REVISED TECHNICAL GUIDANCE ON HOW TO CONDUCT EFFLUENT PLUME DELINEATION STUDIES

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ON

REVISED TECHNICAL GUIDANCE ON HOW TO CONDUCT EFFLUENT PLUME DELINEATION STUDIES (CONTRACT NO. K1130-2-2033)

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1.0 INTRODUCTION

At the request of Environment Canada (Contract No. K1130-2-2033), Jacques Whitford Environment Limited (JWEL) and NATECH Environmental Services Inc. (NATECH) have prepared revised technical guidance for pulp and paper effluent plume delineation for the aquatic environmental effects monitoring (EEM) required under the *Pulp and Paper Effluent Regulations* (*PPER*). This revised guidance replaces the existing guidance for effluent plume delineation in Section 2.2 ("Description of the Study Area") of the April 1998 release of the Pulp and Paper Technical Guidance Document for Aquatic Environmental Effects Monitoring (Environment Canada 1998).

1.1 Purpose of Plume Delineation

Effluent plume delineation is required in the design phase of the EEM program for each pulp and paper mill. The objective of plume delineation is to understand how the mill effluent behaves in the receiving environment and to identify effluent boundaries describing exposure areas and reference areas within which to establish sampling locations.

The exposure area(s) for EEM studies is the area where the effluent concentration is 1% or greater, reflecting a dilution of no more than 1:100. It is important to understand the spatial distribution of effluent in the water column to determine areas for fish collection, as well as to understand where the effluent comes in contact with the bottom substrate to determine areas for sampling the benthic invertebrate community. This is particularly important for effluent that may not exhibit complete vertical or horizontal mixing throughout the receiving environment.

Selection of sampling locations within the reference area(s) for EEM studies requires an understanding of the extended dilution of effluent beyond the 0.1% (1:1000 dilution) effluent concentration limit. This understanding is particularly important for mills discharging into water bodies where flow is not unidirectional.

Delineation of effluent plumes will typically involve field work to track plume movement during a single time period, coupled with the use of numerical modeling to determine target dilution zones over a broader range of environmental conditions. It is recommended that the effluent exposure zone be predicted for the:

- maximum extent, reflecting the zone within which effluent is periodically detectable at a concentration of 1% or greater; and
- long-term average conditions, reflecting the zones within which effluent concentrations of 1% or greater, and 0.1% or greater would be regularly detectable.

Areas beyond the maximum extent delineation under worst case conditions would be expected to be minimally affected by the discharge and may be suitable as “far field” or “reference” areas, depending on the sampling design (*e.g.,* control/impact design or gradient design). The long-term average conditions define what would be considered the “normal” envelop of plume extent and can be use to design an EEM sampling program that will assess the long-term effect of the effluent discharge. It may also be useful to determine the long-term average conditions of 10% or greater effluent concentration to identify areas that may be most impacted by exposure to effluent. It is important to evaluate what are the “normal” environmental conditions to which the effluent will be subjected and what are the extremes that may, on occasion, override the “normal”.

For discharge environments with high receiving water flow, in which the effluent is expected to be rapidly mixed, it is important to determine whether the effluent is diluted to less than 1% within 250 m of the discharge, which would remove the EEM requirement to conduct a fish survey.

The EEM program requires that effluent plume delineation be conducted only once, provided there are no substantive changes in effluent characteristics, discharge quantity, discharge method or location, or in the hydraulic or hydrographic features of the receiving environment. Plume delineation must be reviewed in the design phase of each subsequent cycle of EEM to evaluate the need for a new delineation. The onus is on the mill to ensure that they have an understanding of the hydrographic nature of the receiving waters, sufficient data and numerical modeling to meet the objectives of plume delineation for EEM.

2.0 EFFLUENT DISPERSION

Plume delineation requires information on effluent characteristics, discharge conditions and the nature of the receiving environment.

2.1 Initial Concept of Effluent Dispersion

An initial concept of effluent dispersal should be developed to help plan the field studies. This "first cut" at understanding effluent behaviour in the receiving water requires some basic information, including:

- effluent characteristics, such as density and velocity;
- number of discharges, location, orientation, depth, type (*e.g.,* diffuser, ditch);
- receiving water characteristics including density, flow characteristics, seasonal or lunar factors (*e.g.,* water level, tidal cycle); and
- estimation of the initial effluent dilution when the plume surfaces; this can be estimated using a simple numerical model such as the U.S. EPA's Visual Plumes or the Cormix model.

A sketch of the expected plume behaviour should be made, showing expected initial dilution and subsequent dilution in relation to site features near the discharge location and farther away. It is important at this stage to determine the type of numerical modeling (*i.e.*, one-dimensional, two-dimensional, three-dimensional) that will be needed to analyze the field data and extrapolate these data to describe maximum extent and long-term average concentrations in the receiving waters. The type of numerical modeling required may dictate what data will have to be collected for the field study.

Effluent dispersion in the receiving environment is a two-stage process comprising initial dilution near the point of effluent introduction, followed by subsequent dilution farther from the discharge. Initial dilution of the effluent is determined by the method and dynamics of introduction of effluent and by differences in density between effluent and receiving waters. The introduction of effluent is usually visualized as a rising jet (not necessarily vertical) to the water surface where it encounters an upflow boundary and forms a streaming plume moving down stream, carrying the effluent away. Illustrations of initial dilution of effluent are shown in Figure 2.1; depictions such as these are useful in developing an initial concept of effluent dispersion.

Initial dilution near the discharge can be approximated using numerical models (*e.g.*, Cormix) or nomographs (*i.e.*, graphical representations of equations with multiple variables, such as may be found in Wood *et al.*, 1993). Further dilution of the plume occurs by horizontal and vertical mixing. In most cases, horizontal dispersion of the effluent occurs at least an order of magnitude more rapidly than vertical mixing, such that the plume may disperse horizontally for some distance without being fully mixed in the water column. It is therefore important to consider the depth component of dispersion during the field studies and to incorporate this into numerical modeling to determine the plume location within the water column and where it comes into contact with the bottom substrate.

Discharged effluent usually has higher velocity than the receiving water, which results in shear stress with the receiving water. This shear stress results in turbulent mixing. Initial dilution continues until the energy in the discharge dissipates and the velocity of the plume matches that of the receiving water. Once this occurs, the "natural" turbulence in the receiving water causes further dilution or mixing of the effluent with the receiving water.

In addition to velocity differences, most receiving water and effluents differ in density. The effluent is typically less dense than the receiving water (often due to being warmer, or freshwater effluent discharging to marine waters) and therefore tends to rise in the water column. This results in another shear stress, similar to that resulting from the velocity difference.

In most cases, the combination of velocity and density shearing provides sufficient upward momentum to cause the effluent plume to break the water surface. If the density of the plume mixture is still lighter than the receiving water, then the plume will stay at the surface. If the plume mixture is slightly heavier than the receiving water, it will plunge down to the level at which there is a water mass of equal density and then be transported by and mix with that body of water.

After initial dilution, the effluent plume typically moves horizontally with the receiving waters. Subsequent dilution and dispersion depends on the receiving environment and climatic conditions (see Section 2.4).

Additional resources for guidance on effluent dispersion conceptualization include: Bishop (1984), Day (1975), Jirka *et al.* (1996), Neshyba (1987), Roberts (1989), Roberts and Ferrier (1996), Sorensen (1978), Thomann and Mueller (1987), Tsanis and Valeo (1994), Williams (1985), and Wood (1993).

