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## REMOTE SENSING OF THERMAL LOADINGS ON AQUATIC SYSTEMS

### ABSTRACT

The detrimental effect of thermal cooling water discharges on receiving waters has long been a subject of controversy. Because the potential impacts cover such large areas and can involve subtle changes over time, they have been difficult to study. This paper reports on the development of new tools to study the magnitude and extent of thermal discharges. Thermal infrared remote sensing techniques have been developed to enable mapping of water surface temperatures to within  $0.5^{\circ}\text{C}$  without requiring surface data. In addition, color aerial photographic analysis techniques have been defined for studying the impact of thermal discharges on various aspects of aquatic ecosystems. The development of these techniques employed the use of aerial thermal infrared data, aerial color photography, laboratory modeling of the color characteristics of water, and surface sampling for water quality parameters. The successful intercomparison of the aerial and surface techniques for assessment of water quality and the potential for large-scale application of an aerial approach to water resource studies is discussed.

### INTRODUCTION

The widespread interest in studying the relationships between thermal anomalies in water bodies and water quality parameters has promoted the development of new technologies to observe water resources. The large areas associated with phenomena such as coastal upwelling, stream discharges into lakes and oceans, thermal bars on large lakes and industrial cooling water discharges require the synoptic perspective of remote sensing to adequately assess them. Detailed information on actual temperature values and associated water quality parameters such as chlorophyll, suspended solids and gelbstoffe (yellowing organics) has required extensive ship-based sampling and laboratory analysis in addition to extensive use of interpolation and extrapolation algorithms tied with varying degrees of vigor to the aerial data. This paper discusses the parallel development of two techniques designed to eliminate or minimize requirements for ship-based data while maintaining the concentrated detail and synoptic perspective necessary in studying thermal anomalies. The experimental results presented here were obtained in studies of power plant cooling water discharges. The main body of this paper will, therefore, concentrate on these phenomena. However, the application to other sorts of thermal anomalies with concurrent water quality variations should be obvious to the reader.

The discussion begins with a section describing the development and testing of a wholly airborne technique for aerial measurement of true water surface temperature. The next section discusses the parallel development and

preliminary testing of a procedure for determining the concentration of water quality parameters by densitometric analysis of aerial color photographs using a minimum of "sea truth" in the analysis. The final section provides an illustration of how these technologies could be used to study water quality parameters associated with thermal anomalies and includes suggestions for modifications or improvements necessary for further application of this technology.

#### QUANTITATIVE WATER SURFACE TEMPERATURE MAPPING

Aerial infrared systems operating in the 8-14  $\mu\text{m}$  spectral region have been extensively used to observe thermal patterns in water. In particular, imagery from infrared line scanners has been used to monitor cooling water discharge plumes<sup>1,2,3</sup>. The advantage of this approach is that the thermal scanner can image the entire surface area of a discharge plume in minutes. In this manner, all the internal detail as well as the shape and spatial extent can be easily determined. The disadvantage of this approach is that a boat is needed to collect data required to convert brightness levels on the image to temperature values.

In an effort to resolve technical, operational, and cost problems associated with the existing approaches, a program was initiated to develop and test wholly airborne calibration of a thermal scanner system so that precise thermal maps could be generated without requiring data from boats. This technique involved development of a model incorporating both the surface temperature and the atmospheric effects contributing to the signal at the sensor.

