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Transport and dispersal of sea lice bath therapeutants from salmon farm net-pens and well-boats operated in Southwest New Brunswick: a mid-project perspective and perspective for discussion

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Salmon aquaculture sea lice bath treatments result in the release of the bath water containing the therapeutant into the ambient environment. The consequence of these releases to non-target organisms in the receiving environment depends upon the dilution and toxicity of the therapeutant, and whether the non-target organisms are exposed to the released therapeutant; the latter being controlled by the local current regime, the distribution, behaviour and sensitivity of the organisms in relation to the therapeutant. In this report we review some of the general theories pertaining to the transport and dispersal of the substances in the marine environment, empirical information concerning the transport and dispersal of therapeutants from commercial sea lice treatments using tarpaulins, skirts and well-boats, and test some models aimed at simulating the release, drift and dilution patterns. The empirical information reviewed focuses on the release of dye mixed with the therapeutants prior to treatment, and the modeling focuses on the use of current meter information, and the Okubo relationships describing horizontal patch spread.

Transport et dispersion des produits thérapeutiques contre le pou du poisson des installations salmonicoles utilisés en bassins à partir de parcs en filet et de bateaux viviers

RÉSUMÉ

Les traitements en bassins utilisés dans le cadre de la salmoniculture résultent en la libération du produit thérapeutique dans l'environnement ambiant. Les conséquences de ces rejets sur les organismes non-ciblés dans le milieu récepteur dépend de la dilution et de la toxicité des produits thérapeutiques, et de l'exposition des organismes non-ciblés à l'agent thérapeutique libéré. L'exposition dépend du régime de courant local, ainsi que de la distribution, du comportement et de la sensibilité des organismes en relation avec le produit thérapeutique. Dans ce rapport, nous passons en revue quelques-unes des théories générales concernant le transport et la dispersion de ces substances dans l'environnement marin, des données empiriques concernant le transport ainsi que la dispersion des produits thérapeutiques de traitements commerciaux contre les poux du poisson basés sur l'utilisation de bâches, de jupes et de bateaux. De plus, certains modèles visant à simuler les modes de libération, de dérive et de dilution ont testés. L'information empirique se concentre sur la libération de colorants mélangés avec les produits thérapeutiques avant le traitement, tandis que la modélisation se concentre sur l'utilisation des informations du courantomètre, et des relations Okubo décrivant la propagation horizontale des flaques.

INTRODUCTION

Salmon farmers in southwest New Brunswick, elsewhere in Canada, and the world need to control the abundance of sea lice on the fish within their net-pens. There are several methods available for accomplishing this. One method, the administration of therapeutants in the fish feed is not the subject of this paper. Another method is the use of pesticide bath treatments. In southwest New Brunswick, a production cycle is typically spread over a 12-18 month period and the number of bath treatments varies between years commensurate with the intensity of sea lice infestations. In normal years each farm would be treated two to three times in a production cycle and if effective in-feed treatments were available this frequency would be considerably reduced. However, since available in-feed treatments are presently ineffective and the intensity of sea lice infestation is high, the need for frequent bath treatments has increased. In 2010, thirty-five salmon farm sites within the southwest New Brunswick area conducted a total of over 1900 tarp and skirt bath treatments (New Brunswick Provincial veterinarian, M. Beattie, pers. comm.). In 2011, when sea lice counts were still high, twenty sites conducted over 1000 bath treatments. In contrast to 2010, the vast majority were well-boat treatments with only a few tarp and skirt treatments; (M. Beattie, pers. comm.). These numbers correspond with approximately five treatments per cage per production cycle.

These treatments either require the in situ tarping or skirting of the fish within each net-pen or the pumping of fish into well-boat wells. In both cases, the pesticide is introduced into the water containing the fish, the fish are allowed to swim through the pesticide bath for a specified period of time (dependent on the pesticide), and the water containing the pesticide is released into the ambient environment after the treatment period.

The exposure to the released therapeutant that non-target organisms will experience is controlled by local transport and dispersal processes. These processes control the dilution rate, spatial trajectory and rate of transport of the released therapeutants. These aspects are essential factors and considerations that contribute to the impact and predicted potential for impact on non-target organisms. A knowledge of these processes is of particular interest for the southwest New Brunswick area because the area supports a substantial salmon aquaculture industry as well as a traditional lobster fishery, with some of the aquaculture farms located in close proximity to lobster habitat and the therapeutants used to control sea lice can be toxic to lobster if they are exposed to specific concentration ranges and durations (Burridge 2013).

Previous work on dispersal processes in the Bay of Fundy is limited and work on dispersal of therapeutants from fish farms in the area is restricted to Page et al. (1998, 2000) and Ernst et al. (2001). These latter studies were conducted at several locations using a combination of current meters, drifters, and a mixture of therapeutant and dye. Although the therapeutant-dye mixtures were applied by an approved industry pesticide applicator and the mixtures were released from a tarped fish cage towed to several release locations, the cage did not have a net, did not contain fish, was not part of an operating fish farm and the release locations were distant from local fish farms since the desire was to avoid exposing farmed fish to the rhodamine WT dye that was used. Despite these limitations, the work showed several valuable perspectives. In particular the utility of using dye as a pesticide tracer was established and the dispersal rates away from fish farm infrastructure in the macro-tidal southwest New Brunswick area were shown to be consistent with and at times greater than, dispersion values expected based on measurements made elsewhere in offshore coastal areas (Okubo 1971, 1974, Lewis 1997).

Given the above background there was a desire for additional transport and dispersal work in which dye was released into net-pens that were part of an active farm's net-pen grid array and contained nets and commercial quantities of salmon. Hence, an experimental approach was developed that included the mixing of fluorescein dye with the bath treatment pesticide prior to injection into the tarped cage by the aquaculture industry applicator. The fluorescein dye was chosen because it is relatively non-toxic to fish and humans and hence the farmed salmon could be exposed to it. Although the approach was initially conceived for net-pen bath treatments, the introduction of well-boats to the southwest New Brunswick area during the study period resulted in the work and approach being expanded to include well-boat bath treatments.

The purpose of this paper is to summarize some of this new work that has been conducted by a team lead by DFO to describe and predict the transport and dispersal of pesticides released from tarp and well-boat bath treatments conducted in the southwest New Brunswick area. The report is divided into two main sections. The first section focuses on tarp treatments of fish net-pens. The second section focuses on well-boat treatments. In each of these sections there are a series of sub-sections that describe the concepts and theories as well as some recent observations associated with distinct stages in the therapeutant release sequence. A companion report by Burridge (2013) describes laboratory based toxicity assessment experiments conducted on some key non-target organisms. A third report by Page and Burridge (2013) combines the main findings of Burridge (2013) with the results of this report to arrive at initial estimates of the potential for biological in situ or field effects.

The work described in this paper is part of a multi-year project that is still underway; hence the work is still in progress, and as such this report mainly offers insight into research conducted to date. The project was funded under Fisheries and Oceans Canada's Program for Aquaculture Regulatory Research (PARR) and the work and progress to date will help serve to stimulate discussion. It should not be considered as a complete and rigorous consideration of available theoretical perspectives and analyses of the data collected by the authors. Analysis of data collected in 2010 and 2011, is still underway, and modeling has begun, although it is scheduled to be part of the year two work and as such it will be reported on in a subsequent review process. Hence, new insights are still surfacing and confidence in some perspectives is still maturing and solidifying. An additional year of observations, data analyses and modeling is scheduled with a full reporting of the work tentatively scheduled for the winter of 2013. Despite these limitations, the report does present a glimpse into the nature of the issue, the breadth of the work being undertaken and gives a flavour for the observations being gathered. It also helps identify the factors that influence therapeutant transport and dispersal and hence estimates of exposure to non-target organisms in environmental toxicity risk analyses.

EXPERIMENTAL APPROACH

As briefly mentioned above, in order to track the transport and dispersal of released therapeutants following tarped net-pen or well-boat application, fluorescein dye was added into the treatment volume along with the pesticide. To date seven net-pen and eight well-boat dye release experiments have been undertaken. Not all of this data have been analysed and if circumstances allow, it is hoped that additional work can be conducted in the future.

This approach was taken in order to visually track pesticide transport and dispersion, establish the locations for water sampling and enable the use of in situ fluorometry to estimate dilution of the pesticide. The main advantage of the approach is that it provides visual confirmation of the mixing, dilution and transport processes as well as a quantitative estimate of the concentration of the dye, and by association, the pesticide, as it disperses over time. Dye dispersion patterns were recorded by taking photographs at opportunistic moments and locations and using continuous time lapse photographic series from several fixed locations. The time lapse series consisted of still pictures taken at ten second intervals with Pentax Optio weatherproof cameras. Dye concentrations were quantitatively estimated using fluorometers configured to measure fluorescein. Each fluorometer, a Turner Designs Cyclops 7, was calibrated in the lab prior to each field experiment using seawater since the performance of the fluorometers differs between freshwater and seawater. A dye dilution series was used to determine the shape of the instruments' response curve and the maximum concentration of dye that could be detected, i.e., the concentration at which the response curve began to deviate from linearity. This functional maximum varied between fluorometers and ranged between about 250 and 400 µg/L. The minimum detection limit was <1 µg/L. Multiple measurements made on dilution series concentrations varied by only a few µg/L. These limits meant that the initial concentration of dye needed to be customized to the purpose of the experiment. For example, if the purpose was to measure mixing within the bath treatment volume, the amount of dye required would be a relatively small amount, approximately a hundred grams, due to the limited size of the bath treatment volume. In contrast, in order to track the dye for several hours after release into the receiving environment a much higher amount of dye, a few kilograms, is required, resulting in concentrations within the treatment volume that exceeded the upper detection limit of the fluorometers.

Although this approach has many advantages it also has some limitations. A disadvantage associated with the use of fluorescein, is that the dye is subject to photo-degradation. Initial field observations suggest that this may not be of major concern for the present studies as the rate of photo-degradation is considered to be slow relative to the rates of physical dispersion, especially horizontal dispersion. Additionally, the potential for photo-degradation is expected to decrease with depth. Therefore, the estimated dilution of dye is considered to be indicative of the actual order of magnitude of dilution rates of dye. However, in recognition of the potential for influence, a series of controlled experiments are planned to further explore the magnitude of these effects and the implications of these influences. In the meantime, the dye is considered to give valuable qualitative and quantitative insights into the transport and dispersal processes and interpretations of the data are hopefully relatively independent of these effects.

As alluded to above, water samples were also taken over time at locations determined by reference to the visual pattern of dye dispersal. These water samples will be analysed for pesticide and dye concentration and used to establish calibration curves relating pesticide concentration to dye concentration. Although these analyses have not been completed, the preliminary results indicate that the dye concentrations are indicative of pesticide concentrations and that relative dilutions of dye are consistent with the same relative dilution of pesticide.

NET-PENS: THE TREATMENT PROCESS

The process of conducting a tarpaulin bath treatment of a net-pen involves several steps. Initially, the outside perimeter of the net on the net pen is shallowed to a depth of about 3-4 metres. The net in the middle of the cage sags and is deeper than the net along the perimeter by a few metres. The raised net concentrates the fish in the cage to within a reduced volume. Once the nets are shallowed, a tarpaulin is deployed around and under the net. The edges of the tarpaulin are then pulled out of the water and tied at regular intervals to the hand rails of the cage. Once fully deployed the tarpaulin forms an impermeable bag around the fish and therefore encloses the fish within a stagnant pool of water. Air and/or oxygen is injected into the tarped water in an effort to maintain oxygen levels adequate for the fish to avoid hypoxia-related stress. No attempts are made to mechanically circulate the waters within the tarps. The ability of the farmers to successfully tarp a net-pen depends largely on the ambient water current. If the currents are too strong, or if they change direction during the tarping process, the tarp may not be able to be deployed, or it may be forced to the sea surface in large areas of the net-pen, trapping fish in a restricted portion of the net and causing the fish undue stress. Hence, farmers try to conduct tarp treatments during the relatively weak currents associated with slack water.