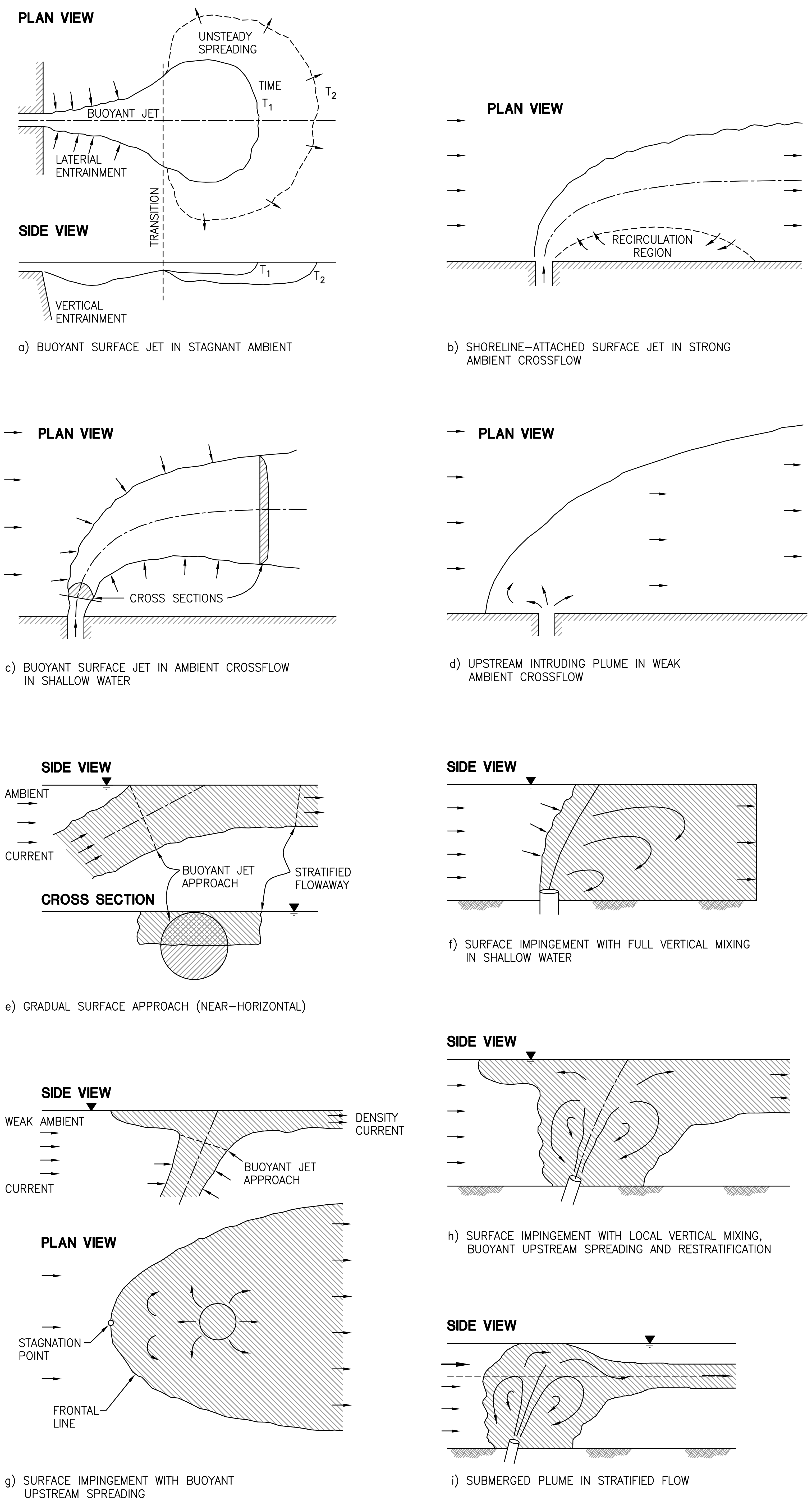

Figure 2.1 Examples of plume behaviour in receiving environments (modified from Jirka et al. 1996)

2.2 Effluent Characteristics

The most important effluent characteristics that influence initial dispersion are density and velocity differences compared to receiving water (see Section 2.1). Velocity will influence the degree of shear and therefore mixing that occurs when effluent is discharged. Effluent density will influence the rate of rise and position of the plume in the water column. Velocity may be measured as effluent flow rate (as a daily average), including whether the discharge is continuous or discontinuous (*e.g.*, batch release). The velocity of flow through each discharge pipe port should be considered, in comparison to the receiving water. Density of the effluent should be determined. Additional information on the effluent for plume delineation may include the presence of tracers, which are substances occurring naturally in the effluent, such as resin acids, sodium, and magnesium. These tracers may be used to track dispersion. Effluent values for the two most recent years should be considered.

2.3 Effluent Discharge Design

The discharge configuration and performance should be described. Using existing data, such as the most recent underwater inspection reports of the discharge, the performance should be compared to the design or the "as built" drawings. The location, length and orientation of the discharge should be known when determining the width of the plume. It is also important to consider the depth of the discharge within the water column in relation to flows and density gradients that may exist.

2.4 Receiving Environment Factors Affecting Plume Dispersion

The receiving environment should be described in terms of flow and currents, physical and chemical water quality and the spatial and temporal variations of these factors. This information is necessary to develop an initial concept of effluent dispersion, as well as to plan the field study. Climatic conditions should be summarized, with a view to their possible influence on plume behaviour.

Field parameters and their general importance in delineating plumes are described below. More detailed guidance for specific receiving environments is provided in Section 5.

2.4.1 Freshwater Flows

Minimum, maximum and average freshwater flows should be described in the receiving environment. This is important for all receiving environments, except those that are strictly marine with no local freshwater inputs. Freshwater flows will influence the initial dilution of the plume as well as subsequent horizontal and vertical mixing. The direction of flow, which may vary with depth and location, will influence the orientation of the plume. Typically, field studies are conducted at near minimum annual flow when effluent dilution will be low and the plume large relative to other times of the year. Field results can be extrapolated to reflect average and maximum flow scenarios for effluent dispersion.

2.4.2 Water Levels

Minimum, maximum and average water levels should be described for all receiving environments. The water level will influence initial dilution and the volume of water available for subsequent dispersion. Fluctuations in water level may occur daily (*i.e.*, tidal areas) or seasonally.

2.4.3 Water Quality

Water quality measures for receiving water that may be useful for plume delineation studies include temperature, density or specific gravity, salinity (for estuarine and marine studies), colour, suspended solids, and substances that may be used as effluent tracers. All of these measures can be used to track the movement of effluent within the receiving environment, as described in Sections 3 and 5.

2.4.4 Variation in Temperature and Salinity

Temperature and salinity both affect the density of the receiving water, and therefore their structure and variation within the water mass over space and time is important in all aspects of conducting a plume delineation study. Plumes that are warmer or less saline than the receiving water will be thermally buoyant when discharged and will rise towards the surface, creating shear that will generate initial mixing and dilution. Subsequent dilution and dispersion will also be influenced by temperature and salinity in the receiving water. Temperature and salinity may vary horizontally and vertically over short (*e.g.*, tidal areas) or long (*e.g.*, seasonal) time frames.

2.4.5 Tides and Seiches

The timing of tides and magnitudes is important to understand when planning the field study for estuarine and marine waters. In addition to marine and estuarine receiving waters, large lakes may also display a tidal cycle, albeit minor by comparison. Large bodies of water, such as lakes, estuaries and fjords, may also display the effects of storm surges and seiches, both in the surface elevation and in internal waves. All of these will influence the direction and pattern of effluent mixing.

2.4.6 Climatic Conditions

Wind and ice may significantly affect effluent dispersion, air temperature, ice conditions and wave action can all influence plume behaviour. Wind acting on large bodies of water may induce currents and waves. Ice may affect dispersion in two ways: by reducing wind-driven currents, and by increasing turbulence by providing a solid rough boundary to flow. Climatic conditions are discussed in more detail in Section 5.

2.4.7 Confounding Conditions

Although plume delineation is intended to capture normal discharge and receiving environment conditions, there are some potentially confounding conditions that may influence interpretation of field study results. Confounding conditions arise from events that are outside of the operational or environmental norms or are transitory events, and may result in a temporary change in the more "normal" location of plume boundaries. These conditions may affect effluent dispersion and therefore, their possibility should be considered when conducting a plume delineation study. Examples of such conditions include the following:

- pulp mill system upsets in the effluent treatment and discharge process that result in a temporary change in effluent quality or quantity;
- adverse weather, in particular wind conditions, that generates currents that are not typical for the receiving environment;
- seasonal events, such as ice conditions or thermal stratification, which can lead to a misleading representation of the plume behaviour; and
- flow regulation for hydro-electric power production..

3.0 FIELD TRACER STUDY

Field work involves tracking the dispersion of effluent using a tracer that is either naturally present in the effluent or is added. The purpose of this study is to obtain sufficient field data on a "snap shot" of effluent dispersion such that numerical modeling can then be used to estimate the maximum extent of the ≥1% effluent plume, and the long term average extent of the ≥1% and the ≥0.1% effluent plumes.

3.1 Study Team Personnel

Table 3.1 outlines the roles and responsibilities of study team personnel for conducting a plume delineation study, including a field tracer study.

Table 3.1 Study Team Roles and Responsibilities

Role	Responsibility
Team Leader	Scientist or engineer who directs and represents the study team and is the liaison with local authorities and the pulp and paper mill.
Field Supervisor	Scientist, engineer or technician with substantial practical field experience who directs and conducts the field work.
Tracer Injection Supervisor	Scientist, engineer or technician who supervises injection of the tracer in to the effluent stream. This person may be accompanied by a technical assistant.
Boat Crews (one or two)	At least one boat crew is required to conduct the field work. A second boat is useful to assist with drogue tracking, if conducted at the same time as the tracer study, and as a support to the main boat during the tracer study. The field supervisor may be a crew member.
Numerical modeler	Scientist or engineer with experience in numerical modeling of plume behaviour.

3.2 Communication

It is important to contact local authorities to notify them of the planned activities and the possible visible presence of dye in the water. Authorities to contact will depend upon the location, but may include one or several of the following: local port authority or harbour master, nearest offices of Environment Canada and Fisheries and Oceans, nearest office for the provincial departments of environment and/or natural resources, local municipal town hall or city hall, local fishing groups, non-governmental environmental groups, and possibly the local radio station. During the course of the field work, continuous communication between the team leader, the dye injection crew and the boat crew(s) is important.

3.3 Boats

The boat hull design and the propulsion unit should minimize disturbance/mixing to the plume as the vessel moves through it. While speed is generally very desirable, it will require judgement as to how much it may compromise some of the other requirements. A hull mounted recording depth sonar, combined with a GPS unit, is very desirable. Radar is also useful in coastal and marine areas.

If a dye tracer is to be used, the boat should include a firmly braced outrigger off the bow (with a restraining wire to the bow) to position the sampling intake or head of the fluorometer at a predetermined depth in the receiving water. The intake or head should be positioned such that it is clear of bow waves and is easy to detach and bring on board, or to reposition to a different water depth. Use a depressor if the intake is towed at depths greater than 2 m. In general, a system towed astern is not recommended because sampling is disturbed by the wake of the vessel; in addition, its positioning depth is very sensitive to the boat speed and length of the tow rope.

If high capacity 12/24V batteries are required for operating equipment, it is recommended to use batteries that are independent of vessel batteries, although the same charger may be used. It may be useful to have a second boat for handling drogues and for collecting bottled grab samples (if required).

3.4 Positioning (GPS)

Positioning of the sample stations, drogues and the boat track in relation to the discharge is important. Use of a Global Positioning System (GPS) unit may be the most convenient and accurate method to obtain and record positioning information. The accuracy of the GPS unit should be better than ± 2.5m, but this accuracy is dependent on a number of factors, including the availability of navigational satellites (maintained by the U.S. Department of Defense), environmental conditions that may result in "shading" of satellite signals, and the differential correction of signals. Differential correction on the GPS (DGPS) is provided by fixed receiver stations located at known positions, maintained by the Canadian Coast Guard for Canadian Atlantic and Pacific coastal waters, as well as the St. Lawrence Seaway. On the Great Lakes, DGPS is provided by Canadian and American receiver stations. Additional accuracy can be obtained using averaging of two or more receiver results. At some sites, more traditional survey methods, such as triangulation, may be equally effective, as long as the target accuracy is obtained.