#### Theory: Aerial Measurement of Temperature

The density at each point in an image formed by an infrared line scanner is a function of the energy reaching the airborne infrared detector at the time the point was imaged. The 8-14  $\mu\text{m}$  radiant energy incident on the detector can be determined from the density of an image point for a carefully calibrated line scanner with an internal blackbody reference cavity. The recorded density can, therefore, be converted to a radiance value,  $W_D$ , or to an equivalent blackbody temperature through the Planck radiation equation,

$$W_D = \int_8^{14} 2\pi C h \lambda^{-5} (e^{hc/\lambda kT} - 1)^{-1} d\lambda. \quad (1)$$

The radiant energy or apparent blackbody temperature recorded by the airborne sensor cannot be directly converted to a water surface temperature. The radiant energy observed by the sensor is a function of several factors which can be expressed as

$$W_D(h,\theta) = \tau(h,\theta) \varepsilon(\theta)W_T + W_A(h,\theta) + \tau(h,\theta)W_S r(\theta). \quad (2)$$

where  $h$  designates the dependence of the variable on aircraft altitude,  
 $\theta$  designates the dependence of the variable on look angles away from normal,  
 $\tau$  is atmospheric transmission (8-14  $\mu\text{m}$ ),

- $\epsilon$  is the emissivity of water (8-14  $\mu\text{m}$ ),
- $W_T$  is the radiant energy associated with a blackbody at the same temperature as the water as in Equation (1) (i.e.,  $\epsilon W_T$  is the radiant energy directly from the water (8-14  $\mu\text{m}$ ),
- $W_A$  is the radiant energy reaching the sensor originating from the air column between the surface and the aircraft (8-14  $\mu\text{m}$ ),
- $W_S$  is the radiant energy from the sky reaching the surface (8-14  $\mu\text{m}$ ), and
- $r$  is the reflectivity of the water,  $r = 1 - \epsilon$  (8-14  $\mu\text{m}$ ),

In order to determine a true water surface temperature, we need to be able to calculate  $W_T$  from the observable value  $W_D$ . The emissivity of water is well defined; therefore, the unknowns in Equation (2) are atmospheric transmission, air radiance and sky radiance.

#### Approach: Aerial Measurement of Temperature

Data collection procedures were defined which permitted collection of data about the atmospheric and background effects on the signal reaching the sensor. The first procedure involved collecting data over the same terrain features at a series of altitudes below the principle collection altitude. This, in essence, enabled us to sample the atmospheric attenuation and air radiance effects at these altitudes so that their effect on the signal at altitude could be calculated.

A second procedure involves flying parallel flight lines over water so that points in the water can be viewed vertically and then off axis. Correcting the signals (from the same points viewed differently) for atmospheric transmission and air radiance leaves differences in signal that are related to changes in the amount of sky radiance reflected due to change in the 8-14  $\mu\text{m}$  reflectances of water with view angle. By evaluating this change in radiance at angle for multiple points (i.e., different temperature points), it is possible to calculate the sky radiance effect.

These two procedures conducted at the time of data collection enable us to calculate the unknown in Equation (2) so that  $W_T$  and hence, through Equation (1), true water surface temperature can be calculated from densitometric analysis of aerial infrared imagery<sup>4</sup>.

#### Testing and Results: Aerial Measurement of Temperature

A ground-truth program was used to evaluate these radiometric calibration techniques. This effort involved aerial overflights of a boat anchored at a series of positions in the Hudson River, both within and beyond the thermal plumes of various power plants.

With the boat anchored at a given position, readings were made on the upstream (downstream if flow was upstream in the estuary) side of the boat. Measurements consisted of temperatures recorded from a submerged thermistor (nominally at a depth of 6 inches) and from a Barnes PRT-5 radiometer. During each fly-over, approximately ten readings were recorded and averaged to predict

the temperature at a point. To ensure unbiased data, all surface measurements were made by independent consultants and surface data were withheld until aerial results had been delivered to the project sponsors at the New York State Energy Research and Development Authority (NYSERDA). The surface radiometer was calibrated in the field under prevailing atmospheric conditions to ensure that all measurements were absolute surface temperature measurements. Because the boat was covered with aluminum foil, it had a low emissivity and could be located as a "cold" spot on the image. Surface temperatures were predicted using the calibration technique discussed above.