The shape, and therefore volume of the tarped net varies during the treatment in response to the speed of the ambient water current. During slack water the shape may be like a cylinder or a half sphere, whereas at times of stronger current the upstream end of the tarpaulin may be forced toward the surface leaving the downstream end of the tarped net lower, creating a tear-drop, oval or compressed cylindrical shaped bag containing the fish and therapeutant.

Once the enclosed fish seem to be comfortable in the reduced volume of water, the therapeutant is pumped into the tarped net from a mixing container located on the treatment vessel (Figure 1). The therapeutant is initially placed into the mixing container along with seawater and manually mixed before being pumped into the treatment volume. Although, it is generally assumed that the pesticide is fully dissolved into the water prior to pumping, anecdotal evidence suggests that this may not always be the case for at least some pesticides such as Salmosan® (M. Beattie, pers. comm.). The therapeutant is assumed to become mixed throughout the enclosed volume by the movements of the fish and the water movement generated by the oxygenation system, as no mechanical mixing is provided (Figure 2). It is interesting to note, however, that the fish may avoid the therapeutant until it becomes mixed throughout the treatment volume and when they swim through the dye they do not appear to drag dye with them, suggesting that fish movements may have a limited effect on mixing. At the end of the treatment period, the tarpaulin is dropped by untying the ropes attached to the hand rails and pulling the tarp back from around and underneath the shallowed net. Once the tarp is completely removed, the net is allowed to drop to its normal depth and the water containing the therapeutant begins to be advected from the net into the ambient receiving waters.

The duration of a commercial treatment is defined as the amount of time between the start of the introduction of the therapeutant to the beginning of the dropping of the tarpaulin. This time is usually between 20 and 40 minutes, with the exact time depending upon the therapeutant used, the health of the fish, water temperature and the oxygen content within the enclosed net-pen.

When the fish appear stressed the treatment duration may be truncated to help avoid further stress to the fish and potentially fish mortality; this happens in less than 5% of the treatments (M. Beattie, pers. comm.) and since there can be 1-2000 bath treatments per year, there may be as many as 50-100 truncated treatments per year. These truncations may result in higher initial concentrations of pesticide being released since the high concentration pesticide being pumped into the bath volume may not have time to be diluted through the process of being mixed throughout the bath volume.

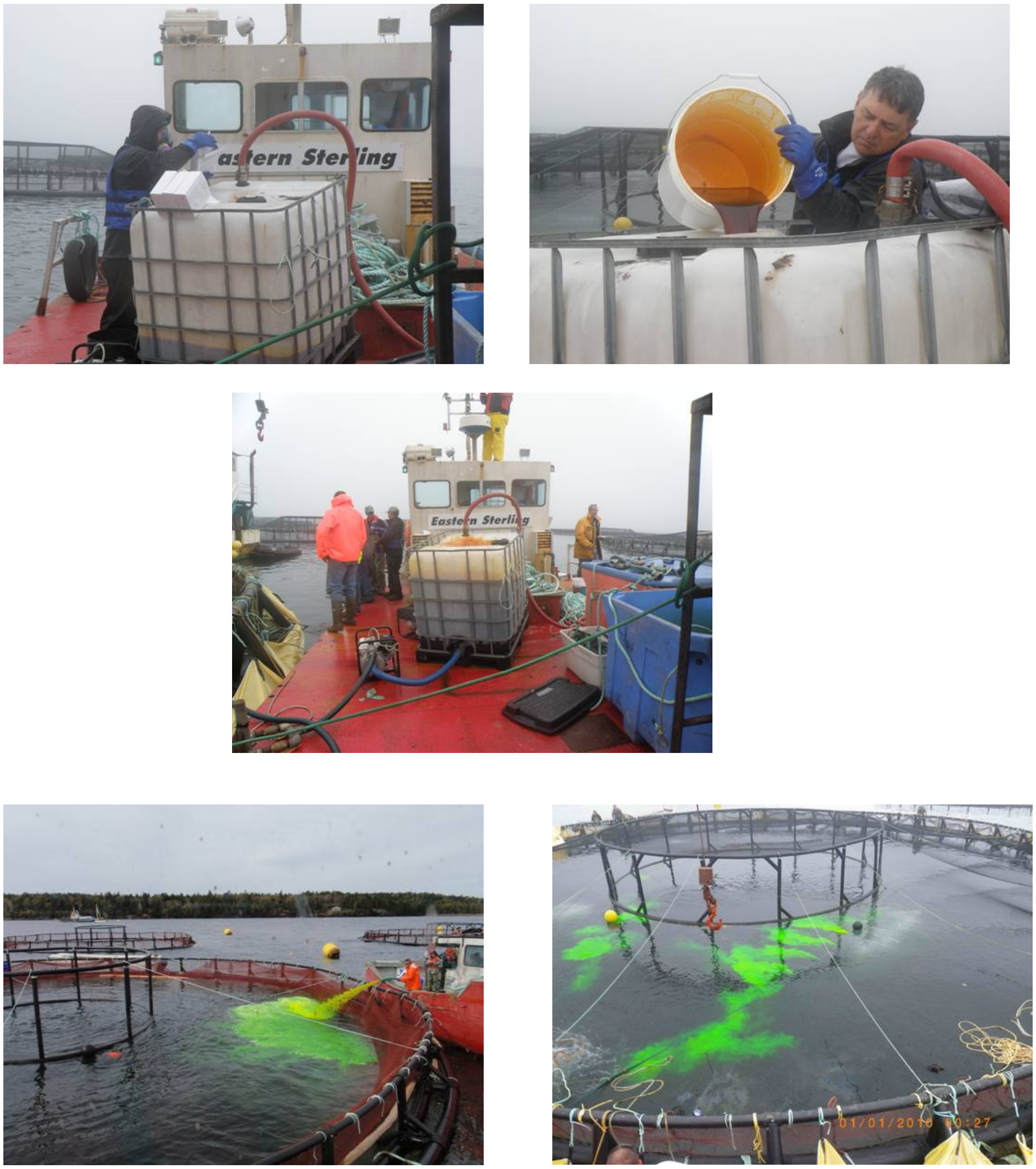


Figure 1: Pictures showing the introduction of therapeutant and dye into a tarped net-pen. The top left shows the therapeutant being added to a mixing tank on a farm vessel tethered to the side of the net-pen to be treated. The top right picture shows a solution of dye being added to the mixing tank. The middle photograph shows the pump and hoses used to deliver the therapeutant and dye into the tarped net-pen. The bottom left shows the therapeutant being hosed into the cage and the bottom right shows the therapeutant being pumped into the cage through two perforated hoses stretched across the diameter of the net-pen.

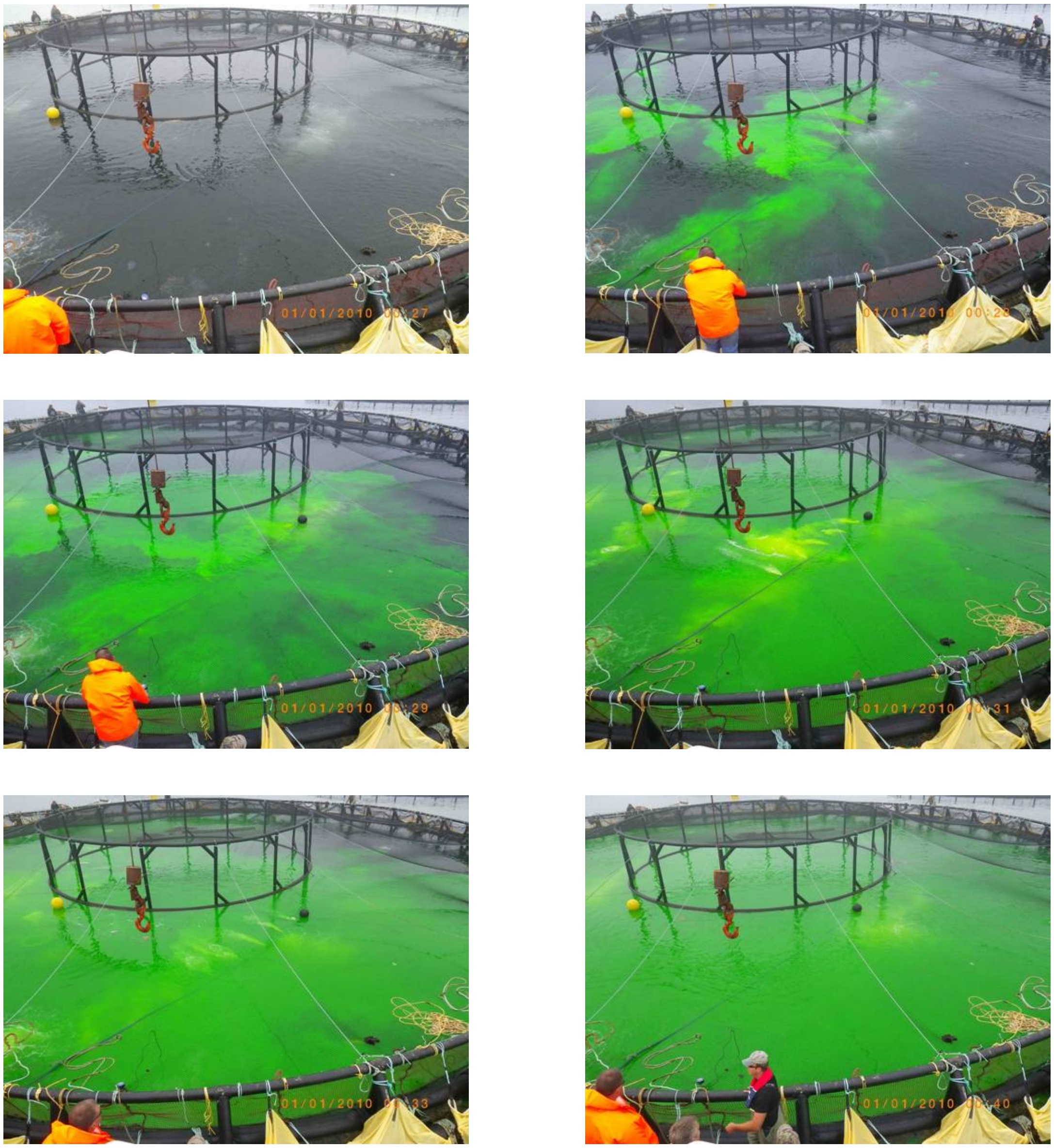


Figure 2: Photographs showing the temporal evolution of the spread of dye and associated therapeutant throughout a tarped net-pen. The photographs were taken before the dosing began (top left), 0.5 minutes (top right), 2 minutes (middle left), 4 minutes (middle right), 6 minutes (bottom left) and 12.5 minutes (bottom right) after dosing began.

TRANSPORT AND DISPERSAL FROM TARPED NET-PENS

There are several classic reference books that provide information of relevance to the problem being addressed here. These include Csanady (1973), Fisher et al. (1979), Bowden (1983), Lewis (1997) and Vesilind et al. (2010). These sources provide an entrance into the extensive literature on transport and dispersal processes. The overview of the underlying theory presented below draws heavily from these sources. It should also be noted that there appears to be very little literature concerning the specific situation of therapeutant transport and dispersal from net-pens and well-boats and with the exception of Ernst et al. (2001) and Page et al. (2000), almost no literature specific to the southwest New Brunswick area.