3.5 Tracer Selection

Ideal plume tracers have the following characteristics:

- not harmful to the environment (dye tracer);
- near-zero background level;

- very slow decay rate (conservative substance) during field work;
- mixes freely into the effluent and receiving water;
- readily measured in the field at low concentrations; and
- released at a rate proportional to the effluent discharge rate.

Two types of tracers may be used: 1) tracers that occur normally in the effluent at known and relatively constant concentrations; and 2) tracers that are added to the effluent for the duration of the test.

The currently preferred added tracer is Rhodamine WT, a fluorescent dye that is most often used for EEM studies. It fulfils the characteristics of an ideal tracer. This dye has been shown to be non-carcinogenic and has low potential for toxicity and adverse effects in the aquatic environment (Parker 1973). It is safe when handled with care, generally available and can be readily measured in the field at concentrations less than 1 μg/L. For practical reasons, it should be obtained in liquid form. Rhodamine WT is considered conservative in most cases and typically has a near zero background level. Fluorescent tracers such as Rhodamine WT can be affected by some types of solids and chemical agents (*e.g.,* bleaches, sulphides, sunlight, and microorganisms). Chlorine in its elemental form rapidly destroys the fluorescence of Rhodamine WT. This effect is particularly noticeable in sea water due to the supporting effects of bromine. Fortunately, elemental chlorine exists only transiently in solution. Chlorine found as NaCl in sea water does not affect the fluorescence. Preliminary tests are recommended of dye-effluent interaction to describe the stability of the tracer and to determine any loss coefficient that should be used with the tracer.

An advantage of using tracers already present in the effluent is that they have an established equilibrium in the receiving environment. Effluents from most mills contain a variety of constituents that could potentially be used as tracers for delineating the zone of effluent mixing, such as effluent colour, sodium, chloride, magnesuim, tannin-lignins, conductivity and chloroform. An evaluation of effluent constituents as tracers should consider the following: detectability, ability to measure in real time, decay rate, variability in concentration in the effluent, and variability in background concentrations in the receiving water.

Additional resources for guidance on tracer selection and use include: Feunstein (1963), Ferrier *et al.* (1993), Kilpatrick and Cobb (1985), and Wright and Collings (1964).

3.6 Tracer Injection (Added Tracer)

The effluent system should be inspected and the dye injection point selected. Key factors for the selection of the injection point should include the following:

- an adequate mixing length (at least 40 times the diameter of the discharge pipe) before the final discharge point;
- no additional discharges after the injection point; and
- a sample access valve from which the fully mixed tracer can be sampled prior to final discharge.

The dye injection pump should be set up in the laboratory to confirm that the desired volumetric dosage rate is obtained. It is also important to determine the total time from introducing the tracer to the suction tube of the pump until it reaches the discharge. This includes the time to prime the injection system and the time for the dye to reach the final discharge point from the dosage point.

A continuous flow-rate injection system is preferred to simulate the operation of a discharge with flow proportional, continuous discharge loading. This type of injection system makes field measurements more reliable. The discharge rate of the pump versus battery charge should be monitored as well as the effect of cold temperature on battery voltage (if relevant).

For pulp mills discharging effluent in batches, mix the dye into the batch prior to release and allow for sufficient time for complete mixing. Sample the discharge pipe at regular intervals during the discharge period.

For an added tracer with zero background levels, the required tracer quantity can be calculated as follows:

$$M = C_x \times q_{eff} \times T \times \%_{eff} \times 3{,}600 \text{ seconds/hour}$$

where:
- M = amount of tracer required for the test (kg)
- C_x = tracer detection limit concentration (*e.g.*, 1×10^{-9} kg/L or 1 ppb)
- q_{eff} = effluent flow rate (*e.g.*, 1,000 L/sec)
- T = duration of the test (*e.g.*, 12 hours)
- $\%_{eff}$ = dilution limit of the plume in % effluent concentration (*e.g.,* for 1:100, use 100)

The injection rate (kg/hr) is obtained by dividing the amount of tracer required by the duration of the test. The concentration of the tracer in the injection mixture (typically 20% by weight) does not have to be considered in the calculation, since the detection limit is based on the diluted initial mixture. Dilution standards are typically prepared based on weight. Should the standards be prepared by volume, the correct specific gravity of the tracer should be applied. The specific gravity of Rhodamine WT is in the range of 1.15 to 1.2, and typically 1.19.

3.6.1 Duration of Dye Injection

Dye must be injected over a sufficient time period to establish an equilibrium concentration in the receiving water and to give sufficient time for the field team to complete the sampling. The duration of dye injection is site-specific. As a minimum in unidirectional flow, dye injection should continue until the plume has been delineated in the field. The more dynamic receiving environments require longer injection times, particularly if the plume is found to be unstable. In lakes and rivers, injection may need to continue for several hours. In estuaries, injection should continue through at least one tidal cycle from low water, to high water, and back to low water (normally 13 hours). In coastal marine environments and fjords where already polluted water may be re-circulated back into the plume, dye may have to be injected over several tidal cycles. A judgement will need to be made on whether the time and effort is best spent continuing dye injection, or using the predictive strength of numerical modeling.

The term "slug release" is used when a known and generally small volume of dye, possibly diluted with receiving water, is introduced into the water column at the level of the anticipated plume with as little disturbance as possible. Great care must be taken to ensure that the dye release liquid has the same density as the receiving water into which it is being released. The movement and subsequent dispersion of this dye patch is monitored in a similar manner as a plume and dispersion coefficients can be computed. In this case, a secondary objective is to determine the extent of, and dye concentrations within, the dye patch at regular timed intervals. As a check on the quality of delineation of the dye patch, the quantity of dye calculated to be present at each time interval should approximate the quantity released. Slug tests will not provide an adequate description of effluent dispersion. However, they may provide useful information on localized dispersion characteristics that can then be used for numerical modeling of effluent behaviour.

3.7 Water Quality Meters

Water quality parameters and tracer concentrations should be measured *in situ* with the probe immersed in the water. Water quality parameters to be measured include fluorescence (dye tracers), temperature, and salinity (estuarine and marine waters). Sample location, time and immersed depth of the sampling probe must be recorded, along with visual observations, if applicable. It is recommended that as many of the desired parameters as possible be measured simultaneously.

3.7.1 Fluorometer

The fluorometer measures fluorescence of injected dyes, and must be in clean and reliable condition. Since the fluorometer readings must be converted to effluent concentrations, a site-specific calibration curve is required, and this will be generated in the laboratory. A typical calibration curve is illustrated in Figure 3.1.

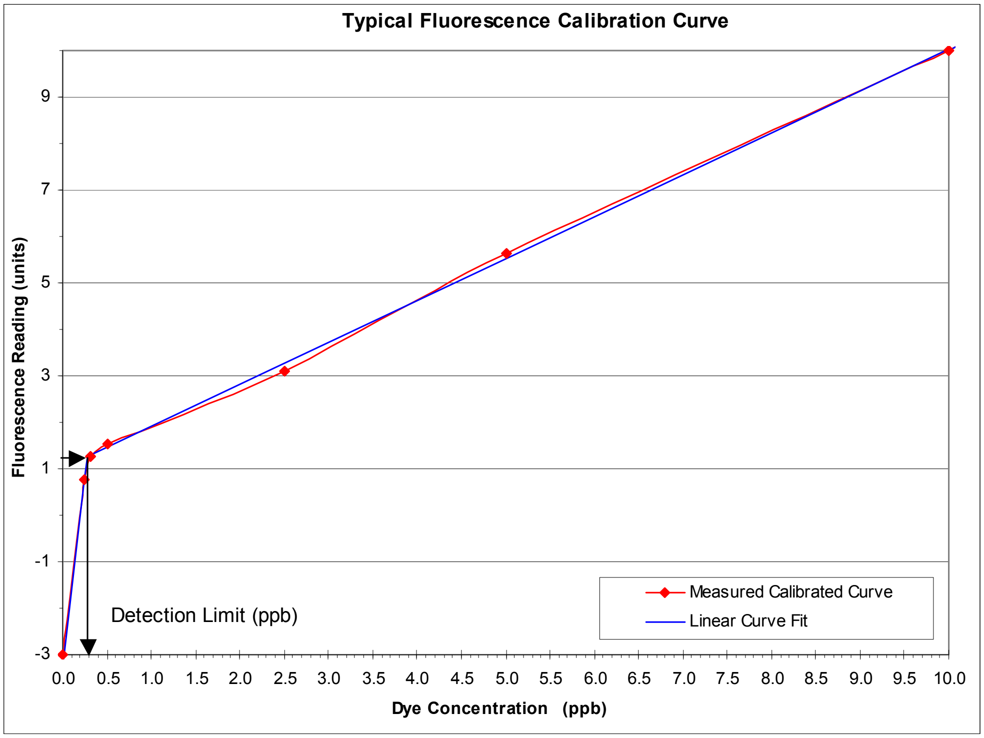

Figure 3.1 Typical calibration curve relating fluorescence to tracer dye concentration

The relationship between dye concentration and corresponding effluent concentration must be established prior to initiating field measurement, in order to be able to determine, in the field, at what fluorescence readings the target effluent concentrations have been found. In addition, the dye detection limit of the fluorometer in the receiving water will be determined. This concentration is required for the computation of the dye injection rate (see equation in Section 3.6).

To prepare the calibration curve, a dilution series for the dye should be established for the expected ranges of concentrations. Separate dilution series must be established for dye mixtures in the receiving water, pulp mill effluent and clean water. For saline receiving waters, at least a maximum and minimum salinity should be used. Any variations between the types of water used should be recorded and considered in the interpretation of field results.