In all, sixty-one sample points were obtained from two days of sampling. These points included data taken under different atmospheric conditions at different times of the day and at a range of true surface temperature values. Comparison of the ground truth and aerial measurements yielded a standard error, S, of 0.5°C where  $S = \frac{\sum(T_{\text{TRUE}} - T_{\text{AERIAL}})^2}{\text{Number of points}}$ . This compares

quite favorably with a standard deviation about the mean of boat measurements for each point of approximately 0.3°C. The data were also analyzed to determine what the error would be if no atmospheric or background corrections were applied and only internal scanner calibration was used to estimate the surface temperature. In this case, the standard error would have been 2.0°C. By using the described advanced analytical procedures, accurate measurement and mapping of the true surface temperature pattern of a waterway is possible.

The next section discusses techniques developed to assess the concentration of certain water quality parameters using photographic remote sensing. In the applications section, we will discuss how these photographic and thermal infrared techniques can be combined to study the relationships between thermal anomalies and water quality.

#### ASSESSMENT OF WATER QUALITY PARAMETERS

Observation of concentration values of water quality parameters using passive photographic systems limits us to certain parameters. We can only expect to observe materials or coloring agents that are suspended in the water. For our purposes, we have defined three major parameters that can be expected to provide most of the "color" variation in water. The "coloring" agents identified for consideration were total suspended solids (indicative of sediment loadings and nutrient availability), chlorophyll (indicative of algal standing crop) and yellowing organics (indicative of certain types of runoff and pollutants, i.e., humic acid, tannic acid and sewage). Conveniently, these three coloring agents can provide considerable insight into water quality. The problem is to determine if their effect on the optical properties of water is significant and if it can be observed and quantified through aerial observation.

#### Theory: Assessment of Water Quality

The property of water observable by remote sensing is the volume spectral reflectance (VSR). This is the fraction of the amount of light in a given spectral band that enters the water column and is scattered back out. Using a mirrored cell, it is possible to measure the VSR and optical trans-

mission of a volume of water as deep as the cell is long and having infinite breadth. It is then possible to mathematically extrapolate these results to obtain the VSR of a volume of water of infinite depth<sup>5</sup>. The VSR of a volume of water of infinite depth and breadth is exactly the VSR we would expect to observe at the surface of a natural water body. Using an experimental cell, it is possible to observe how the VSR of water is related to concentrations of various parameters in the water column.

Piech and Schott (1974) demonstrated that the VSR of a water body could be measured by proper densitometric analysis of color aerial photographs. The analysis is based on the exposure observed on the aerial record being a function of the VSR of the water, i.e.,

$$E_{\lambda} = \alpha_{\lambda} R_{\lambda} + \frac{\alpha'}{\pi} R_S + \beta_{\lambda}$$

where E is the exposure recorded on the film,

$\alpha$  is proportional to sunlight and skylight illumination and atmospheric transmission,

R is volume reflectance of the water,

$\frac{\alpha'}{\pi}$  is the fraction of the skylight illumination specularly reflected into the camera from the water surface,

$R_S$  is the surface reflectance of the water,

$\beta$  is a function of the light scattered into the camera by the air column, and

$\lambda$  indicates the dependence of each variable on the red, green or blue spectral sensitivity of the recording film.

Thus, by calculating the illumination and atmospheric parameters ( $\alpha, \alpha'$  and  $\beta$ ), the VSR ( $R_{\lambda}$ ) of the water can be determined. Using the relationships derived in the laboratory between VSR and the concentration of color agents, the concentration of various parameters in the water can then be determined.

#### Approach: Assessment of Water Quality

In an effort to evaluate the theoretical approach described above, a laboratory experiment was undertaken to measure the VSR of water containing varying concentrations of water quality parameters. Chlorophyll, total suspended solids (TSS) and yellowing organics were modeled using water soluble chlorophyll, lignin (bleached hardwood) and humic acid, respectively. The VSR of water was measured in the three spectral bands, corresponding to the sensitivity of Ektachrome color film, for varying concentrations and mixtures of the three parameters. A multiple linear regression was performed on the resultant data set which indicated that chlorophyll, lignin and humic acids could be predicted from reflectance data to within 6.8 ppb, 2.8 ppm and 0.6 ppm for ranges of 0-60 ppb, 0-30 ppm and 0-6 ppm, respectively. These results were based on observed variations in measured reflectance of about 0.2%.