As a first approximation the dilution rate of a passive substance is independent of the translation or advection rate. In other words, the rate at which a patch of dissolved substance is diluted is not affected by how fast or how far the patch is carried by the currents. The rate of therapeutant dilution is controlled by the rates of horizontal and vertical mixing in the area of release, as well as rates of chemical behaviour and reaction in the ambient water. Although this paper does not address these chemical processes, it should be noted that the empirical dye results reported below were associated with releases of specific chemicals and that water samples taken during the releases support an interpretation that the dye results are indicative of therapeutant transport and dispersal, at least over the short time scales considered here.

NET-PENS: INITIAL DISTRIBUTION OF THERAPEUTANT

The initial concentration of therapeutant within a tarped net-pen is somewhat uncertain. Operationally, Health Canada specifies the treatment concentration, as listed on the product registration label. The quantity of therapeutant required to reach this concentration in the net-pen is calculated by the industry personnel in charge. The mass of therapeutant needed to achieve this target is estimated by multiplying the desired target concentration (C_0) by an estimate of the volume (V) of water enclosed by the tarpaulin. Whether the target concentration is achieved depends upon the accuracy of the volume estimate and the degree to which the therapeutant gets mixed throughout the enclosed volume of water. For the purposes of the calculations and models presented here the therapeutant is assumed to be reasonably well-mixed throughout the tarped volume prior to the time of tarp release. However, based on preliminary examinations of time series photographs and fluorometry from within tarped net-pens (not presented), and discussed above, this may not always be the case.

The volume of enclosed water is estimated by assuming the tarp around the raised net forms a relatively simple shape. The volumes associated with a variety of assumed cage sizes and tarpaulin shapes are presented in Table 1. All cages are assumed to be circular since few square cages are used in southwest New Brunswick. The circumference or perimeter (P) of the cages is assumed to be 70, 100, 120 or 150 m. The corresponding diameters (d) or length scales ($l_{cage\_x} = l_{cage\_y}$) of these cages are approximately 22, 32, 38 and 48 m, respectively, where the diameters or length scales are estimated as $d = l = P/\pi$. The depth of the tarp along the outside edge of the cage is assumed to be approximately 4 m. When the tarp is assumed to be deeper in the middle than at the edge, the depth in the centre is assumed to be 6 m. For the purpose of applying analytical equations to the dispersion of therapeutant when it is released from a cage, the initial distribution of the therapeutant patch is often assumed to be a three dimensional Guassian or normal curve shape with initial horizontal and vertical standard deviations of $\sigma_{x0} = \sigma_{y0} = l/4 = d/4$. The vertical standard deviation is usually given as $\sigma_{z0} = h/2$ where h is the height equal to the depth of the tarp at either the net-pen edge or centre, both are presented in Table 1. Since these are often not precisely known, the average of the cage edge and centre values could be used as a compromise (not shown in Table 1). These standard deviations are also included in Table 1.

The minimum volume is obtained by assuming the shape of the tarped cage is a perfect cylinder ($V = \pi r^2 h_e = \pi d^2 h_e/4$) with a height ($h_e$) equal to the depth of the tarp at the cage edge. For the dimensions listed in Table 1, the minimum estimates of the enclosed volume range from 1560 to 7162 m^3 as the cage size increases from a perimeter of 70 to 150 m. When the volume is estimated as a cylinder with a depth equal to the depth at the centre of the cage (h_c), the volumes range from 2340 to 10743 m^3.

The maximum volume estimate is obtained by assuming the tarped volume is cubed shaped. In this case the volume is estimated as $V = l_x l_y l_z$ with dimensions of $l_x = d = 4\sigma_x$, $l_y = d = 4\sigma_y$ and $l_z = \sigma_z = 2h_c$. These volume estimates range from 2979 to 13678 m^3. The maximum estimates are approximately a factor of 2 higher than the minimum estimates.

Some other ways of estimating the volume are also included in Table 1. For, example, the volume estimated by assuming the tarp is a cube with horizontal length scales $l_x = l_y = d$, and a vertical length equal to the depth of the tarp at the edge of the cage ($l_z = h_e$) range from 1986 to 9119 m^3. When the volume is estimated as a semi-ellipsoid ($V= [(4/3)\pi r^2 h_c]/2$) the volumes range from 1560 to 7162 m^3. When the volume is estimated by assuming the tarped volume has the shape of an upper cylinder with cone added to it representing the central sagging of the net, the volume is estimated as $V = \pi r^2 h_e + (1/3)\pi r^2 (h_c - h_e)$ where $h_c - h_e$ is the height of the cone underlying the upper cylinder. These volume estimates range from 1820 to 8356 m^3.

The concentration of therapeutant in the tarpaulin is estimated as M/V, where M is the total mass of therapeutant added and V is the estimated volume of water enclosed by the tarp. The uncertainty in the volume of water within the tarped net-pen therefore translates into uncertainty in the treatment concentration. Calculations estimating the concentration of an assumed addition of 1000 units of therapeutant shows that the ratio of the maximum to minimum concentrations is also 1.9 (Table 1). For the shapes, cage perimeters and masses assumed here, the range in volume and concentration estimates increase somewhat as the estimates of the tarp depths decrease. However, the maximum to minimum range is still within an order of 2.

It should be noted that some sampling has been conducted during commercial bath treatment applications in an effort to gain empirical insight into the achieved concentrations within the tarped volume as well as the distribution of the concentrations within the tarped volume. Although some of these data are presented below, much of the data are still being analyzed and will be summarized elsewhere.

NET-PENS: FLUSHING FROM CAGES INTO THE ENVIRONMENT

Once a tarpaulin is removed from the cage the pesticide is released into the environment. This release is characterized by a combination of transport and dispersal processes. Transport or advection processes carry the therapeutant with the ambient water as it flows through the treated net-pen and farm site and eventually away from the farm. During this transport process, the initial concentration of therapeutant is diluted by ambient eddy dispersion processes.

The rate at which the therapeutant leaves the treated net-pen depends upon many factors including the size of the cage, the rate of water flow through the cage, the size of the net mesh, and the degree of bio-fouling on the mesh. The rate at which the therapeutant subsequently moves away from the cage and disperses depends upon the ambient current velocities and rates of ambient eddy mixing. All these aspects can be site, cage, and time specific since they depend upon site specific oceanography, farm layout and farm husbandry.

In the absence of the fish cage, fish net, adjacent fish cages and their nets, and all of the other farm infrastructure, an estimate of the flushing time of the cage or the time to transport the therapeutant out of the cage is $t_{fl} = d/U$, where d is the diameter of the cage and U is the speed of the ambient current running through the cage. Table 2 shows estimates for a range of water speeds and cage sizes. For speeds between 5 and 50 cm/s, the times range from less than a minute to about 15 minutes. Under these circumstances the initial therapeutant patch would be transported away from the cage and farm in a matter of minutes and the dispersion of the therapeutant could be approximated by the theories described below. For slower speeds (e.g., 2 cm/s), the flushing time of the cage was a few tens of minutes.

Table 1: Dimensions and volume estimates for tarped circular fish cages under different assumptions of cage size and volume shape.

Dimension Type	Dimension Values			
Cage Perimeter or Circumference (*P* in m)	70	100	120	150
Cage Diameter (*d* in m)	22.3	31.8	38.2	47.7
Cage Radius (*r* in m)	11.1	15.9	19.1	23.9
Horizontal length scale ($\sigma_x = \sigma_y = d/4$ in m)	5.6	8.0	9.5	11.9
Net Depth at cage edge (h_e in m)	4	4	4	4
Net depth at cage centre (h_c in m)	6	6	6	6
Vertical length scale ($\sigma_z = h_e/2$ *or* $\sigma_z = h_c/2$ in m)	2 or 3	2 or 3	2 or 3	2 or 3
Volume (*V*) enclosed (m^3)				
Cylinder $h = h_e$	1560	3183	4584	7162
Cylinder $h = h_c$	2340	4775	6875	10743
Semi-Ellipsoid	1560	3183	4584	7162
Cylinder plus cone	1820	3714	5348	8356
Cylinder $h=(h_e + h_c)/2$	1950	3979	5730	8952
Cube $\sigma_z = h_e/2$	1986	4053	5836	9119
Cube $\sigma_z = h_c/2$	2979	6079	8754	13678
Ratio of V_{max}/V_{min}	1.9	1.9	1.9	1.9
Ratio of Min/Cylinder plus cone	0.9	0.9	0.9	0.9
Ratio of Max/Cylinder plus cone	1.6	1.6	1.6	1.6
Ratio of cube $\sigma_z = h_e/2$/cylinder plus cone	1.1	1.1	1.1	1.1
Mass (*M*)	1000	1000	1000	1000
Maximum Concentration ($C_{max} = M/V_{min}$)	0.64	0.31	0.22	0.14
Minimum Concentration ($C_{min} = M/V_{max}$)	0.34	0.16	0.11	0.07
Ratio of C_{max}/C_{min}	1.9	1.9	1.9	1.9

Table 2: Estimates of the time, in units of minutes, needed for ambient water currents to advect or transport therapeutant out of the treated cage. P = perimeter, d = diameter.

Water Speed *U* (m/s)	**Cage Size (m)**			
	P = 70	*P* = 100	*P* = 120	*P* = 150
	d = 22.3	*d* = 31.8	*d* = 38.2	*d* = 47.7
0.02	18.6	26.5	31.8	39.8
0.05	7.4	10.6	12.7	15.9
0.10	3.7	5.3	6.4	8.0
0.20	1.9	2.7	3.2	4.0
0.30	1.2	1.8	2.1	2.7
0.40	0.9	1.3	1.6	2.0
0.50	0.4	0.6	0.7	0.9

It is well known that the cages impede the flow of water and that the velocities within a net cage are substantially reduced relative to the ambient speeds. Although we were unable to measure water velocities within the cages, the measurements and photographs of dye concentrations indicate that flushing times varied from a few minutes to more than two hours with the variation representing differences between cages, sites and release dates and times, especially in relation to the tidal cycle. The observed flushing times are considerably longer than those estimated above using simple assumptions. Hence, the assumption that the therapeutant leaves the cages quickly and can be estimated from the ambient current speed and diameter of the cage is not always accurate nor a good representation of the initial release condition. The release from the cage is at times significantly impeded by the cage, net with its bio-fouling and farm infrastructure. Efforts to develop a better quantitative characterization of the release condition are being explored.

Photographs from two of the studied releases help to illustrate the observed patterns of flushing (Figures 3 and 4). In the first example (Figure 3) the dye did not leave the cage as an intact circular patch, instead it left as an elongated streamer. It had completely left the cage in about 25 minutes and the patch encountered other cages during its transport away from the farm into the ambient receiving waters.