Dilutions typically range from 0.1 x 10^{-9} kg/L (0.1 ppb) to 10^{-6} kg/L (1 ppm). The fluorescence measurements should show a linear correlation with dye concentration over the range of interest. A regression analysis will provide the mathematical expression required for converting fluorescence readings to effluent concentrations.

3.8 Equipment Used to Track Currents and Effluent Movement

Drogues and current meters are the basic types of equipment that may be used to track the movement of currents and thereby also the movement of an effluent. A description of each type is provided below.

3.8.1 Drogues

Drogues are used to determine movement of water in the effluent plume and also other current speeds and directions in the field. Drogues may also be used to assist in determining where to sample for tracers, particularly for sub-surface plumes. Drogues released near the discharge will drift with the current, indicating where the plume is being transported, provided it stays within the same water mass. Should the plume lie beneath the surface water mass, the drogue must be designed (weighted) to allow it to stay within the appropriate water mass. Examples of drogues are shown in Figure 3.2.

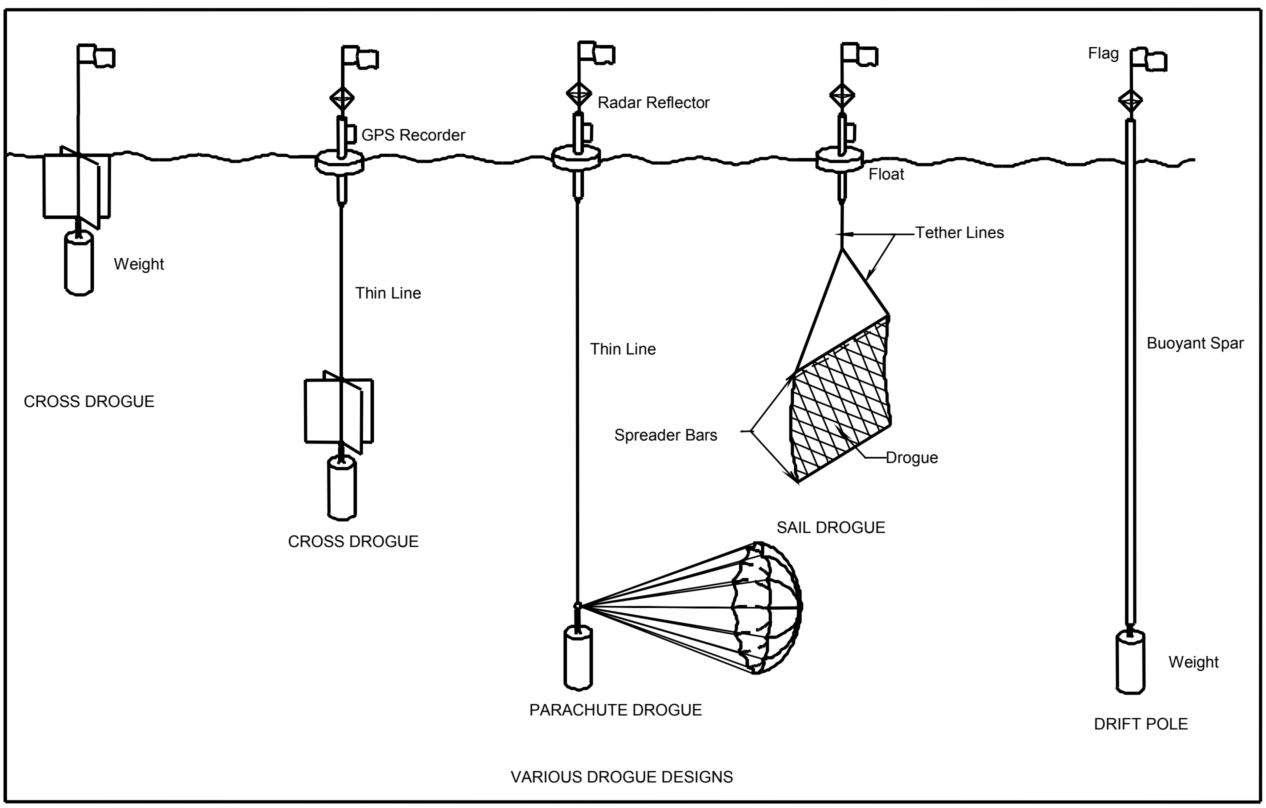

Figure 3.2 A variety of drogue types used for plume delineation (adapted from the Canadian Tidal Manual)

Drogues that are used to follow surface waters should be a relatively simple design, such as the "cross drogue" (Figure 3.2) made of two sheets of plywood weighted to keep the upper edge of plywood just below the water surface (50 cm or less). The dimensions of each vane should be not less than about 30 cm but otherwise can be constructed to a scale appropriate to conditions. Visual location of the drogue is typically marked by a flagged rod sticking out of the water and/or by a surface float, although acoustic markers may also be used (see below). The use of a surface float with some reserve buoyancy makes sure the drogue always remains at the correct depth in the water column. It is important that the wind resistance of any marker or the drag of the surface float will be minimal compared to that of the drogue itself. If there is considerable wave action or turbulence, then the distance between the surface float and drogue should be increased (see "cross drogue" with longer shaft in Figure 3.2) to ensure that the upper edge of the drogue does not flip out of the water and become influenced by wind forces. To check that the drogue is remaining within the same water mass as the plume, measurement of a simple parameter (*e.g.,* temperature, salinity) alongside the drogue may be used.

Some drogues should be placed in the water to determine surface water movement and a few should be placed at greater depth, particularly if the plume may plunge or be entrapped at a lower layer. The drogue tracks will give visual confirmation of the likely plume track. In estuarine and marine conditions, the drogues need to be dropped in the discharge area at high water, low water and both mid tides. Since it is desirable that some of the earlier drogues are allowed to run the full course, a significant number of drogues may be required. On board plots on charts can be used to track drogue movement, which should greatly assist in recovery of the drogues.

There may be situations in which the plume may remain below the surface or may plunge later. In both cases, the plume will be moving below a less dense water mass at the surface. Some guidance can still be obtained in these cases using the same basic drogue design but taking care to weight the drogue so that it represents the same density as the displaced water of the plume. A long, slack line to the surface buoy of the drogue will enable the drogue location to be approximated. Alternatively, an acoustic locator can be attached to the drogue. These "acoustic drogues" are used to track movement of submerged plumes in the open ocean and may also be used in shallower water to estimate drift (below the threshold of most current meters) of the lower layers in a fjord or a large lake. Depending on the mixing in the plume this will suffice only for a few kilometres because the density in the plume will be constantly changing as it mixes with lighter surface and denser deeper water on its upper and lower boundaries. These types of plume behaviour are discussed in more detail in Section 5.

3.8.2 Current Meters

Current meters may be used to describe the hydrodynamics of receiving waters, and in particular the spatial variability in currents for use in a numerical model. Most current meters can record temperature and salinity as well, providing additional information about the types of water masses that are moving. However, current meters are typically more expensive to use than drogues in plume delineation studies.

Current meters are particularly useful for large lakes and marine waters where currents are rotary, or where wind and wave action may be the dominant current inducer. In these environments, current meters may be deployed at near-surface and mid-depth during selected seasons of the year (minimum 30 day deployment) to describe the currents. A good description of modern current meters is given in IEEE (2003).

The Acoustic Doppler current meter is a more sophisticated type of current meter that is versatile and has been used in EEM studies. There are limitations for use of this meter type for plume delineation, including the following: it is expensive; interpretation of the results requires an experienced hydrographer; poor resolution of data obtained close to the water-air and water-bottom substrate interfaces when using the full depth range (this is a problem when tracking buoyant plumes that tend to be initially in the upper meter of water).

3.9 Tracking Effluent Dispersion

Standard guidance is provided in this section for tracking effluent in a simple unidirectional flow receiving environment, using Rhodamine WT as a tracer. Additional guidance is provided in Section 5 for specific types of receiving environments: rivers, small lakes and impoundments, large lakes, estuaries and fjords and coastal marine. Use of an alternative tracer will require appropriate modifications to the recommended procedure. Details on the use of Rhodamine WT are available from fluorometer manufacturers and the U.S. Geological Survey (1996).

For a mill with multiple discharges, each discharge should be traced separately at different times to determine the configuration of each effluent plume. In most cases, the cumulative plume may be evaluated using numerical models. However, most of the mills in Canada have consolidated their effluent discharges so that only one point of discharge is typically relevant.

3.9.1 Sampling in the Initial Dilution Zone

Sampling in the rising plume is difficult and unproductive for the purpose of plume delineation. Instead, sampling should be focused in the area where the plume breaks the surface or is arrested in its vertical ascent. This point may be several tens of meters down drift of the discharge point. Concentrations or dilutions may vary as much as 50% around the point of emergence. Sampling should be undertaken to confirm the variability of effluent concentration at right angles to the flow of the receiving water and also parallel to the flow.

Additional sampling should be undertaken at right angles to the flow approximately 50 to 100 m down-flow from the surface plume break-out to determine the plume width, thickness and depth. From this point on, further mixing would be considered to be beyond the initial dilution zone and sampling should be as recommended below.

3.9.2 Subsequent Dispersion

Beyond the initial dilution zone, the effluent plume typically moves horizontally, borne by the velocity of the receiving waters. At this point, drogues released within the surface plume will provide guidance on plume location. The following description of subsequent dispersion refers to surface plumes; specific guidance for plunging or trapped plumes is provided in Section 5.4.

Sampling traverses should be conducted at right angles to the flow of the plume and at intervals of approximately 5 times the last plume width. The fluorometer or hose intake should be held at a constant depth while the boat traverses the plume. The recommended sampling depth is 1 m in homogeneous water, possibly less in stratified flow, and possibly deeper in homogeneous water if it has been determined that the plume is well mixed with depth. The depth of maximum tracer concentration is used for profiling the tracer concentration.

