1975) for a complete set of data). Note the increase in distance between Floaters 3:1 and 3:2 as time progresses. Results show that the most shoreward site had the highest dispersion during early ebb, but in late ebb the dispersion was highest at the furthest offshore site. At all sites, late ebb had lower currents and smaller dispersion. Because the outer site had the greater dispersion in late ebb, VIMS recommended the outer site for the outfall.

The flood tide case was studied on September 9, 1974. The surface flow on flood tide was not dispersive; rather, it was strongly convergent, with a convergence zone associated with a visible color boundary in the imagery. All surface water in the study area passed into this zone and submerged. The first evidence for convergence was that the floating dye markers converged rapidly into a color boundary, exited in disarray, and remained in a small area for the rest of flood tide. (A similar behavior had been noted but not understood during an earlier study of I-664 highway routing (Fang *et al.*, 1972), when radar-tracked buoys floated through the same region.) The disordering of the arrays caused confusion in buoy identification, which prevented the construction of grid diagrams. Second, streamer plumes flowed to the color boundary and disappeared, giving direct evidence for submergence of the water mass at the boundary. The color boundary was present for over four hours. A time-sequence of the flood-tide pattern is presented in Plate 1 and Figure 2. Inspection of these figures shows that the front was moving in the ebb direction against a flooding current.

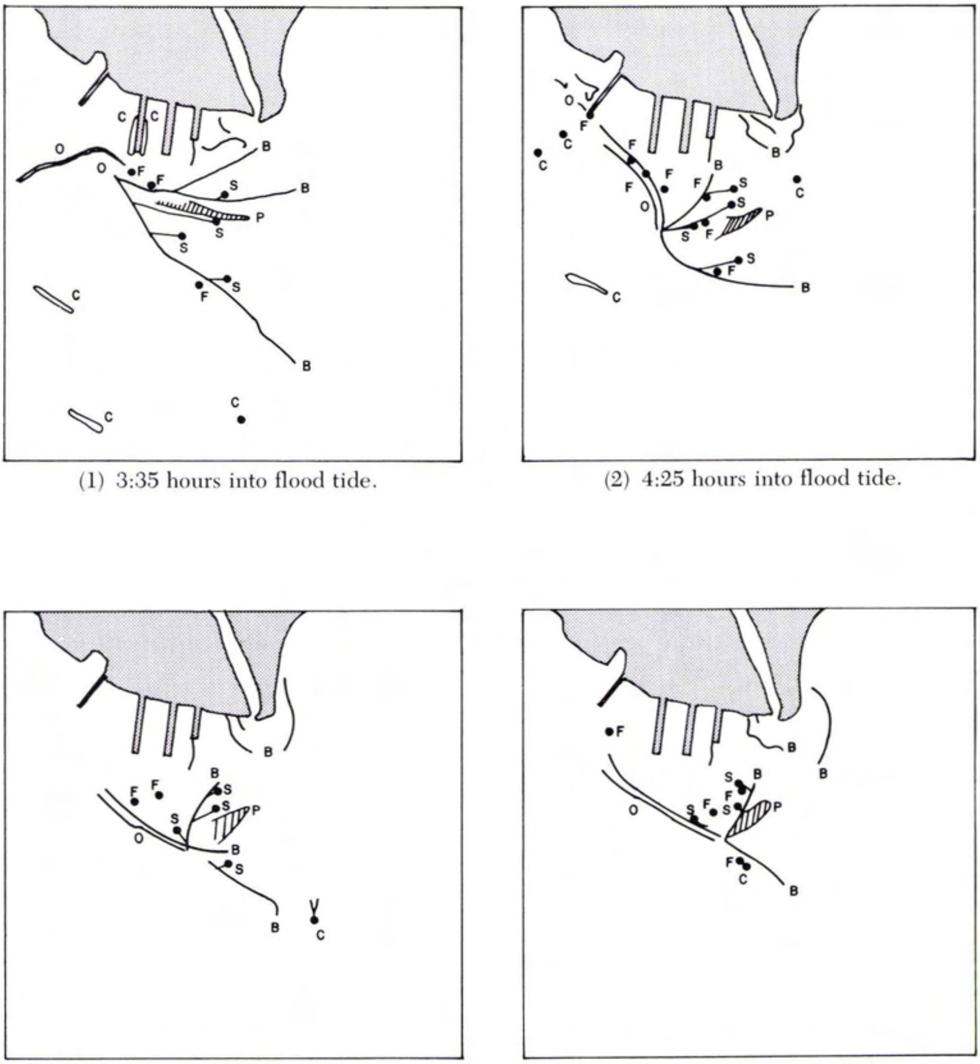
The consequences of the results are significant because color boundaries are a common feature in tidal estuaries. If color boundaries signify convergence zones and sites where floating materials congregate, then

- color boundaries can be used to find convergence zones.
- floating pollutants can be most easily cleaned up in these convergence zones, and
- specific areas of the estuary can be identified as particularly sensitive to the presence of floating materials.