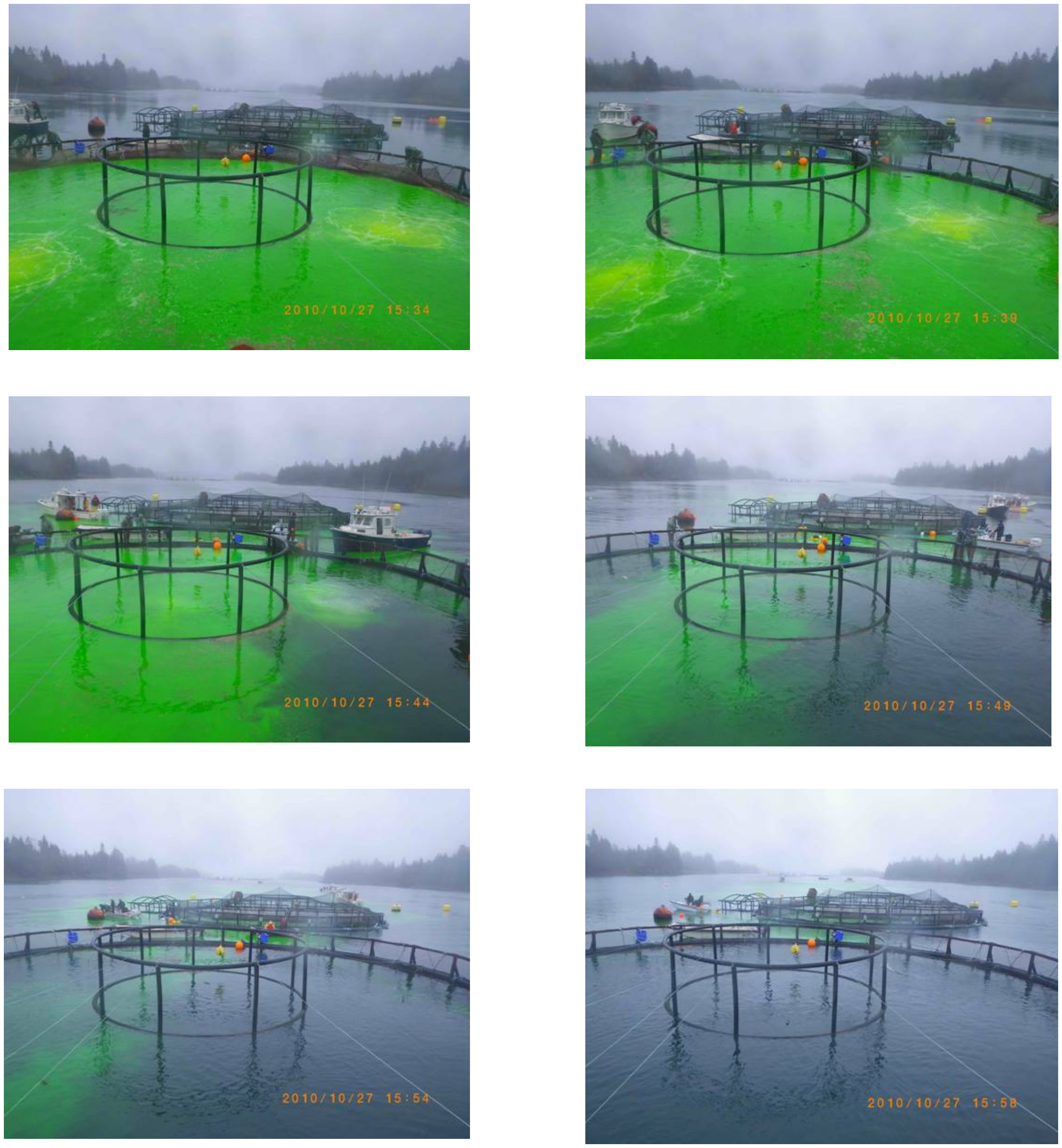


Figure 3: A series of photographs showing the temporal evolution of dye, and hence therapeutant, leaving a tarped fish cage. The photographs were taken just prior to the beginning of flushing (top left), 5 minutes (top right), 10 minutes (middle left), 15 minutes (middle right), 20 minutes (bottom left) and 24.5 minutes (bottom right) after flushing began.

In the second example (Figure 4), the dye slowly dispersed from the cage over a 2-3 hour period. The dye remaining in the cage seemed to remain distributed throughout the cage rather than form a narrow strip.

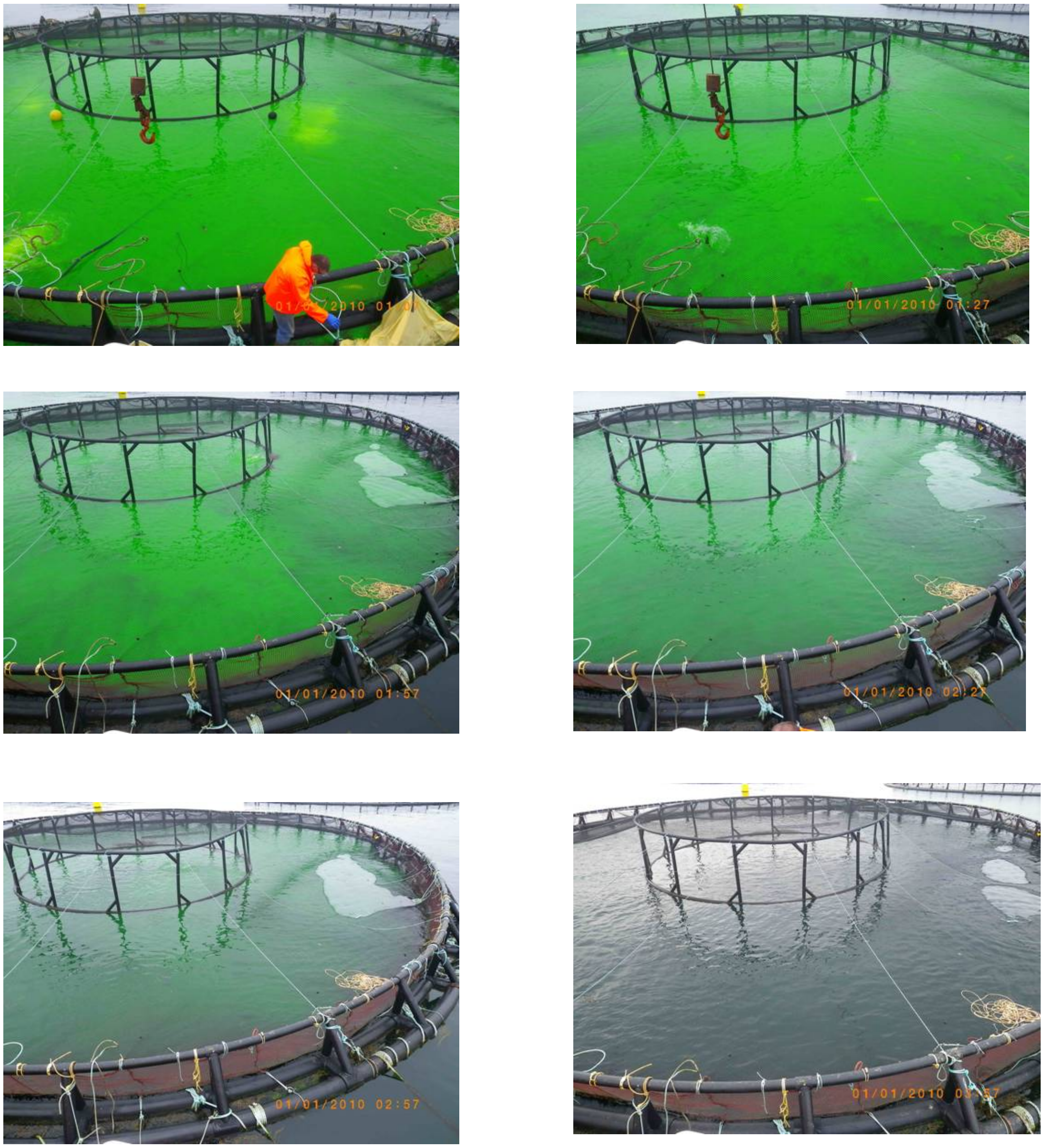


Figure 4: A second series of photographs showing the temporal evolution of dye, and hence therapeutant, flushing from a different tarped fish cage. The photographs were taken just prior to the beginning of flushing (top left), and 20 minutes (top right), 50 minutes (middle left), 80 minutes or 1.3 hours (middle right), 110 minutes or 1.8 hours (bottom left) and 170 minutes or 2.8 hours (bottom right) after flushing began.

Time series of dye concentrations recorded inside each quadrant of the cage are also consistent with the visual impressions (Figure 5). These time series were collected by Turner designs Cyclops 7 fluorescein fluorometers suspended inside the cage at a distance of 1-2 meters from the cage perimeter and at depths of about 1 m. The time series show the initial mixing of the dye throughout the tarp as well as the subsequent decrease in concentration after the tarp has been removed. The dye and therapeutant dosing began at about 14:34. The dye concentration in each quadrant increased until the upper threshold of the instruments was exceeded. A decrease in concentration was not detected until about 30 minutes after the tarps had been removed. This delay is assumed to be the time needed for the concentration to drop below the upper threshold of the fluorometers. The decrease in concentration continued until about 17:40, about 2.5 hours after the release of the tarpaulin. The release from this cage was influenced by heavy bio-fouling of the cage net.

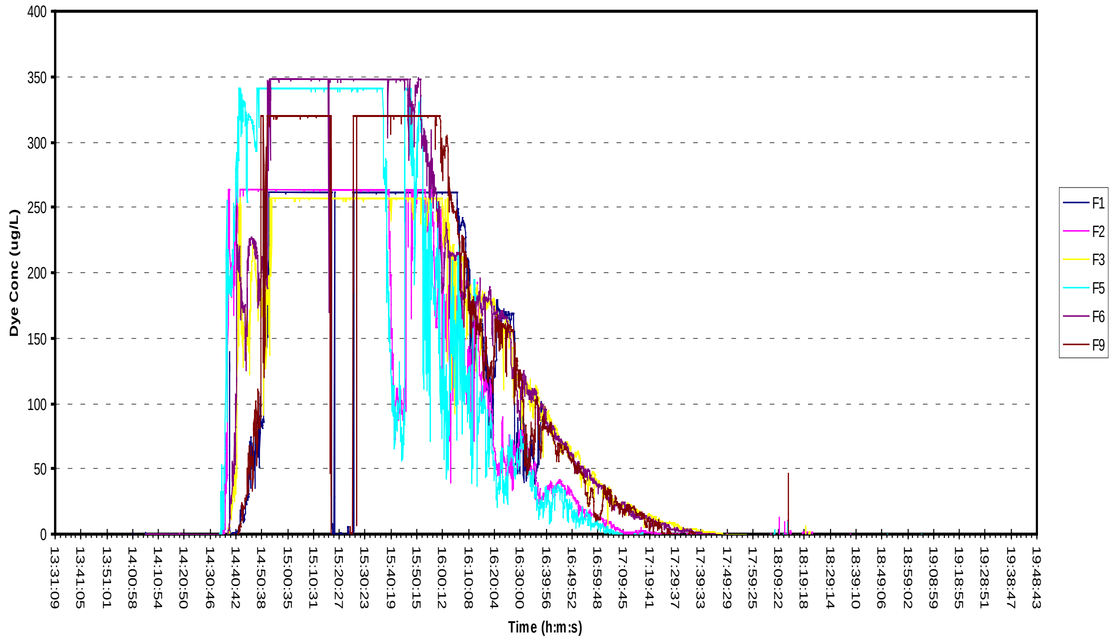


Figure 5: Time series of dye concentrations recorded by fluorometers (F1-F3, F5-F6 and F9) located inside the cage shown in Figure 4. The concentrations were recorded by Turner Designs Cyclops 7 fluorometers deployed in each of four quadrants within the cage and at a distance of a couple of meters from the cage perimeter. The flat lines in the middle of each time series indicate that the fluorometer measurement threshold was exceeded.

NET-PENS: DISPERSION OF THE RELEASED THERAPEUTANT

There is a considerable amount of literature that is useful to the dispersion component of the transport and dispersal of the therapeutant from the fish cages. A brief overview of the classical theoretical aspects of dispersal is given below since this provides analytical solutions to that are useful for developing understanding of the transport and dispersal process, and an order of magnitude sense of the dispersal and dilution rates. The theory is also the conceptual foundation of dispersal models, including the Scottish Environmental Protection Agency model for therapeutant dispersal from fish farms. The existing theory assumes the presence of fish cages, fish nets and farm infrastructure does not influence the dispersal and unfortunately this may not be a good assumption as indicated by the data presented here. However, since we are not aware of a more complete quantitative basis, the classical equations can still be of use in providing general insight into the dispersal process. This can then be used to help interpret observations, give order of magnitude estimates of dispersal processes and help identify the potential modifications resulting from influences of farm infrastructure.