It is particularly important to locate both edges of the plume and to determine if the edge of the plume touches a shoreline. In the first few traverses, the boat should return to the center of the plume and the fluorometer or hose intake should be lowered to determine the vertical extent of the plume, and this should be compared with the expectation from the conceptualization of dispersion. If necessary, the boat should then return along the traverse with the fluorometer of hose intake at a deeper depth (*e.g.,* 2 to 3m) to better delineate the lower surface concentrations.

Sampling should continue until the 1:1000 dilution (*i.e.,* 0.1% effluent concentration) limit is determined. It should be recognized that at the far edges of the plume, sections of the plume may become separated from the main plume and form independent patches of effluent that float with the current.

Under no circumstances should a flow-through fluorometer be placed within 2 m of the bottom substrate, as this may result in equipment damage or failure. If it is suspected that the effluent plume is in or near contact with the bottom substrate, then bottled samples should be collected for subsequent analysis (see paragraph below on “grab” samples). To confirm that this is the case, at least five samples per cross section should be taken.

Any unusual characteristics in terms of plume location or concentration should be noted. Examples could include high concentrations observed at places beyond where the effluent concentration has dropped below the specified concentration (*e.g.,* accumulation in an inlet or bay), or where an undertow moves effluent downstream or off-shore such that effluent resurfaces elsewhere.

Bathymetry should be measured and recorded at tracer profiling locations. Sonar techniques are generally adequate. Where a detailed hydrographic chart is already available, a survey of bathymetry may not be necessary. It is recommended that bathymetric data for the receiving water be presented on a map of the exposure area.

Measurements of fresh water flow and tidal water level changes should be recorded for at least 24 hours prior to and during the tracer release. At a minimum, these measurements should be taken hourly, but continuous recording is recommended.

Grab samples are recommended only if the plume is not directly accessible by the fluorometer or hose intake. The grab sampling procedure is slower, has poor spatial resolution, and does not provide a continuous profile of the tracer concentrations. Consequently, it is difficult to carry out a mass balance of the tracer. Nevertheless, it is sometimes necessary to collect grab samples. Grab samples should be collected using a water pump or by lowering sample bottles that are under vacuum pressure. Use of a Niskin or similar sample collection bottle for multiple-use is not recommended because of the risk of contamination from previous sampling. Grab samples should be stored in the dark under refrigeration, and be analyzed within 24 to 48 hours. If samples are to be collected only by this method, then at least 12 samples at each transect are recommended from within the plume to adequately define the plume configuration. It is expected that at least 10 cross sections would be sampled for any of the plumes resulting from a discharge.

3.10 Data Quality

Using the site-specific calibration curve (Figure 3.1), fluorescence readings are converted from unit-less values to dye concentrations in µg/L (*i.e.,* ppb), and then to percent effluent. A similar unit conversion is necessary for naturally occurring tracers. Compensation for temperature changes and varying effluent discharge quantities during the field test may be required. The results should be displayed in tabular format listing time (for marine conditions, use time relative to high or low tide), water level, position, salinity (if applicable), immersion depth of the sonde or sampling tube, local water depth (optional), dye concentration and calculated effluent concentration.

A discussion on the confidence limits of the results should consider the effects of such factors as environmental conditions during the test, method of testing to measure fluoresence (*e.g.,* grab samples, pump-through, immersed fluorometer), accuracy of the positioning data, variation in effluent discharge, and confidence in the calibration curve.

3.11 Numerical Modeling

Numerical modeling provides a means of extrapolating from the plume measurements in the field to simulate effluent dispersion over a much wider range of environmental conditions at the site. Numerical models have been developed that superimpose water quality computations onto hydrodynamic processes. The models allow for a qualitative and graphic representation of the transport and dispersion of the effluent (tracer) in time and space.

Depending on the nature of the receiving water, two or three-dimensional models may be used. Principal processes in numerical modeling include model setup, model calibration and verification (both of which use the field tracer study results), and a sensitivity analysis to determine what limitations may have to be placed on input parameters. While model calibration should be carried out against the most recent tracer measurements, verification can be achieved by applying the model to an historical event with different environmental and discharge conditions. After successful calibration, verification and sensitivity analysis, the model is then ready to be applied to a number of environmental conditions that may lead to effluent plume dispersions other than the dispersion observed during the field measurements. A discussion should be provided on the frequency of the various environmental conditions being considered.

As a minimum, the models used should be able to accurately reproduce the hydrodynamic process of the study area and the behaviour of a conservative substance introduced near the discharge. The initial near field dilution may be computed using descriptive models, such as Cormix or Visual Plumes. The tracer concentrations computed for the edge of the near field can then be used as boundary conditions for the far field model. Other typical boundary conditions for far field models are the fresh water input on the upstream end and the water level on the downstream end. In river systems with fast flowing currents, the models have to be able to simulate sub and supercritical flow conditions. In tidal waters, where the shore line near the discharge changes from high to low tide, the model should be able to reproduce wetting and drying of tidal flats.

The near field and two-dimensional far field models are readily available and have been commonly used for effluent plume delineations of pulp mill effluents. The three-dimensional models are very costly to purchase and require a significant effort for data collection, model setup and calibration. Some hydrographic research institutes are well equipped for applying three-dimensional models.

Table 3.2 lists potentially applicable models for a variety of effluent discharge scenarios, and includes models that are commercially available and routinely used. This table is intended as a preliminary guide only because models are constantly being developed and modified, and because there are many models not listed that are developed for in-house use only, and are therefore not commercially available.

Table 3.2 Numerical Models for Describing Effluent Dispersion

Typical Scenario	Information Needs for EEM	Examples of Commercially Available Numerical Models [1]
Plume is highly transitory or there is rapid plume dilution in the initial dilution zone to within target level (*i.e.,* 1% effluent concentration)	Conceptual spatial delineation of 1% and 0.1% limits of effluent concentration. Whether the 1% concentration limit is reached within 250 m from the discharge.	Numerical models such as Cormix and Visual Plumes for the initial dilution assessment only
Effluent is discharged into turbulent, narrow stream; complete mixing is achieved rapidly over a short distance	Linear distance until plume is dissipated to within target levels (*i.e.,* 0.1% and 1% effluent concentration)	1D numerical models, such as HEC-5Q, Qual 1E , WASP5/Dynhyd5
Effluent is discharged into uniform, wide body of water. No stratification is observed.	Length and width distance until plume as dissipated to target levels (*i.e.,* 0.1% and 1% effluent concentration)	Numerical models such as Cormix for initial plume dilution, 2D numerical models, such as RMA 2/RMA 4, Qual 2E, MIKE 21, for subsequent dilution simulations
Effluent is discharged into non-uniform, wide body of water. Stratification is observed as result of thermal or salinity differences in the receiving water or between the effluent and the receiving water. Stratification may be non-uniform and dynamic.	Length, widths and depth dilutions until plume as dissipated to target levels (*i.e.,* 0.1% and 1% effluent concentration)	Numerical models such as Cormix and Visual Plumes for initial dilution assessments, only. 3D numerical models, such as RMA 10/RMA11, WASP5/Dynhyd5, MIKE 3, TELEMAC, DELFT 3D for far field simulations.

[1] Sources for these models vary; some may be obtained directly from the model developers while others may be obtained from one or a number of commercial distributors.

The selected numerical model should be used to estimate the desired regions of maximum extent, average conditions, and minimum dilution. A discussion on the confidence limits of the results should be provided (see Section 3.10).

If current meters are being used to measure ambient currents (see Section 3.8.2), the modeled plume configuration may be modified through statistical analysis of the current meter data. For conditions of a long flushing period, the measured dye concentrations may be used to calibrate a numerical transport-diffusion model. The model can then be used to simulate the effluent delineation and characteristics arising from a continuous discharge. The model can be run for a variety of conditions (*e.g.,* seasonal variations of water movements and wind patterns), thereby overcoming the limitations of the particular conditions recorded in a single field study.

Additional resources for guidance on numerical modeling include: Baumgartner *et al.* (1994), Chung and Roberts (1998), Ettema *et al.* (2000), Frick *et al.* (2000), and Sharp (1989).

4.0 REPORTING

Reporting of the study results should include the following:

1. Summary of information collected to aid in developing the conceptual model of effluent plume behaviour, including:
   - description of the effluent in terms of flow, temperature, specific gravity and TSS (if applicable);
   - description of the effluent discharge configuration and performance;
   - description of the receiving environment in terms of flows and currents, physical and chemical water quality (*e.g.,* thermal and salinity variation horizontally and vertically), climatic conditions, and any other relevant site-specific parameters used to develop the conceptual model of plume behaviour; and
   - confounding conditions, such as pulp and paper mill upsets, atypical climatic conditions.

2. A conceptualized model of plume behaviour.

3. Documentation of tracer study conducted, including:
   - pre-tracer laboratory testing, fluorometer calibration curve;
   - pre-trial field testing; and
   - trial field tracer measurements.

4. The Numerical model used and mapping depicting predicted plume envelopes for:
   - maximum extent (1% and 0.1% effluent concentrations); and
   - long-term average conditions (1% and 0.1% effluent concentrations).

Computer animation is a useful option for depicting effluent plume behaviour in more complex receiving environments, such as estuaries and coastal locations.

The measured tracer concentrations should be provided in the appendix of the report.

5.0 RECEIVING ENVIRONMENT – SPECIFIC CONSIDERATIONS

Five general types of receiving environments are considered for this guidance:

- Rivers – predominantly driven by gravity flow;
- Small lakes or impoundments – with directional flow;
- Large lakes – less predictable currents that are often wind-driven; may exhibit internal waves, or "seiches";
- Estuaries and fjords – tidal areas with both freshwater and marine influences; fjords are special types of estuaries where the shape is narrow and deep with a shallow freshwater surface flow and deep saline layer;
- Marine – tidal areas dominated by salt water.

Specific factors that should be considered in each type of receiving environment are outlined in Table 5.1, and described in this section. The influences of climatic conditions such as ice and wind on plume behaviour are described at the end of this section. This section also provides specific guidance for conducting plume delineations to supplement guidance provided in Section 3.