At the turn of the tide, the observed color boundary disappeared and the floaters spread out again during ebb tide across much of Hampton Roads. In effect, the stagnant area formed during flood tide acted as a source of floating material on the following ebb. We term such areas secondary sources.

A secondary source can be misinterpreted as a primary source. This could be important in detecting and identifying sources of pollution in that a pollutant from a wide-spread source could be attributed to an apparent point source. Interestingly, the ebb phase imagery showed a number of oil slicks downstream of Newport News Point. These had apparently originated from near Newport News Point but were not traceable back to a "point" source. Our interpretation is that these slicks came from the gathering of material which took place throughout the preceding flood phase. This "carpet sweeper" action at color boundaries provides the key to cost-effective strategy for reclaiming spilled oil.

Outcome. The findings were reported to the engineering consultants in March, 1975. The substance of the VIMS findings was that "an outfall site somewhat further from shore would be better than the existing site" (Neilson, 1975, p. 3). During ebb, the flow past the outer site turns toward the middle of Hampton Roads and thus will avoid the nearshore shallows. For flood tide, "no qualitative differences in the four study sites for flood conditions could be determined" (p. 2) because of the submergence zone upstream of Newport News Point, which promotes mixing for all except buoyant materials which become trapped at the boundary.



(1) 3:35 hours into flood tide.

(2) 4:25 hours into flood tide.

(3) 4:50 hours into flood tide.

(4) 5:05 hours into flood tide.

FIG. 2. Interpretation of flood tide photographic sequence.
B: water color boundary
C: cargo vessel, tug-boat, or small craft.
F: dye patch from free-floating dye buoy.
O: oil slick.
P: sewage outfall plume (hatch marks).
S: dye stream (line) flowing from anchor buoy (dot) indicating current direction.

The engineering consultants consequently recommended to HRSDC that "a new outfall be constructed . . . to extend to a discharge point 600′ (ft) south of the existing discharge" (Hayes *et al.*, 1975, p. 1-7). At a public hearing in July, 1975, the VIMS study was acknowledged as having "pinpointed the preferred locations of the discharge . . ." (HRSDC Public Hearing, 1975).

Savings, benefits, and costs. The cost of choosing the site by using remote sensing was roughly $10,000. A conventional dye-dispersion study for any one site would have cost about $18,000. Study of only one site would have been clearly insufficient, and at least two and perhaps all four sites would have been studied in order to answer the question adequately. Based on past experience, $50,000 might have been spent on dye-dispersion studies (five times more expensive than remote sensing) had remote sensing not been available. Note that a dye-dispersion study would have yielded dispersion coefficients (not obtained in this instance from remote sensing) which might be useful. However, the understanding of the convergence zones obtained from dye-buoy remote sensing would have been completely missed.

APPLICATION 2. PIG POINT SEWAGE OUTFALL

The problem. The Hampton Roads Sanitation District Commission has decided to build a new sewage treatment plant to serve the City of Portsmouth and Nansemond County, on the southern side of Hampton Roads, Virginia. In an earlier study (Kuo and Jacobson, 1975), VIMS determined the dispersion capability of the general area first proposed for the outfall by using a dye release from an abandoned munitions pier located in the center of Hampton Roads (see Figure 3). The results indicated that seed oyster beds on Nansemond Ridge to the west would not be severely affected by effluent from the pier area. These seed oyster beds are critical to the Virginia oyster industry because they are among the largest and best oyster beds in the James River, which produces virtually all the seed oysters for the Chesapeake Bay oyster industry.

Later, McGaughy *et al.* (1975) proposed an outfall site southeast of the pier to allow the outfall pipe to be placed adjacent to the route of the proposed I-664 bridge-tunnel. Concern was expressed by the Virginia Bureau of Shellfish Sanitation at a public hearing that the flood tide flow past this new site might reach the Nansemond channel and the nearby oyster beds. VIMS was asked to quickly perform a new circulation study to address this concern.