The simplest form of dispersion solutions assumes that the material to be dispersed is instantaneously introduced into the dispersing environment, the rate of dispersal is constant over time and the rates of dispersal along orthogonal x, y, z Cartesian coordinates are independent of each other (Csanady 1973, Lewis 1997). This is called Fickian dispersion and in a horizontally and vertically unbounded situation an analytical solution for the case of a point source release has been reported by (Lewis 1997) as equation 1

$$c(x,y,z,t) = \frac{M}{(2\pi)^{3/2}\,\sigma_x\sigma_y\sigma_z} exp\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}+\frac{z^2}{\sigma_z^2}\right)\right] \quad 1$$

This solution is of limited use to the spread of therapeutant released from a cage since it assumes the initial release has all of the material (M) contained within an infinitely small volume, i.e., the concentration is infinitely large (Csanady 1973). However, it is the foundation of the Fickian dispersion perspective and more useful modifications of the solution have been developed.

A solution that assumes the material is initially distributed over some finite space has been given by (Lewis 1997) as equation 2

$$c(x,y,z,t) = \frac{M exp\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_{x0}^2+\sigma_{xt}^2}+\frac{y^2}{\sigma_{y0}^2+\sigma_{yt}^2}+\frac{z^2}{\sigma_{z0}^2+\sigma_{zt}^2}\right)\right]}{(2\pi)^{3/2}\,(\sigma_{x0}^2+\sigma_{xt}^2)^{1/2}\left(\sigma_{y0}^2+\sigma_{yt}^2\right)^{1/2}(\sigma_{z0}^2+\sigma_{zt}^2)^{1/2}} \quad 2$$

The initial dimensions are assumed to be a three dimensional Gaussian distribution with σ_{x0}, σ_{y0} and σ_{z0} being the standard deviations of the source distribution along their respective orthogonal Cartesian x, y and z coordinates. Values for these initial standard deviations can be estimated from the length scales (l_x, l_y, l_z) of the initial patch (Lewis 1997) as

$$\sigma_x = l_x/4$$
$$\sigma_y = l_y/4$$
$$\sigma_z = l_z/2$$

The σ_{xt}, σ_{yt} and σ_{zt} signify the subsequent increase in variance due to water turbulence. The solution for the concentration at the centre ($x = y = z = 0$) of this evolving patch is given by equation 3

$$c(0,0,0,t) = \frac{M}{(2\pi)^{3/2}\,(\sigma_{x0}^2+\sigma_{xt}^2)^{1/2}\left(\sigma_{y0}^2+\sigma_{yt}^2\right)^{1/2}(\sigma_{z0}^2+\sigma_{zt}^2)^{1/2}} \quad 3$$

This solution is still of limited use, since it continues to assume the patch is horizontally and vertically unbounded, which is not the case for aquaculture cages floating at the sea surface.

A more appropriate solution in which vertical diffusion is bounded by the sea surface and unbounded below the surface, is given by (Lewis 1997) for the case of a point release as equation 4

$$c(x,y,z,t) = \frac{M exp\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_{x0}^2+\sigma_{xt}^2}+\frac{y^2}{\sigma_{y0}^2+\sigma_{yt}^2}+\frac{z^2}{\sigma_{z0}^2+\sigma_{zt}^2}\right)\right]}{\sqrt{2}\pi^{3/2}(\sigma_{x0}^2+\sigma_{xt}^2)^{1/2}\left(\sigma_{y0}^2+\sigma_{yt}^2\right)^{1/2}(\sigma_{z0}^2+\sigma_{zt}^2)^{1/2}} \quad 4$$

for a finite sized initial patch. In the latter situation, the solution at the horizontal centre of the unadvected source ($x = 0, y = 0$) is equation 5

$$c(0,0,0,t) = \frac{M}{\sqrt{2}\pi^{3/2}(\sigma_{x0}^2 + \sigma_{xt}^2)^{1/2}\left(\sigma_{y0}^2 + \sigma_{yt}^2\right)^{1/2}(\sigma_{z0}^2 + \sigma_{zt}^2)^{1/2}} \quad 5$$

The solution changes again when the vertical dispersal is bounded by the seabed or the bottom of a surface mixed layer. When the therapeutant is considered to be vertically well-mixed it continues to disperse horizontally but not vertically and the appropriate solution for the dispersal is given by Lewis (1997) as equation 6

$$c(x,y,t) = \frac{M exp\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_{x0}^2 + \sigma_{xt}^2} + \frac{y^2}{\sigma_{y0}^2 + \sigma_{yt}^2}\right)\right]}{2\pi(\sigma_{x0}^2 + \sigma_{xt}^2)^{1/2}\left(\sigma_{y0}^2 + \sigma_{yt}^2\right)^{1/2} h} \quad 6$$

In this case the temporal reduction in concentration at the centre of the patch ($x = 0, y = 0$) is given by equation 7

$$c(0,0,t) = \frac{M}{2\pi(\sigma_{x0}^2 + \sigma_{xt}^2)^{1/2}\left(\sigma_{y0}^2 + \sigma_{yt}^2\right)^{1/2} h} \quad 7$$

In all of the above solutions, advection of the patch away from its point of release can be incorporated by replacing x with $x_o + ut$, y with $y_o + vt$ and z with $z_o + wt$, where u, v and w are the water velocities along the x, y and z axes of the Cartesian coordinate system.

Continuous Release into the Environment

All of the above solutions assume the removal of the tarpaulin is fast, i.e., a few minutes, and that the therapeutant disperses as though the net was no longer present. However, as illustrated above, the presence of the cage nets sometimes causes the therapeutant to escape from the net-pen over time. In these situations the therapeutant is continuously released into the receiving waters over a finite duration of time, rather than in one instantaneous dump. During this type of release the concentration at the source decreases with time.

An approximate solution for the horizontally and vertically unbounded dispersion of material released at a continuous and constant rate (Q) into ambient water with a spatially homogeneous flow field moving in a single direction, x, with a velocity u_0, has been given by Lewis (1997) as

$$c(y,z,t) = \frac{Q}{2\pi u_0 \sigma_y \sigma_z} exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right)\right] \quad 8$$

In this solution mixing along the direction of flow (x) is assumed to be small relative to the advection and hence it is ignored. When the solution is assumed to have an initial discharge size of σ_{y0}, σ_{z0}, and unit length in the x direction, the solution is equation 9

$$c(y,z,t) = \frac{Q exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_{y0}^2 + \sigma_{yt}^2} + \frac{z^2}{\sigma_{z0}^2 + \sigma_{zt}^2}\right)\right]}{2\pi u_0 \left(\sigma_{y0}^2 + \sigma_{yt}^2\right)^{1/2}(\sigma_{z0}^2 + \sigma_{zt}^2)^{1/2}} \quad 9$$

The above solution is of limited value to the bath treatment situation since it assumes dispersal of the material is spatially unbounded. As in the case of an instantaneous release, the solution can be modified to account for the presence of the sea surface and hence only horizontal and downward mixing. This solution is given by Lewis (1997) as equation 10

$$c(y,z,t) = \frac{Q}{\pi u_0 \sigma_{yt} \sigma_{zt}} exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_{yt}^2} + \frac{z^2}{\sigma_{zt}^2}\right)\right] \qquad 10$$

and equation 11

$$c(y,z,t) = \frac{Q exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_{y0}^2 + \sigma_{yt}^2} + \frac{z^2}{\sigma_{z0}^2 + \sigma_{zt}^2}\right)\right]}{\pi u_0 \left(\sigma_{y0}^2 + \sigma_{yt}^2\right)^{1/2} (\sigma_{z0}^2 + \sigma_{zt}^2)^{1/2}} \qquad 11$$

when a finite sized initial release is assumed.

When it is further assumed that the rate of vertical mixing is sufficient to maintain a vertically homogenous distribution of the material over a surface layer of constant depth h, the solution becomes equation 12 (Lewis 1997)

$$c(y,t) = \frac{Q}{(2\pi)^{1/2} u_0 h \sigma_{yt}} exp\left(-\frac{1}{2}\frac{y^2}{\sigma_{yt}^2}\right) \qquad 12$$

where u_0 is now the depth average velocity within the surface layer. A solution when the discharge has an initial size in the y direction is equation 13

$$c(y,t) = \frac{Q}{(2\pi)^{1/2} u_0 h \left(\sigma_{y0}^2 + \sigma_{yt}^2\right)^{1/2}} exp\left(-\frac{1}{2}\frac{y^2}{\left(\sigma_{y0}^2 + \sigma_{yt}^2\right)}\right) \qquad 13$$

These equations indicate that as the rate of flow in the receiving water increases, the concentration in the resulting plume of material decreases. This suggests that therapeutants slowly released from tarpaulins will have lower concentrations at any particular time and relative location than when the therapeutant is suddenly released. It also suggests that exposure time to the therapeutant at a particular location may be extended relative to the instantaneous release.

Rates of Eddy Diffusion

In all of the above, the standard deviations of dispersing patches are usually assumed to increase with time according to equation 14, which are the relationships provided by Csanady (1973) and Lewis (1997).

$$\sigma_{xt} = \sqrt{2K_x t}$$ 14

$$\sigma_{yt} = \sqrt{2K_y t}$$

$$\sigma_{zt} = \sqrt{2K_z t}$$

or

$$\sigma_{xt}^2 = 2K_x t$$ 15

$$\sigma_{yt}^2 = 2K_y t$$

$$\sigma_{zt}^2 = 2K_z t$$

In these equations K_x and K_y are the coefficients of horizontal eddy diffusivity along the horizontal x, y axes and K_z is the coefficient of vertical eddy diffusivity along the vertical, z axis.

Although it is convenient to assume the values of K_x and K_y are constant, it has been well documented that they actually increase with the scale of the patch, which in turn increases with time, so that K_x, and K_y are effectively functions of time (Okubo 1971, Okubo 1974, Lewis 1997, Bowden 1983). Okubo provides a relationship describing the rate of horizontal radial eddy diffusivity as a function of patch size. For patch length scales between 100 and 1000 m, the relationship is $K_{hr} = 7.56*10^{-5}\ l^{4/3}$ where $l = 3\sigma_{re}$ (Okubo 1974, Page et al. 2000), where K_{hr} is the effective rate of horizontal radial diffusivity and σ_{re} is the radial standard deviation of the patch at a given time.

VERTICAL MIXING

The depth to which the therapeutant is mixed depends on the vertical velocity of the water in the area of release, the density of the solution being released, and the rate of vertical mixing in the area of release. For the purposes described in this paper it is assumed that the density of the solution being released is the same as the ambient seawater and that there are no vertical water velocities of consequence. Under these assumptions the vertical distance travelled depends upon the rate of vertical eddy diffusivity and the amount of time needed for a solution to vertically mix throughout a depth of h is estimated as $t_v = 0.32h^2/K_z$ where t_v is the vertical mixing time scale (Lewis 1997). At this time the vertical standard deviation is approximately equal to $\sigma_z \approx 0.8$ h (Lewis 1997).

Assuming a typical rate of vertical eddy diffusivity for vertically well-mixed conditions, i.e., K_z equal to 0.01 m^2/s (Lewis 1997), and a range of water depths, the time required to mix vertically ranges from 0.9 to 32 h (Table 3). Fish farms in the Bay of Fundy are typically in waters with a depth of about 20-30 m, so the time scale for the therapeutant to become vertically well mixed is 1-8 h. However, if it is assumed that the mixing rates may be an order of magnitude stronger due to winds on a particular day or due to strong tidal currents, such as those that exist in some areas of the Bay of Fundy, the time to mix vertically to a depth of 30 m or less may be reduced to less than one hour (Table 3). In either case, the implication is that there is potential for organisms living on the seabed to be exposed to therapeutants that persist in the water for time periods of minutes to hours.