Table 5.1 Summary of factors to be considered for each type of receiving environment

Field Parameter	Rivers	Small Lakes or Impoundments	Large Lakes	Estuaries	Marine
Freshwater flows (minimum, maximum, average)	YES	YES	YES	YES	YES, IF RIVERS ARE PRESENT
Water levels	YES	YES	YES	YES	YES
Water quality	YES	YES	YES	YES	YES
Thermal variation horizontally & vertically	NOT IF WELL MIXED	YES	YES	YES	YES
Tide times and magnitudes	NO	NO	NO	YES	YES
Salinity variation horizontally & vertically	NO	NO	NO	YES	YES
Wind conditions	NO	YES	YES	YES	YES
Ice conditions	YES	YES	YES	YES	YES

5.1 Rivers

In rivers, currents are typically unidirectional, and flows and water levels are seasonally variable. Considerations for determining plume behaviour include the characteristics of the discharge point, shoreline and bottom attachment and rising or sinking of the plume due to density effects caused by thermal or chemical factors. The river may consist of different zones that should be delineated, including fast and slow flowing, with various depositional and erosional zones influencing any suspended solids transport from the effluent. A discussion on the temporal changes (seasonal and long term) of the river regime on the reaches affected by the plume should be provided.

Plume delineation studies should be conducted during a period that approaches the annual low river flow, which typically occurs in late summer. This will leave the extreme high and medium flows to be predicted using numerical models. Low river flows typically correspond with low overall dilution potential and reduced rates of turbulent mixing in the system. As a result, spatial extent of plumes tends to be larger during periods of low flow.

If a dye tracer is used, it should be added using a continuous flow rate injection system. The number of field tracer measurements to take will be site-specific. It is recommended that concentrations be measured at various distances downstream and that the spatial extent of the plume be determined. Slug tests (*i.e.,* batch release of dye, as opposed to continuous flow rate tracer injection) may be a also a suitable technique for monitoring mixing in some rivers, but this generally requires a very good understanding of the plume behaviour and may require repeated slugs.

5.2 Small Lakes and Impoundments

Guidance for rivers (above) will apply if there are large effluent volume discharges, because there will typically be an easily discernable and measurable flow through the system. However, this guidance will not apply to some small lakes and impoundments where there are residual currents, or where the long-term drift is masked or even reversed by short term effects induced by factors such as wind shear, lake overturning, development of thermocline, or freshets, separately or in combination. It is important to assess the magnitude and significance of each of these comparatively short-term phenomena. This is most easily done using numerical modeling, provided there are adequate field data available for model calibration.

The residual flow, or even transitory currents, may be below the threshold of regular recording current meters. In these cases, a mass balance of the flows entering the body of water and the flows leaving will provide an estimate of the retention time in the system. This retention time may be reduced further by assessment of special circumstances or geometry. However, where currents are very low (*e.g.,* a few cm/min), only field tracer studies can provide the confidence that an effluent will be carried away and that re-circulation does not take place. Re-circulation takes place where eddies from the plume are brought back to the mixing system and used instead of clean new receiving water. After some time this may significantly reduce the dilution of the effluent and significantly extend the 1% concentration boundary.

The residual flow through the area should be estimated as well as the currents that are induced by wind at various strengths and from various directions. An onshore wind will typically trap water against the shore and cause the surface water layer to thicken. Conversely, an offshore wind will cause deeper water to be brought inshore and upwell to replace the water being carried offshore by the wind.

The relative density of effluent and receiving water may be important to determine, because if a thermocline is present, most water movement in the lake will take place above it. If the plume stays above the thermocline, vertical mixing will be restricted and dilution will result more from horizontal mixing. Should the initial dilution be such that the plume is entrapped below the thermocline, mixing will likely be slower and movement could almost approach the volume being displaced by the effluent discharge.

Tracer studies should be designed to fulfill the general requirements and to consider seasonal variations. Prevailing currents will influence the duration and timing of each study. The recommended method for the delineation of the effluent plume for a lake discharge is the continuous flow rate injection system using a dye tracer. This is particularly true if there is any likelihood of eddies and re-circulation or entrapment back into the plume. The slug test can be used to determine dispersion characteristics, but does not give as good a visual picture, nor the same guidance regarding re-circulation.

To measure water currents, drogues should be released and tracked concurrent with dye tracing. For buoyant surface plumes, drogue vanes should be set with the upper edge at or just below the surface (within top 50 cm). For submerged plumes, drogues should be weighted and sails set so that they travel at the same initial depth of the plume, which can be determined on site from the initial tracer monitoring. If clusters of drogues are released, dispersion for a batch release may be obtained from the paths of the individual drogues by determining the variance of the individual drogues about the centroid.

Unlike the river receiving water where the plume configuration can be predicted using simple numerical models, plume behaviour in lakes is not as easily predicted. If data on water currents in the vicinity of the discharge are lacking, current meters (see Section 3.8.2) may be needed to obtain information for use in the numerical model. Climatic data may be obtained from the local airport or other local weather data source. The statistical relationship between the dilution and travel time of the effluent should be combined with the statistical characteristics of the water currents to develop spatial dilution zones around the discharge. This may be depicted as a graph showing the frequency of the dilution factor as a function of dilution and travel time.

The dilution zones should show the probability of the effluent plume being present at any receiving water location and the mean and standard deviation of the effluent concentration at any location in the receiving water. The dilution zones do not show the configuration of the effluent plume under specific current speed and direction conditions.

5.3 Large Lakes

Water currents in large lakes are often wind driven, seasonally variable, and generally less predictable that those encountered in fluvial and tidal areas. Thermal and density stratification is important to understand because the effluent may be more dense than lake water due to chemical factors, or less dense than lake water due to thermal factors. Wind and wave advection, seiches, shore-line and bottom attachment are all important. Many of the factors considered for small lakes and impoundments are also relevant to large lakes.

In large lakes, it is useful to have information on the variability in long-term water movement and the resulting residual movement. This information may be obtained using moored current meters with a low current threshold. Temperature recorders on the current meters may be used to determine whether internal waves or seiches occur. On shore anemometers may be used to obtain concurrent wind data if wind data are otherwise unavailable.

Initial dispersion of the surface plume into a relatively quiescent lake will be significantly influenced by the volume of the upwelling plume. Numerical modeling is the strongest tool to delineate the plume to this stage. Subsequent dispersion using numerical modeling will require estimates of horizontal and vertical dispersion coefficients, as well information about water currents obtained from current meters. The dispersion coefficients are best determined by either a slug release of dye or by continuous release and subsequent monitoring of a tracer in the effluent plume. If wind is present, an estimate of induced wind drift current can be determined using wind drift forecasting curves (see Section 5.6.2). Winds can also induce tilting of the water surface and of the thermocline, which may result in seiche motions that oscillate within the basin. See Section 5.6.2 for more discussion on wind-induced seiches.

Two-dimensional numerical modeling may be adequate, however in situations where there is stratification, three-dimensional modeling may be necessary.

5.4 Estuaries and Fjords

Estuaries and fjords are complicated environments in which to conduct plume studies. An understanding of the nature of the receiving waters is very important for planning the field study. This section will first provide a description of hydrographic considerations in estuaries and fjords, followed by guidance for conducting field studies.

5.4.1 Hydrographic Considerations

The most significant influences on effluent dispersion in estuaries and fjords are tidal flows and density differences between freshwater and saltwater. Tides cause water to flow into an estuary on the rising tide and flow out again during the falling tide, causing mixing to take place. Effluents are typically similar in density to fresh water and will therefore tend to follow the fresh water in their mixing pattern. Freshwater has a specific gravity of about 1.00. Effluent and freshwater will typically rise and flow along the top of saltwater, which has a specific gravity of about 1.026.

Figure 5.1 depicts a "salt wedge estuary" in which a large river flows into an estuary with small tides and creates a sharp interface between fresh and salt water. Figure 5.1 (a) shows the fresh water layer thinning as the estuary widens and extends seaward. If the freshwater velocities get high, there will be shear created at the interface and salt water drawn into the upper layer. Figure 5.1 (b) shows how the turbulence of the tide coming in creates shear at the interface, creating waves and causing mixing to occur.