Based on the success of the laboratory model, a field experiment was designed to evaluate the utility of the approach. Color aerial photographs and aerial thermograms were collected in coordination with grab samples taken

at various points in the discharge plume of a power plant on the lower Hudson River in New York State. Approximately twelve samples were taken on each of two occasions. The grab samples were analyzed for chlorophyll, TSS and total organic carbons (as a partial indicator of yellowing organics). The aerial imagery was calibrated to remove atmospheric and illumination effects. Densitometric data obtained at image points where grab samples had been taken were then converted to VSR values.

The data were analyzed for systematic errors by running the grab sample concentration values backward through the laboratory models to predict reflectance and then comparing the predicted reflectances with those measured from the air. This comparison indicated that a very strong linear correlation existed between the aerially measured and predicted reflectance values in each band. However, an identity correlation did not exist, indicating the presence of systematic errors. The existing data set did not allow separation of the systematic error into a component due to the laboratory modeling and a component due to the aerial calibration. However, the systematic nature of the error did allow us to account for it by arbitrarily adjusting the reflectance values measured from the air to the equivalent reflectances needed for the model using band-by-band linear regressions derived from the grab samples. In this manner, aerial reflectance measurements could be used to predict water quality concentration values not only at the grab sample locations but anywhere in the scene.

#### Results: Assessment of Water Quality

The grab samples were taken in the estuary over a period of about one hour. In order to compare the concentration values predicted from the aerial data with the actual values, some of which were taken as much as 45 minutes from when the overflight took place, the data were grouped into "within plume" and "beyond plume" sets and the average values compared. We felt that this grouping would tend to counteract discrepancies introduced by the time variant nature of concentration values at a given point in an estuary plume. The within plume and beyond plume data sets from the two overflight dates provided the basis for comparison of surface concentrations and aerial predictions. The standard error was 5.5 ppb when chlorophyll concentrations were compared and 3.0 ppm when the lignin and total suspended solids concentrations were compared. The humic acid values could not be directly compared because the grab samples were not analyzed for this parameter. The results of the chlorophyll and lignin analysis are very promising especially when we note that the variation in TSS and chlorophyll found in the vicinity of a plume may typically be 5 to 10 times greater than the observed errors.

#### APPLICATION: OBSERVING A THERMAL DISCHARGE

The data collection and analysis techniques described above were used to generate isopleth maps of temperature, chlorophyll, lignin and yellowing organic concentrations in the vicinity of the power plant thermal plume as seen in Figures 1 and 2. Consideration of the tidal cycle data indicates that the thermal plume should be moving south along the western shore at the time the photographic imagery was taken at 9:30 A.M. on 1976 August 31 (cf. Figure 1.a.). Consideration of the water quality maps for lignin and humics (Figures 1.b and 2.a) indicates that an increase in suspended solids appears to be associated with the thermal plume in this area. This is most probably the result of bottom scouring and increased turbulence associated with high volume discharges.

It appears, however, to show some time delay from the thermal plume. This is apparent because the lignin isopleths are oriented approximately where the thermal plume might have been perhaps an hour earlier near slack tide. The chlorophyll data mapped in Figure 2.b tend to indicate that even larger time delays may be associated with the algal standing crop plume.