Table 3: Estimated order of magnitude time scales for vertical mixing over a range of depths when K_z has values of 0.01 m^2/s and 0.1 m^2/s.

Water Depth or Depth of Mixed Layer (m)	**Time Scale (h) to become well mixed over the Depth range when K_z=0 0.01 m^2/s**	**Time Scale (h) to become well mixed over the Depth range when K_z=0.1 m^2/s**
10	1	0.1 (5 min)
20	4	0.4 (21 min)
30	8	0.8 (48 min)
40	14	1.4 (85 min)
50	22	2.2 (133 min)
60	32	3.2 (192 min)

Vertical dye distribution measurements taken as part of the dye release studies being actively conducted in southwest New Brunswick support these general indications (Figure 6). The dye in these experiments was released as part of commercial bath tarp treatments and was initially confined to the upper few meters of the water column. The data indicate that in one case the dye did not get mixed below 2-3 m and in the other case the dye was mixed to between 5 and 10 m within the first hour after the release. In other cases, the dye was observed to be mixed to depths of 15 m or more, and vertically mixed to the sea bottom at a depth of approximately 20 m within an hour of therapeutant release.

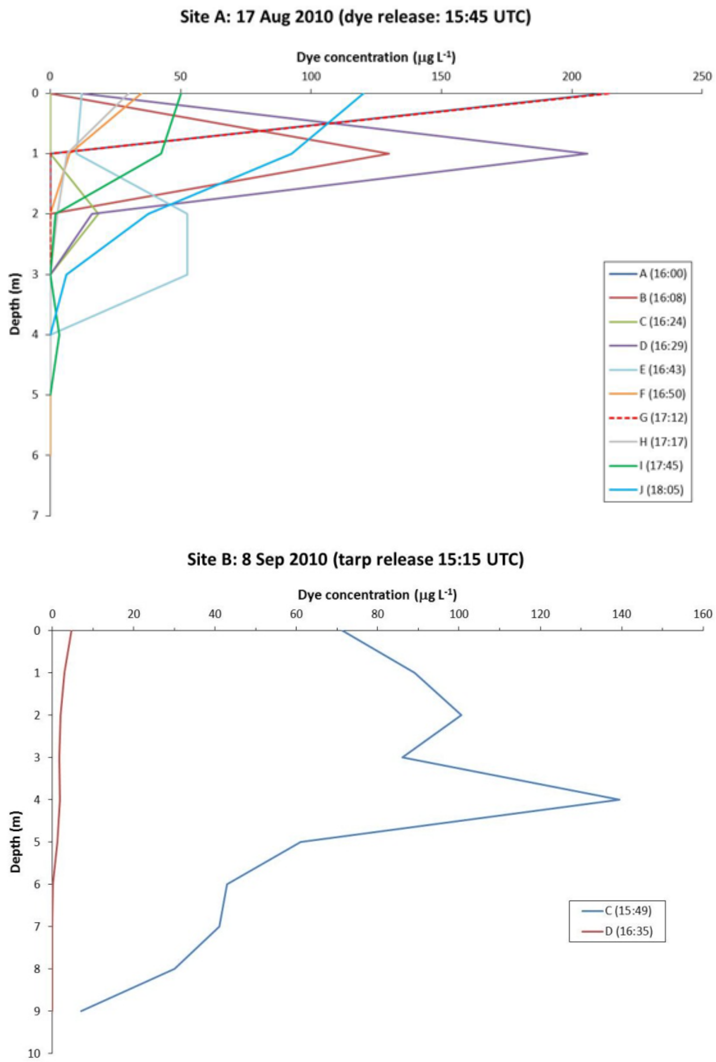


Figure 6. Vertical profiles of dye concentration taken within dye patches during September 8, 2010. The lines represent averages of two fluorometers deployed simultaneously at the same location. The lower concentrations near the surface are believed to be artificially low due to the influence of sunlight.

The above assumes that there is no farm infrastructure in the path of the effluent plume and hence only considers the effects of vertical diffusivity. However, when the bath treatment is first released from the treated net-pen, the resulting effluent plume may encounter adjacent net-pens during its advection away from the treated net-pen. In many cases the plume will flow through a portion of the farm and hence the vertical and horizontal path may be affected by the net-pens it encounters. When the effluent plume encounters an adjacent net-pen, some of the plume will enter the obstructing net-pen but most of the plume will be diverted around and/or under the net-pen. The specifics of this effect will vary with the water velocity and the porosity of the obstructing net-pen. At low water velocities the effects are expected to be minimal, but as velocities increase the effects are expected to increase. The magnitude of the effects are also expected to vary with the mesh size and degree of net bio-fouling since the porosity of the obstructing net-pen will decrease as mesh size decreases and bio-fouling increases. This will correspond with increasing deflections of the flow. Although unpublished flume tank studies (Page and Losier, pers. comm.) coupled with the visual observations of the behaviour of the dye plumes during the dye release studies reported on in this paper suggest that these effects can exist (see Figure 10 for an example of the potential horizontal effect), the magnitude of these effects is not well understood. Nevertheless, in some farm treatment situations there may be the potential for the farm infrastructure to cause the plume to advect vertically at a rate faster than expected by diffusivity alone. For farms located in water depths that are not much greater than the depth of the net-pen, the potential for the benthic substrate near the farm to be exposed to the treatment plume may be under-estimated by vertical diffusivity considers alone.

DILUTION AND DISPERSAL OF THERAPEUTANT

The dilution of released pesticide effluent is determined by the ambient mixing rates within the ambient water and in the absence of chemical behaviour specific to pesticide such as decay or binding to suspended organics or sediments, mixing is the sole determinant of the dilution rate. (Advection does not directly influence dilution.) To illustrate the magnitude of the temporal reduction in the concentration of therapeutant released from the fish cages a time series of predicted normalized concentrations for the situation of a therapeutant treatment in a 100 m circular cage situated in an environment with a shallow mixed layer ($h = 5\ m$) is shown in Figure 7. The figure contains two curves, one representing predictions from the above Fickian solution and the other representing a dilution derived from Okubo's (1974) variance relationship. Although the rates of horizontal eddy dispersion vary by an order of magnitude or more (e.g., Lewis 1997), the rates chosen for the Fickian prediction ($K_x = K_y$ = 0.1 m^2/s) were selected so that they were consistent with literature values and provided a dilution rate similar to the Okubo-based dilution. The local rates of dispersion have not yet been estimated from the data, but the observed sizes of dispersing patches to the Okubo predictions have been compared (see below).

The Fickian and Okubo approaches showed similar results for about the first hour, but the Fickian approach underestimated the Okubo dilutions after that. This is consistent with the Fickian approach assuming that rates of eddy mixing remain constant over space and time whereas the Okubo approach assumes the eddy mixing rate increases with time. The predicted dilutions are also consistent with the results of Ernst et al. (2001) and the patch scales observed in recent dye experiments (see below). The comparisons will become more rigorous as more data are collected and analysed and the modeling matures. In general it appears that average concentrations of therapeutants can be expected to be diluted by an order of magnitude, i.e., a factor of ten, within the first hour, and by a factor of 10 to 100 within three hours (Figure 7) after release. It should also be acknowledged that this dilution rate is likely to be quite variable between treatments. A better appreciation and quantification of the level of variability will hopefully be developed as more data are collected and analysed.

The Okubo dilution relationship was derived from Okubo's (1971, 1974) relationship describing the variance in patch size as a function of the cube of time ($\sigma^2 \propto t^3$). For patch sizes characterized by length scales of between about 100 and 1000 m, the equivalent radial variance in the patch size increases with time according to the specific relationship $\sigma^2_{re} = 2.5 \cdot 10^{-5} t^3$ and for patch length scales greater than about 1 km, the variance increases according to $\sigma^2_{re} = 5.4 \cdot 10^5 t^3$ Okubo (1971, 1974). In these relationships σ^2_{re} is the size of the patch in terms of the equivalent radius of the patch or the radius that gives an area equivalent to that of the observed patch. Okubo defined the variance of this equivalent patch size as $\sigma^2_{re} = 2\ \sigma_x \sigma_y$, where σ_x and σ_y are the standard deviations of the concentration weighted distances along the major and minor axes of a patch.

The approximate dilution rate of the average concentration ($\overline{C}(t)$) within a patch of therapeutant released from a fish cage can be estimated as the mass (M) of added therapeutant divided by the volume (V) of water it has been mixed into, i.e., $\overline{C}(t) = M / V(t)$. The volume of water can be estimated as the horizontal area ($A(t)$) over which the therapeutant patch is spread times the vertical thickness of the layer ($h(t)$) over which it is spread, i.e., $V(t) = A(t)h(t)$. The area of the patch at the time of release ($t=0$) is given by equation 16

$$A = \pi\, d^2/4 = \pi\,(3\sigma_{rc})^2/4 = 9\pi\,\sigma_{rc}^2/4 \qquad 16$$

where the diameter of the cage is defined $d=3\sigma_{rc}$, σ_{rc} is the standard deviation length scale for the cage, and $h(t)$ is specified from local knowledge or estimated from the rate of vertical eddy diffusion. The variance at $t=0$ is therefore given by $\sigma^2_{re} = 4A/9\pi$, the standard deviation of the initial patch is given by $\sigma_{re} = \sqrt{(4A/9\pi)}$, $\sigma^2_{re} = d^2/3^2$ and $\sigma_{re} = d/3$. In the Okubo relationship, the time at which $\sigma^2_{re} = d^2/3^2$ is given by $\sigma^2_{re} = d^2/3^2 = 2*10^{-5}t^3$ which rearranged gives equation 17

$$t_0 = \sqrt[3]{\sigma_{rc}^2/2.5\cdot 10^{-5}} = \sqrt[3]{\pi d^2/3^2\cdot 2.5\cdot 10^{-5}} \qquad 17$$

In this equation d has units of centimeters and t_0 has units of seconds. The variance of the patch at times subsequent to t_0 are therefore given by $\sigma^2_{re} = 2.5\cdot 10^{-5}(t_0+\Delta t)^3$, where Δt is the time in seconds elapsed after release. The average concentration of therapeutant therefore decreases in time according to equation 18

$$\bar{C}(t) = \frac{M}{V} = \frac{M}{Ah} = \frac{M}{\pi(d/2)^2h} = \frac{4M}{\pi\cdot(3\sigma_{re})^2h} = \frac{4M}{9\pi\cdot 2.5\cdot 10^{-5}(t_0+\Delta t)^3h} \qquad 18$$

This is the relationship shown in Figure 7 and the basis of the temporal increase in the dilution factors summarized in Table 4.