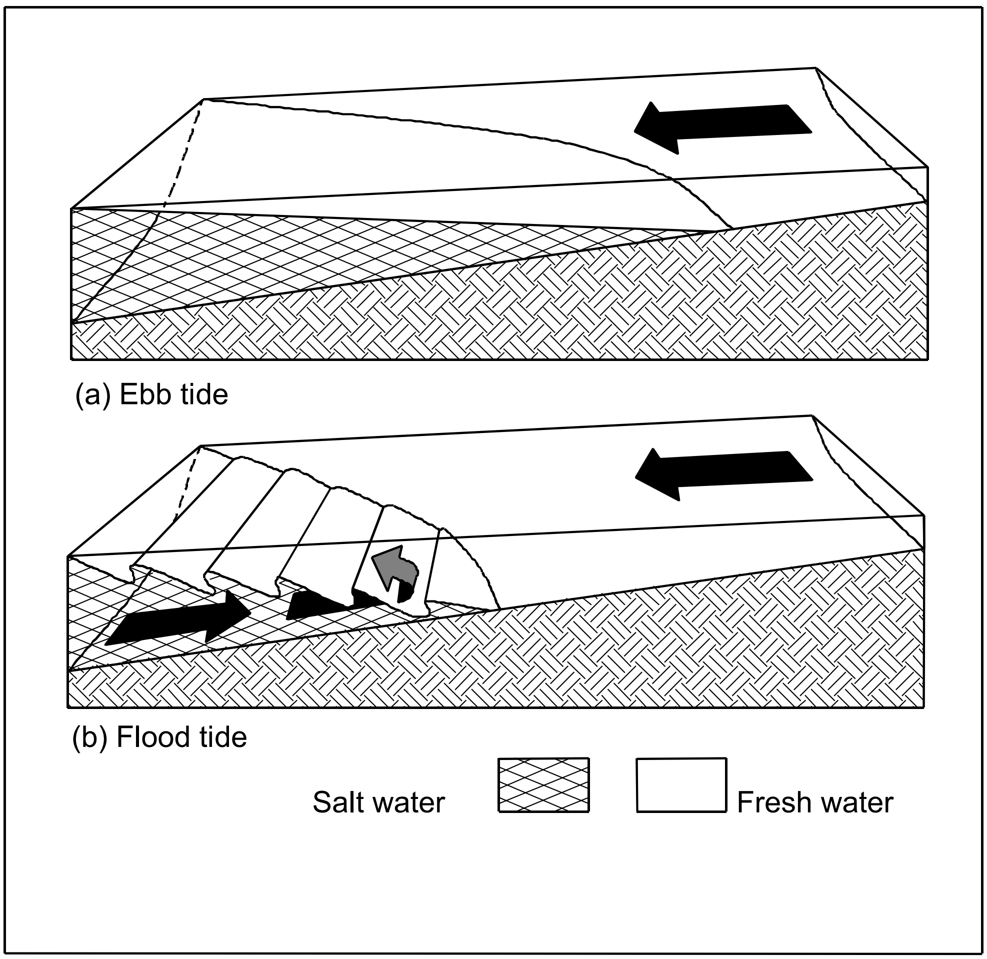

Figure 5.1 Generalized Profile of an Estuary, Showing Circulation During Ebb Tide (a) and Flood Tide (b).

The amount of shear and mixing that occurs between the freshwater and saltwater lays depends on the relative volume and velocity of freshwater (confined by the estuary sides) and of saltwater (confined more by depth). Figure 5.2 depicts stratification in a salt wedge estuary under different levels of tidal energy. A highly stratified estuary (a) can occur if tidal energy is relatively low and the gradual rise of the tide causes some mixing. As the tidal energy ("tidal prism") increases relative to freshwater flow, more mixing takes place to produce a partially mixed (b) and fully mixed (c) estuary.

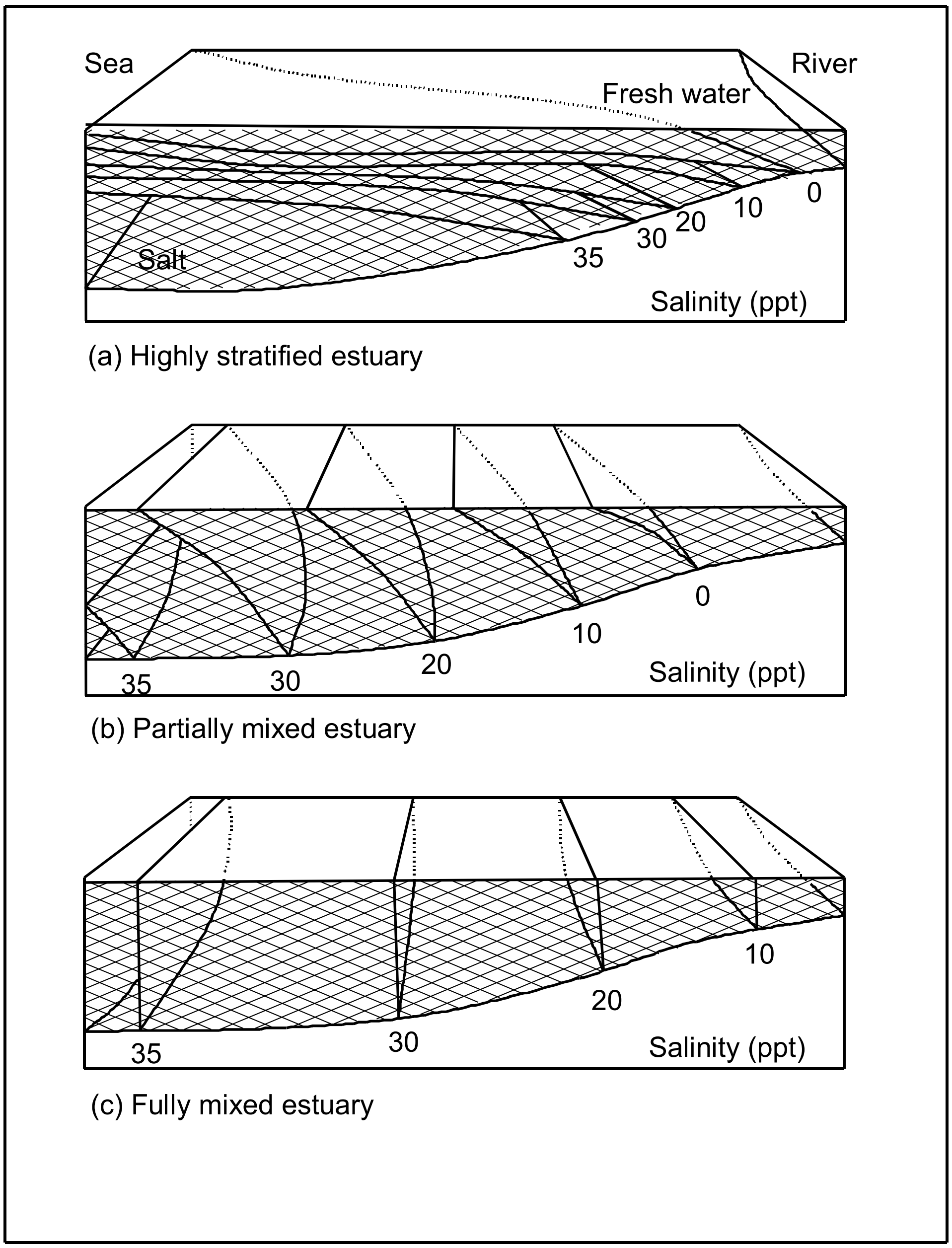

Figure 5.2 Profiles of typical estuarine water masses, showing an highly stratified estuary (a), a partially mixed estuary (b), and a fully mixed estuary (c).

Tidal frequency and magnitude are considered when planning a plume delineation study and in subsequent numerical modeling. Tides in Canadian estuaries typically rise and fall with approximately 12.42 hours between high waters. The vertical range between high and low water, even within one coastal system, can range is from a few centimetres to several metres. Also, there is a beat every 7, 14 and 29 days indicating the “spring and neap” cycles where the forces of the sun and moon first act together and then oppose. In some areas of Canada every second high or low water differs considerably from its predecessor. These differences are generally referred to as semidiurnal and diurnal responses of the particular water mass to the differing pulls of sun and moon.

Other considerations for conducting plume delineation studies in estuaries include the following:

- duration of the tidal cycle: it is not uncommon for the duration of the falling tide to exceed 7 hours and the time of the rising tide to be significantly less than 6 hours; and
- slack tide: in some estuaries, a slack period can occur in vertical and horizontal movement around high and low water; this can amount to a few minutes or in exceptional cases almost an hour (in this case generally low water only); lack of significant horizontal movement for a period can lead to considerable pooling of effluent in the area of the discharge, leading to possible expansion of the boundary of the zone of >10% effluent concentration.

A special case occurs in fjords where the depth of the estuary is well over ten times the thickness of the tidal prism. Here the longitudinal profile will look like a salt wedge estuary or a well-stratified estuary with the fresh water lying in a layer at the surface and very significant water depth below. The tide can rise and fall, causing negligible mixing, except possibly at the entrance where there is typically a sharp sill. In some fiords there may be a 2 to 10 m thick layer of fresh water that extends the full length of the estuary with an interface of less than a meter thick. In longer fjords extending over several tens of kilometres, diffusion and other influences such as wind and internal waves will cause this interfacial layer to thicken and the upper layer to become brackish.

Estuaries may demonstrate two or more estuarine types along their length or during seasonal variation in river flow or in the spring to neap tidal cycle. In partially mixed estuaries or well stratified estuaries, there is often little seaward movement along the bed during the ebbing tide creating an increase in stratification during this period. On the flood tide, the stronger currents run deep and conditions closer to well mixed are more likely to occur. In Canada, because of the Coriolis force and the difference in density between salt and fresh water, ebb currents tend to run stronger and salinity tends to be lower towards the right hand bank (looking seaward) of an estuary when looking seaward. Similarly, flood tide currents are stronger and salinities higher towards the left when looking seaward. This can be very marked in wide estuaries. Where an estuary has a high fresh water discharge or a narrow exit to the open coastal waters, a fresh or brackish water plume can extend well out to sea particularly during the ebb tide. Depending on the dynamics at such an entrance a portion of this plume may re-enter the estuary with the flood tide.

An estuary can change from one stratification type to another, either with distance or with time. During spring run-off, freshwater may dominate the upper reaches of the estuary and create a higher degree of stratification downstream. During lower flow periods, the upper reaches of the estuary will return to partially mixed conditions and the lower salinity water will penetrate much further upstream. Internal waves (or seiches) may form along the fresh or brackish water/salt water boundary in fjords and estuaries as a result of wind action, and may temporarily affect plume dispersion. These seiches are discussed in more detail in Section 5.6.2.

During slack tide, a significant pool of effluent can gather in the vicinity of the discharge pipe and at a concentration close to that delivered at the top of the rising plume. Once the horizontal tidal currents begin to move again, this large effluent pool is the leading edge of the effluent plume and may take some time to dissipate. As the tidal currents strengthen, the effluent leaving the discharge area will behave more like a standard streaming pool. If the effluent pool gathered during the low water slack, the rising tide will typically come underneath the plume as denser water and carry the effluent pool upstream. The somewhat diluted effluent in the pool may pass down through the discharge area on the falling tide and provide already polluted water to the discharging effluent. If the effluent pool gathered during the high water slack, it will tend to stream off downstream in a very thin layer due to density differences. When the tidal currents strengthen, this high water pool of effluent will tend to disperse more quickly than the low water effluent pool, but it may substantially extend the limit of the plume at the surface, particularly if it is shore-attached.