These effects can be understood if we consider the nature of the processes being observed. The thermal plume is the direct effect of the cooling water discharged at the point of the power plant and should, therefore, be expected to fairly closely follow the tidal cycle at that point. The lignin and humic acid concentrations are a primary effect of the turbulence of the discharged water and are, therefore, only indirectly tied to the discharge point. They might be expected to show some time-delayed coupling with the thermal plume. The chlorophyll concentrations and the indicated increases in algal levels are generally considered to be a combined result of increased water temperature and increased nutrient availability associated with the increased suspended and dissolved material in the vicinity of the plume. The chlorophyll levels can, therefore, be seen as a secondary effect and might be expected to have an even longer time delay in following changes at the discharge point. This can be better understood if we recognize that the river at this point undergoes complete flow reversal driven by the tidal cycle. Therefore, "packages" of warmer water move up and down the river in the vicinity of the power plant, permitting development of an increased standing crop which we would expect to be only loosely coupled to the plume location at any given time.

Several other interesting factors can be observed with the quantitative synoptic perspective provided by this approach. For example, although there is an increase in the algal standing crop in the vicinity of the power plant, it is quite small compared to other presumably natural increases indicated by the high chlorophyll levels shown in Figure 2.b to the southeast of the plant. In addition, other aspects of the receiving waters, such as the increase in dissolved organics at certain places along the east side of the river, can be observed using this approach. These factors are very important in sighting and monitoring thermal discharges. The techniques developed as part of this research offer the potential to monitor the interaction and effects of thermal plumes on a regular basis. Periodic seasonal sampling, as well as intensive short-term sampling, are facilitated using this approach.

#### CONCLUSIONS

The wholly airborne measurement of temperature, the detailed laboratory modeling of VSR and the aerial measurement of VSR were shown to be extremely useful in studying the impact of cooling water discharges. The development and demonstration of the thermal infrared measurement techniques and the photometric-VSR techniques represent significant advances in the state-of-the-art of water resources surveys. These techniques are generally applicable to many aspects of remote sensing. The thermal infrared interpretation techniques developed as part of this research are being refined for further application to measurement of rooftop heat loss. The photometric-VSR techniques can be useful for nearly any water resources study. Another important application of the technologies developed here would be in studying the interplay of ocean upwelling areas, which is extremely important to the world's fishing

industry. To realize this type of application, the potential for satellite application of the thermal calibration and photometric-VSR techniques would have to be demonstrated.

The unique combination of the thermal and photometric techniques demonstrated here should be more fully evaluated and expanded on through time/rate studies. These studies would allow the evaluation of large-area time/rate processes over seasonal and short-term cycles (tidal) which to now have completely eluded researchers.

Significant reduction in the number of grab samples can be expected as the photometric calibration techniques improve or if ground reflectance measurements are included in the calibration process. It is currently necessary to have at least two samples of considerably different turbidity to correct for systematic errors in the photometric-VSR modeling technique. Six samples with a wide range of turbidity values are recommended. Future efforts should attempt to more closely model natural parameters in the laboratory VSR models. The use of ground reflectance data could permit reduction of systematic errors to a point where grab samples become unnecessary.

In concluding, we want to point out that we believe the thermal calibration techniques discussed here have reached an operational status for wholly airborne measurement of water surface temperatures. The VSR measurement techniques are in a less mature stage of development, but have already proven quite useful and show considerable promise toward evolving into an operational tool.