In the case of Fickian diffusion the average concentration of therapeutant is given by equation 19 in which σ_{xt} and σ_{yt} are defined by equation 14, and $\sigma^2_{re} = 2\,\sigma_x\sigma_y$ (Okubo 1971).

$$\bar{C}(t) = \frac{M}{V} = \frac{M}{Ah} = \frac{M}{\pi(d/2)^2h} = \frac{4M}{\pi 2\sigma_{xt}\sigma_{yt}h} \qquad 19$$

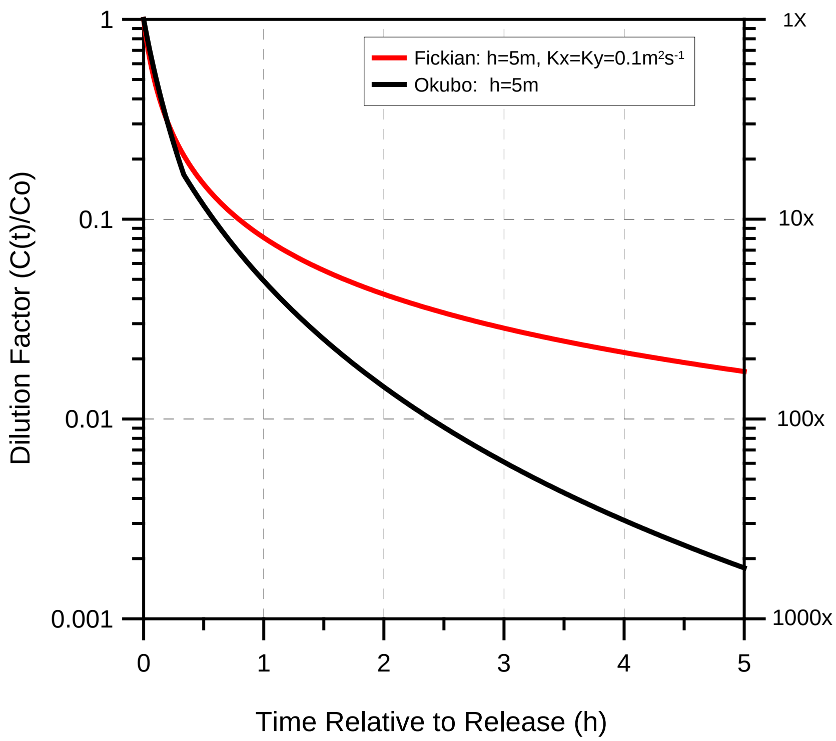


Figure 7: Model estimate of the temporal decrease in standardized concentration (C(t)/C(t=0)) of a released patch. The Okubo dilution (equation 18) assumes an Okubo increase in the horizontal size of the patch and a patch depth that remains at a constant depth of 5 m. The Fickian solution (equation 19) assumes a constant depth of 5 m and values of $K_x = K_y = 0.1\ m^2/s$.

Table 4: A summary of estimated dilution factors at intervals of time after dye/pesticide release into the ambient environment. The dilution factors are estimated from the Okubo based curve shown in Figure 7. They are meant to be an order of magnitude guide only, due to the variety of factors influencing the applicability of the model estimates.

Time (h) after Release	Dilution Factor [C(t)/C(0)]
0	0
0.5	1-10
1	10+
2	10-100
3	100-1000
5+	~1000+

These general considerations appear, at least so far, to be consistent with the observations we have been collecting from the southwest New Brunswick area. Although much of the data are still being processed and analyzed, the patterns observed during two of the releases serve to demonstrate the main points.

A dye release study was undertaken at a fallowed farm which had no cages or fish on site. As the dye moved away from the release point the shape and size of the dye patch evolved. The outline or perimeter of the dye patch was estimated by tracing the visible edge of the patch with a small boat and recording the position of the boat at 10 second intervals with a hand held GPS unit. The patch outline at several time intervals is shown in the upper panel of Figure 8. The patch shape became roughly elliptic with the long axis being in the direction of the mean flow. The patch eventually intersected the intertidal zone about 2 hours after release. The length of the major and minor axes of the patch at various times was estimated from the patch outlines. The patch dimensions were also checked with fluorometry transects run through the patch using fluorometers towed at 1-2 m below the surface. The faster increase in the length of the major axis of the patch relative to that of the minor axis (Figure 9 upper panel) is consistent with shear dispersion. The vertical distribution of the dye was also measured at various times during the evolution of the patch. These data indicate that the patch remained for the most part in the upper 5 meters (Figure 6 upper panel). A comparison of the temporal increase in the observed patch size, σ^2_{re}, with the Okubo predicted patch size shows a good agreement (Figure 10 upper panel).

A subsequent dye-release study was conducted during a commercial therapeutant bath treatment of a net-pen containing about 17,000 fish. As the dye moved out of the treatment cage the shape and size of the dye patch evolved (Figure 8 lower panel). The dye originated in one cage and gradually moved through other cages on the site before being advected away from the site. As in the release described above, the patch shape became elliptic with the long axis being in the direction of the mean flow. The faster increase in the length of the major axis of the patch relative to that of the minor axis (Figure 9 lower panel) is consistent with shear dispersion. The vertical distribution of the dye was also measured during the evolution of the patch. The data indicate that the patch remained for the most part in the upper 8 meters (Figure 6 lower panel).

A comparison of the temporal increase in the observed patch size with the Okubo predicted patch size (σ^2_{re}) can be made by calculating the surface area within the observed ellipse and calculating an Okubo length scale (σ_{re}) assuming a circle with an equivalent area. When this is done, the rate of increase in the observed size is consistent with the Okubo predictions but the observed patch sizes are sometimes larger than the predicted sizes (Figure 10 lower panel). This initial enhancement to the increase in patch size may be associated with the plume needing to go around one or more of the other net-pens within the farm being treated during its journey away from the farm. Once the plume has drifted away from the farm infrastructure, this no longer has an effect. The magnitude of this effect seems to be variable and may be related to factors such as mesh size, net-pen size and shape as well as the degree of bio-fouling on the net-pen mesh.

The above results, although still preliminary, suggest that the dispersal of therapeutants from fish cages is consistent with the existing theories with the amendment that the presence of farm cages and infrastructure seems to cause an initial rate of increase in patch size that is greater than expected from unobstructed ambient physical processes. However, once a therapeutant patch moves away from the release site the dispersion seems to follow the expected pattern.

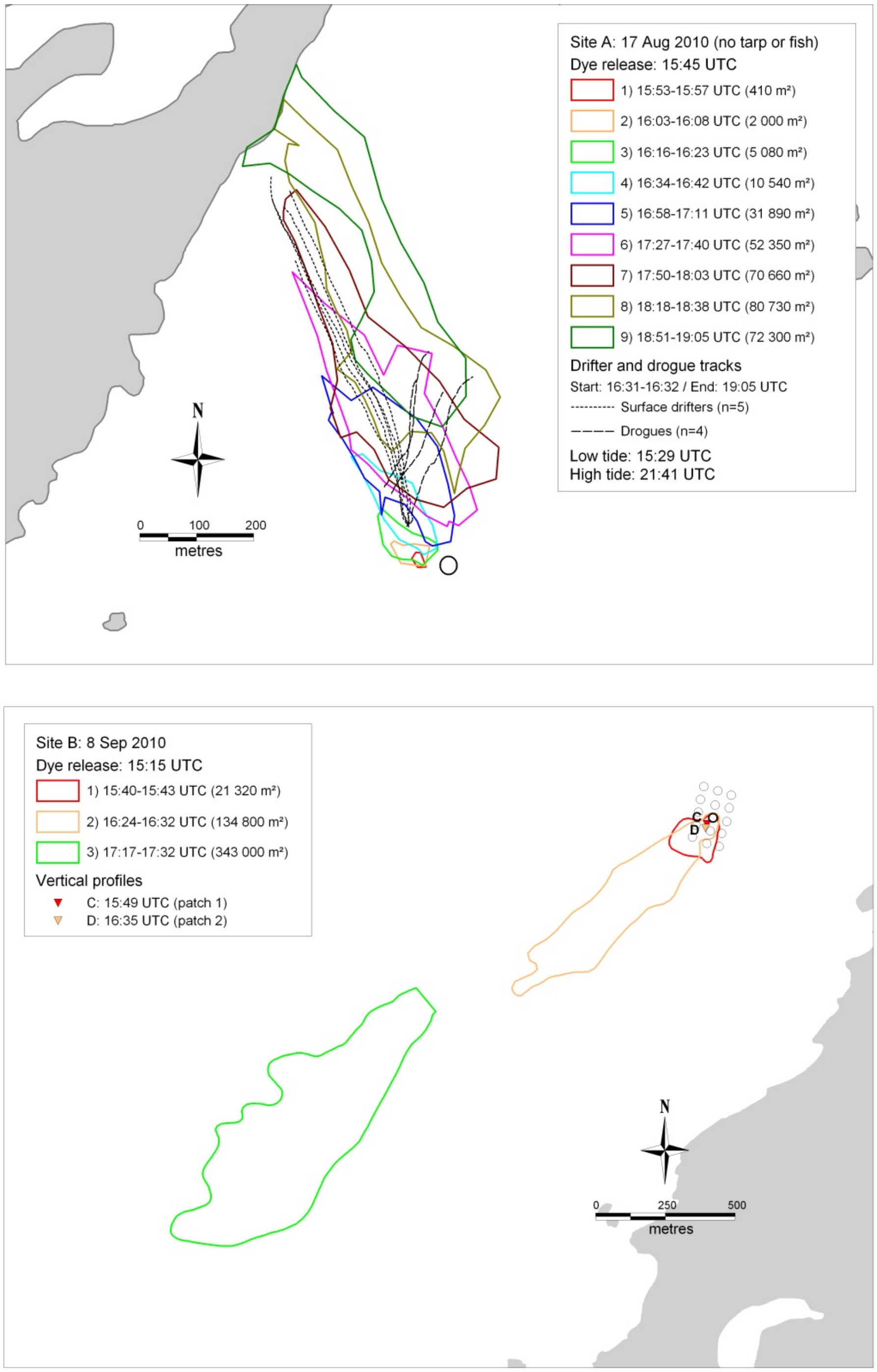


Figure 8. Dye patch outlines for a dye trial on 17 August 2010 (top panel) and on 8 September 2010 (lower panel). The top figure also shows the trajectories of surface drifters and drogues released in the patch near the beginning of the trial.

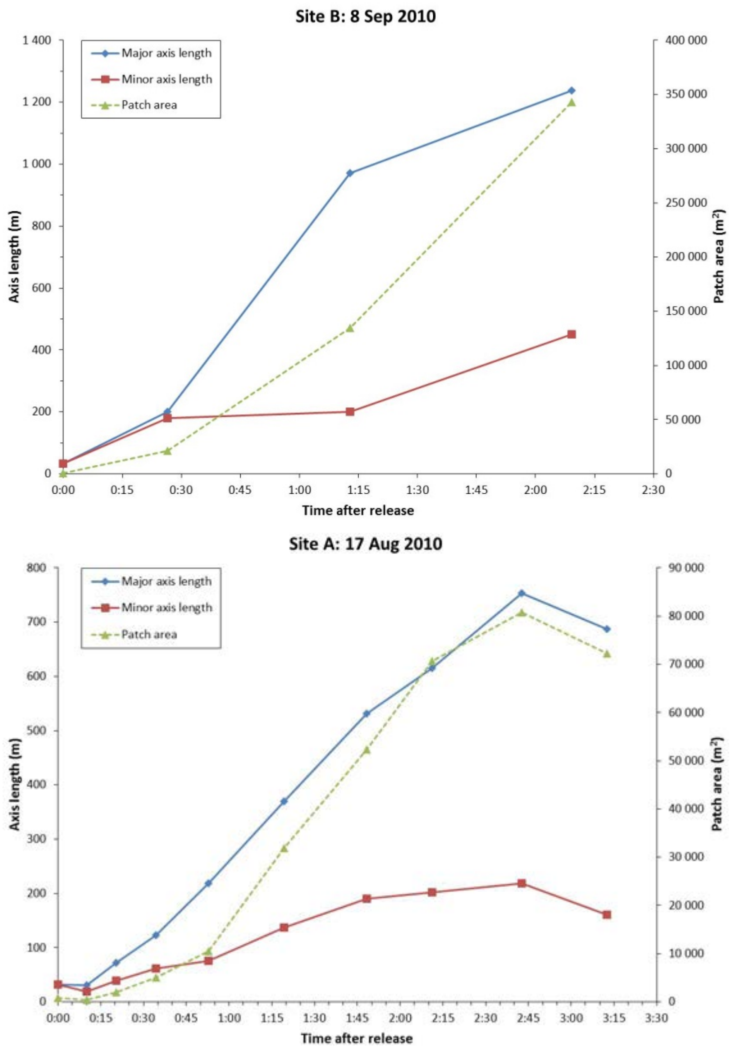
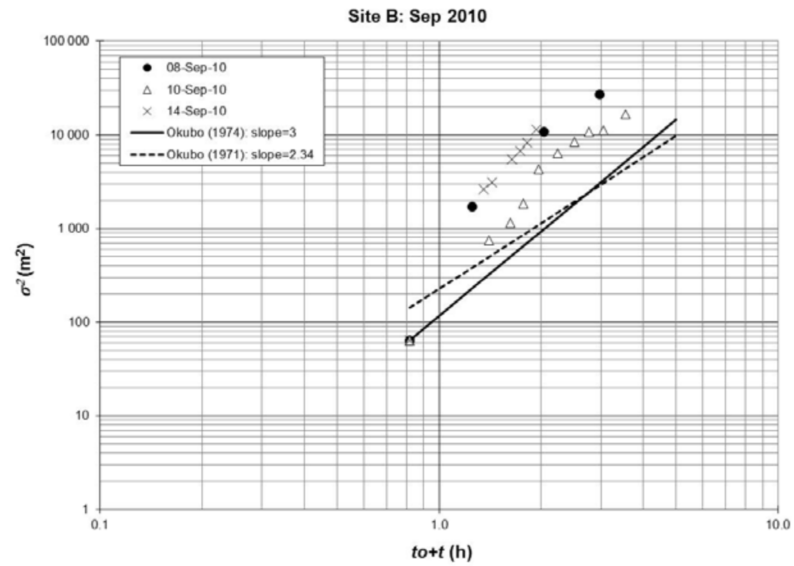