Plunging plumes may occur in estuaries and fjords. Effluents with a fairly high initial dilution on the rising jet can pick up salinity from the lower layers such that the plume attains a density greater than that of the surface layer. If the rising momentum is sufficient, the plume may break the surface and then slowly plunge or sink down to a water layer consistent with its density and travel and mix with this lower layer. This is depicted in Figure 2.1 (i).

In other situations, particularly where the surface layer is thick or very distinct, the jet will rise but be trapped at the interface between the upper and lower layer. This is likely to be the case in fjords if the initial discharge is located in the deep saline layer. Effluent mixing into the upper layer is more likely during an ebbing tide. During a rising tide, the strength of the current in a shallow estuary is close to the sea floor and may cause significant mixing with, and entrainment into, the lower layers.

Submerged plumes may resurface when the plume encounters an influx of differing density water coming into the receiving water. In this case, surface water will initially plunge, but will resurface down drift. This scenario may occur if there is an influx of less dense water downstream of the discharge, such as from a tributary or another major effluent discharge.

5.4.2 Conducting the Field Work

Two boats are recommended for tracer studies in estuary environments. The recommended technique for dye tracer measurement is use of a fluorescence sensor or sampler intake off the bow of the boat, as described in Section 3.3.3. Salinity and temperature verticals should be taken along the centre line of the estuary and in the vicinity of the discharge. The sampling time should be noted relative to time of high or low water, and sampling should always proceed in a counter current direction relative to the receiving water movement.

It is important to consider the differences between successive high waters and between spring and neap tidal ranges and reconcile them with establishing the representative density regime in the estuary and also the objectives of the plume delineation study. The vertical range relative to the water depth at low tide gives some indication of potential turbulence. Another method, but requiring more work, is to estimate the water volume passing various sections during flood and ebb and hence to obtain the average velocities. This is particularly valuable where there are large inter-tidal volumes or additional river flows added at particular points along the estuary.

If using a dye tracer, injection should begin about half an hour before the turn of the tide so that the study may begin around low water. For most estuary studies, the plumes can be delineated in the field in the same way as a river plume. When sampling, the boat should always work against the tidal currents to avoid just drifting with the receiving water and possibly sampling the same water mass. If a separate boat is doing the drogue work or when being done on a separate day, it is useful to check salinity and temperature at the drogue depth each time the position is confirmed. Care must be taken when the tide reverses and the partly diluted effluent comes back over the discharge point as there will probably be a new thin poorly diluted plume on top of a thicker well mixed plume. When the difference in flood and ebb tide surface excursions is small (*e.g.,* < 20% of the excursion) there may be a build up of effluent from more than one tide. Generally the numerical model can provide the most effective predictions of this phenomenon.

For plunging plumes, drogues can be set to follow the plume at depth. However, caution should be taken to ensure that the vertical dimension of vanes is not too large, because the upper and lower edges may get caught in two different water flows. If the depth of the plume is known from initial field sampling, the plume may be tracked as outlined in Section 3.9, except that instead of air there is a layer of water above the plume. This is one case where a fluorescence sensor or sampler intake may be towed astern, because it is likely to be well below the influence of mixing from the boat hull and propulsion unit. This technique requires more boat operator skill to maintain constant speed either with a water speed gauge or a revolution counter. A depressor will hold the fluorometer head or intake down, but a depth gauge (either pressure or upward looking sonar) is essential to record depth.

It is much more challenging to follow a plume that rises to the surface and then plunges and also where there is no well marked interface. Initial field measurements of salinity taken to characterize the environment will demonstrate how the naturally occurring surface layer behaves relative to the lower layer down drift.

Numerical modeling may need to be carried out over a number of tidal cycles to show short-term and long term effluent dilution fields. Three-dimensional modeling may be required for stratified receiving waters.

5.5 Marine

Thermal and salinity stratification are important features to assess for coastal marine environments because the effluent is usually less dense than sea water due to chemical and thermal factors. In very calm weather, the plume may be contained within a few centimetres of the water surface. Significant influences in this environment include wind and wave advection, shore-line attachment, bottom attachment, and tidal activity (often with rotary currents). Oceanic receiving waters are distinguished from estuaries in that the main circulation is not dominated by fresh water in the vicinity of the discharge. The effluent plume is diluted and transported by currents. Tidal activity, while present, does not always provide the main contribution to net effluent movement, but does affect effluent dispersion. A continuous dye release of one tide cycle is generally sufficient, but the duration of the numerical modeling program may be over several tidal cycles.

The residual current patterns may be dominated by a coastal circulation pattern or by local wind and wave influences. It is useful to have local water current data, such as may be obtained from positioning coastal current meters near the discharge. Likewise, local salinity, water temperature and wind records are also useful.

Prior to any dye release, the tidal heights and times at the site should be correlated to the nearest recording tide gauge maintained by the Canadian Hydrographic Service. This is of value for the dye study and also in the use of current and other longer term records. Spatial salinity and temperature profiling should also be conducted at this time.

The initial concept of effluent dispersion should be useful for planning the dye release. Field delineation of a surface plume may follow the standard practice outlined in Section 3.9, although judgement will be required on the spacing of the transects, particularly if the rotary current is marked and the plume begins to come back over the discharge area. Tracking of submerged plumes should be conducted as described in Section 5.4 above. It is usually beneficial to use larger scale drogues with radar reflectors and GPS receivers in coastal areas, especially if wave action is present.

From the dye tracer profiles, the effluent plume envelopes will be developed and related to the measured currents, wind and waves on that day. The probability of the occurrence of these envelopes may be determined using statistical data from available data on water currents, and numerical models used to extend these envelopes over a broader time period to represent "average" conditions.

5.6 Climatic Conditions

Ice and wind may have significant effects on effluent dispersion. The following sections provide guidance on incorporating ice and wind conditions in interpreting plume behaviour. The applicability of numerical models using ice are very limited at this time.

5.6.1 Ice

Ice is a common occurrence in many Canadian water bodies during winter. Its general effect on the effluent discharge is two-fold. Ice cover shields the receiving waters from the effects of wind stress and may also alter or cause stratification in the water column and hence modify water circulation. However, in the case of land fast ice, the underside of the ice provides a solid rough boundary to flow and creates turbulence similar to flowing over the stream bottom.

Most effluents are warm and this will cause some melting and a weakened ice surface. The buoyant plume will cling to this ice surface in the same way that a dense plume will cling to the bottom substrate. As far as is known, no detailed effluent plume field studies have been made under ice conditions, but it is reasonable to assume that mixing is likely to be decreased. This can result in the extent of plume concentrations being under-estimated when based on open water considerations alone.

Land fast ice cover removes wind stress mixing from the surface waters. In the presence of fresh water discharges (*e.g.,* river discharges), mixing will be reduced between the effluent and river water. Ridges may appear in the formation of the ice surface. Some of these ridges may be the result of early ice flows colliding, and others may be formed by thermal expansion of the ice. Ridges may form in the same position each year and may have a keel or downward projection as much as 7 times the height of the surface ridge. These ridges can interfere with the plume and may divert it in a very different direction to its normal open water mode.

Moving ice still generally shields the surface water from direct wind effects. However, wind influences may be greater than initially predicted, because wind motion will be transmitted from the below water profile of ice flows to the receiving water and/or the plume. Where moving ice comes in contact with land fast ice or an island, a significant ice ridge may form.

The standard numerical models for plume delineation are generally not appropriate for considering ice conditions since they assume a free water surface (*i.e.*, open channel flow).

5.6.2 Wind

Wind acting on large bodies of water induces currents and waves in direct proportion to its strength, its duration, and fetch over the water body. Fortunately, nomographs are available to provide estimates of current speed, and wave height and period that can contribute to understanding wind effects on the dispersion of effluents. One of the most valuable sources of information is literature relating to oil spill trajectory modeling, or ocean search and rescue. For wind currents, the James wind-drift forecasting curves (James 1966) are probably the easiest to use to obtain a magnitude. When using the James curves, the direction is usually taken as being 20 degrees to the right of the wind direction, due to Coriolis forces.

In more detailed work this can be modified to accommodate variations in duration, fetch, wind speed and water depth, among other factors. In many coastal areas it is the predominant wind direction coupled with local underwater topography that provides the driving force for currents along the shore. The momentum built up can make these currents very persistent. Wind waves also transport water, particularly when they get into shallow water. These waves can run out of the wind field and continue to transport their energy over hundreds of miles.

The nomograms most commonly used for wave predictions are those developed by the U.S. Army Corps of Engineers (1984). Wind wave energy is transmitted in two ways: first, on the surface by water particles orbiting in a circular motion with a radius of half the wave height at the surface; and second, at depth with the radius diminishing to almost zero at a depth of half the wave length. Typical coastal waves have periods of 4, 6, and 8 seconds, and have wave-lengths of 25 m, 56 m and 100 m, respectively. When this motion at a depth of half wave length comes in contact with the bottom substrate, friction causes the wave to slow and the circular particle motion changes to elliptical. On a long beach, this will cause the wave crests to try to align themselves parallel to the contours and eventually the shore. This has two effects on the plume: increased mixing within the plume and currents along the shore generated by the waves.

Internal waves, or seiches, moving along the interfacial boundary between two water masses can also impact the dispersion of a plume. The generation of these waves is not well understood but they are formed as eddies by the shear forces acting between the two opposing water layers, and they may be found moving along the thermocline in lakes, the sharp fresh water/salt water boundary in fiords, or between the estuarine and marine water in large estuaries or coastal waters. These internal waves can be of large amplitude (*e.g.*, on the order of meters) with waves of 80 m being recorded in the St Lawrence off the Saguenay. Their impact on the plume is transitory, and are mentioned here only for guidance should an anomaly occur during a dye test. Their occurrence would be picked up on the records of recording thermographs or salinometers.

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