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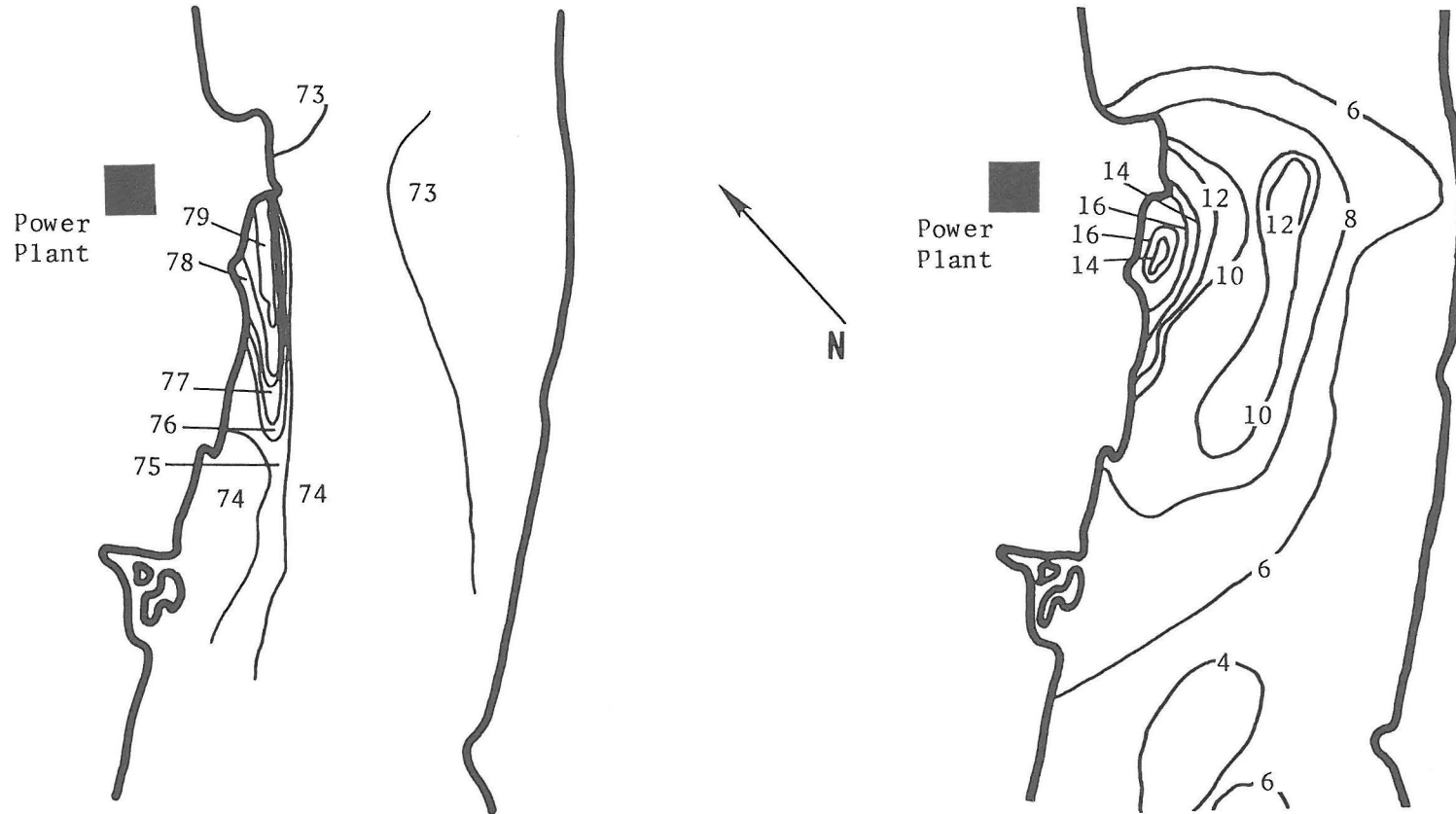


Figure 1

a) Temperatures ( $^{\circ}$ F) of the thermal plume collected during sampling efforts in August 1976.

b) Lignin concentrations (ppm) in the Hudson River obtained from aerial data collected August, 1976. Of particular interest is the increase in lignin probably associated with increased bottom turbulence at the power plant discharge.