Methods. An estimate of the tidal excursion for this region was obtained by presuming the intertidal volume of the Nansemond River to flow as a slug of water from

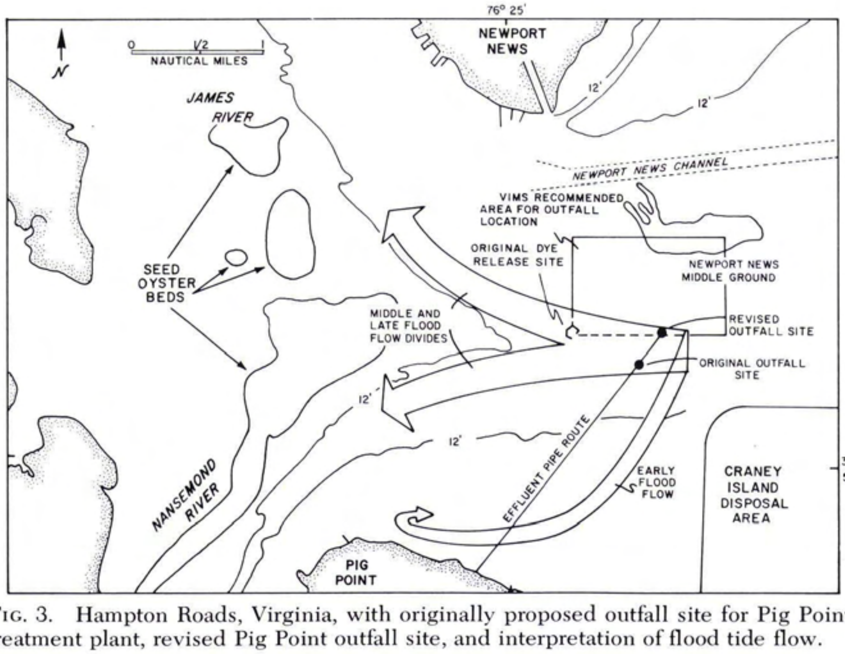


FIG. 3. Hampton Roads, Virginia, with originally proposed outfall site for Pig Point treatment plant, revised Pig Point outfall site, and interpretation of flood tide flow.

Hampton Roads. From the size of the slug, a preliminary assessment was made of the potential for water from the proposed outfall site to reach the Nansemond River. The results of this crude calculation were that water flowing past the site had the potential to reach the sensitive oyster regions and that a field study was in order.

The decision on initial placement of dye buoys was made with substantial help from NASA high altitude imagery. In 1972, NASA obtained color infrared and thermal infrared scanner imagery in a sequence of flights during a half-tidal cycle. Interpretation of this sequence revealed that west of the proposed site the James River started to ebb sooner than the Nansemond River, allowing the possibility that James River water might cross Nansemond Ridge toward the Nansemond River mouth. This finding led to the decision to place extra dye buoys in a north-south pattern westward of the site, in order to discover exactly when and where the flow lines which pass the site would diverge, and which portion would more directly reach Nansemond Ridge.

After several days of initial experimentation, a final experiment was conducted on August 28, 1975. To provide a location reference when buoys drifted far from shore, the study boat fixed its position during photography by obtaining a several minute sequence of Loran C data.

Results and discussion. The results showed that effluent from the site would reach the oyster beds, and that a relatively short northward shift of the site would keep effluent away from the oyster beds. During early flood, waters flow past the site in a southerly arc toward the Nansemond County shoreline, but never reach the significant oyster beds. However, during middle and late flood, the flow divides just south of the munitions pier, the southern flow heading directly toward the Nansemond River and the oyster beds (see Figure 3). VIMS therefore recommended that the site be located north of 36°56′N, to keep the effluent in the northern branch of the flood flow during middle and late flood.

Outcome. A full report prepared by Welch and Neilson (1976) was submitted to McGaughy *et al.* for ultimate presentation to HRSDC. The VIMS recommendation for the more northerly outfall site was accepted by HRSDC, the Virginia State Department of Health (Bureau of Shellfish Sanitation), the Virginia State Water Control Board, the Environmental Protection Agency (Philadelphia), and the Food and Drug Administration.

Summary Comments

The success of the dye-buoy remote sensing technique in elucidating circulation was confirmed by HRSDC in accepting the siting recommendations. The consequence for our future work is that the technique is fully integrated as one of the standard tools used at VIMS for answering siting questions. It is easily implemented, provides the needed circulation data, and is inexpensive. A particular advantage is that it enhances fronts and convergence zones by revealing nearby current directions as well as submergence at boundaries.

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