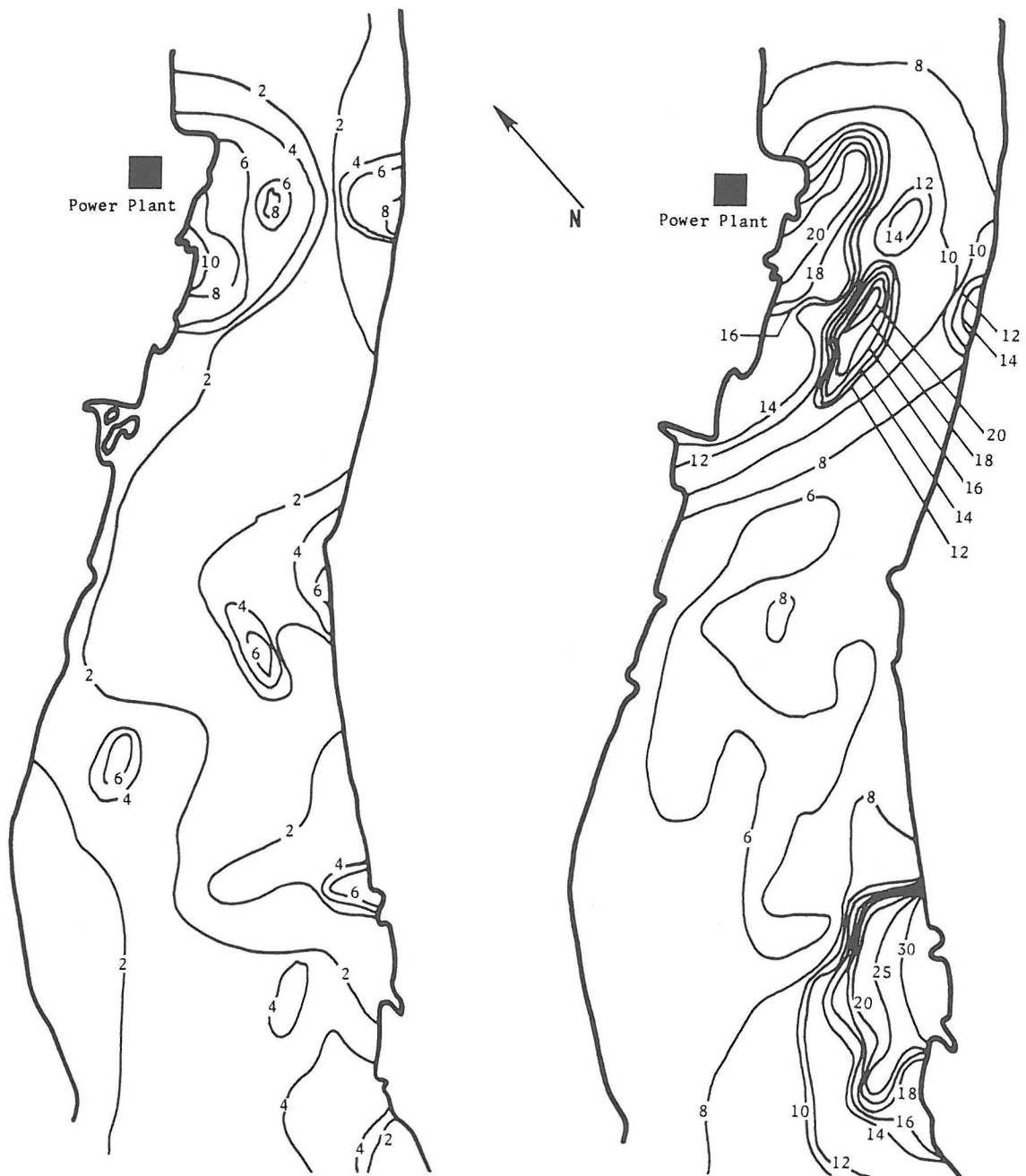


Figure 2

a) Humic acid concentrations (parts per  $10^7$ ) in the Hudson River obtained from analysis of aerial data collected August, 1976. Of particular interest are slight increases in concentration along the East shore. These increases are attributed to municipal discharges or swamp drainage.

b) Chlorophyll concentrations (ppb) in the Hudson River obtained from aerial data collected August, 1976. Increases in chlorophyll near the power plant are related to the increased turbidity and associated nutrients, and the warmer water near the power plant. The increased algal activity on the East shore is probably related to a shallow region with decreased flow permitting an increase in standing crop.