Figure 9. Time trends in the size of the dye patch observed during 17 August 2010 (top panel) and 8 September 2010 (lower panel) dye release trials. The patch sizes are indicated by their area and the lengths of the major and minor axes.



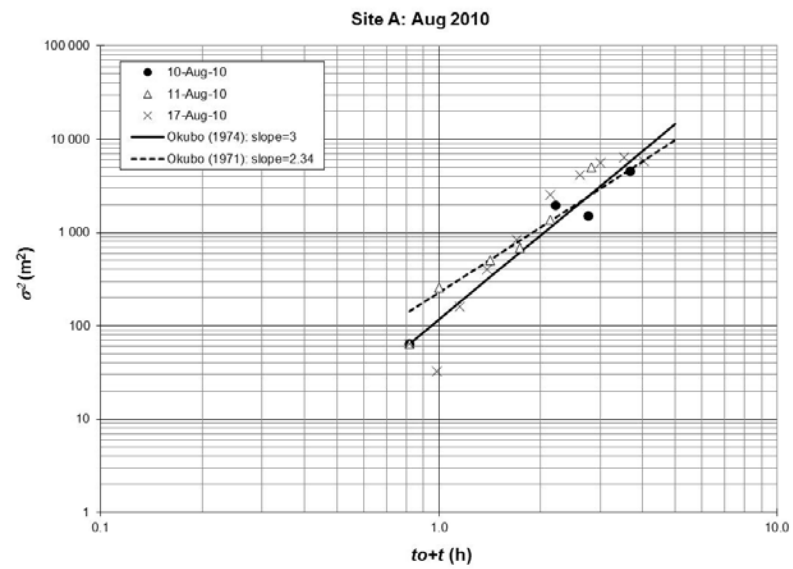


Figure 10: A comparison of patch sizes observed during dye releases with sizes predicted by the Okubo relationships (Equation 18). The releases conducted in August 2010 were from a farm site without cages and those conducted in September 2010 were from a fully stocked site.

HORIZONTAL DISTANCE TRAVELLED

The horizontal distance travelled by a patch or plume affects where and when the patch is likely to encounter non-target organisms; it does not affect the dilution of the released pesticide. The distance travelled can be estimated as speed times time. Tidal current speeds in the southwest New Brunswick area vary with the phase of the tide. In the vicinity of fish farms, the current speeds typically range from 0 to 0.5 m/s (equivalent to one knot). However, in a few locations current speeds may at times be on the order of 1.0 m/s (equivalent to 2 knots). Therapeutant treatments are usually not conducted at times of strong current since the current makes it difficult to deploy the tarpaulin and to keep the tarpaulin from bagging and trapping the fish in a small volume of water. Hence, most tarp treatments are conducted near slack tide when the currents are of order 0.1 m/s.

Table 5 shows some distance values for a range of constant speeds and times. The range of currents results in travel distances of 0 to 3.6 km for a drift period of one hour and 0 to 11 km for a three hour drift period. Since current speeds do not remain constant over time and space, the above distances may overestimate the potential distances that therapeutant patches will travel. The centre of mass of patches of dye released from fish farms in southwest New Brunswick shows that patches move a few hundred metres during the first hour after release and several hundred meters to over a thousand meters (> a kilometre) after two hours (Figure 11). This rate of advection is consistent with a constant current speed of approximately 0.1 m/s (Figure 12). The variation in the observed distances travelled over the longer time periods is due to variations in the ambient currents, including an increase in the tidal current speed after the treatments were conducted. The estimates discussed above suggest that concentrations of therapeutants at these distances are likely to be 1 to 3 orders of magnitude less than the treatment target concentrations.

Table 5: Distance traveled over time durations of 1 and 3 h.

Water Current Speed (m/s)		**Distance Travelled (km)**	
(m/s)	(knots)	in 1h	in 3 h
0.0	0.0	0.0	0.0
0.1	0.2	0.4	1.1
0.2	0.4	0.7	2.2
0.3	0.6	1.1	3.2
0.4	0.8	1.4	4.3
0.5	1.0	1.8	5.4
0.6	1.2	2.2	6.5
1.0	2.0	3.6	10.8

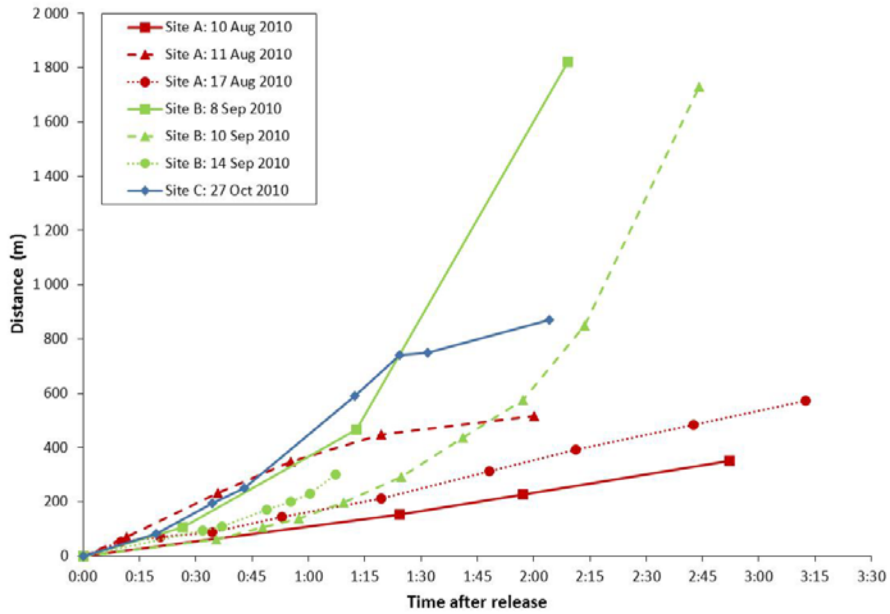


Figure 11. Distance of dye patch centre from the treatment cage vs. time after dye release.

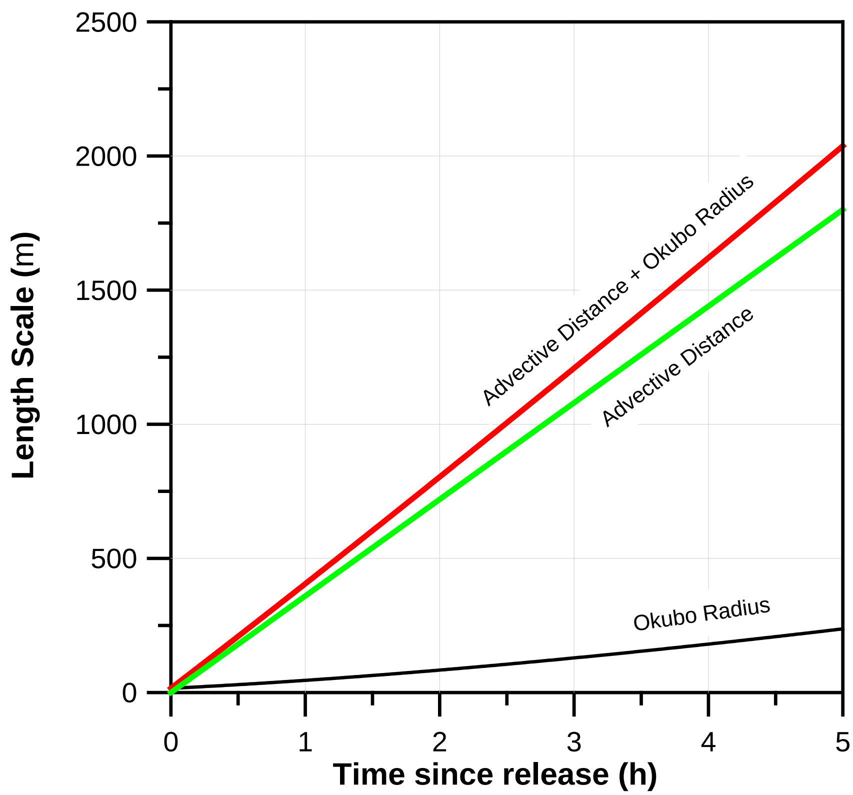


Figure 12. Estimated distance travelled by a dye patch (advective distance) and the size of the patch (radius) as a function of time. The distance travelled is estimated assuming a constant advective velocity of 0.1 m/s. The radius is given by the Okubo (1974) relationship assuming an initial patch radius of 16 m (Equation 18).

NET-PENS: SUMMARY

The above section presents a summary of the net-pen bath treatment process, a brief overview of classical analytical transport and dispersal models and a brief overview of the dye release work that has been conducted during the first year of a recent two year DFO research project. The work is still in progress and evolving, especially as industry practices and circumstances evolve.

The work presented above is not the first effort to work toward a better understanding and predictive capability for the transport and dispersal of pesticides used in fish farm bath treatments. However, it is perhaps the first to conduct dye release experiments in which the dye has been released from within actively treated net-pens within active farms.

From a modeling perspective, the most well-known work is that conducted by the Scottish Environmental Protection Agency (SEPA) and it is therefore worth contrasting the present effort to their pesticide modeling effort. As expected there are some similarities and differences between the two modeling approaches. Both modeling approaches are relatively simple and hence have the advantages and disadvantages inherent in simple models. The SEPA model was developed in the context of the Scottish physiographic situation and the present work is developed to deal with the physiography of southwest New Brunswick. In Scotland much of the fish farming occurs in straight and narrow fjords whereas in southwestern New Brunswick the farming occurs within a very complex coastal bathymetry and coastline. The Scottish situation lends itself to the development of their model which assumes Fickian dispersal and horizontal advection at a rate of the mean residual flow that is assumed to be parallel to the coastline. The SEPA approach was not adopted for application in southwest New Brunswick because the currents are tidally dominated and the complex bathymetry and coastline coupled with the tidally varying flow makes it hard to determine what the flow direction will be for any given release. However, there are similarities between the approach that was taken for application in southwest New Brunswick and the SEPA model. These similarities include: similar Fickian diffusivity rates, assuming instantaneous releases and no influence by farm infrastructure, and limiting the depth of dispersal to a specified depth. The depth in Scotland is usually determined by the depth of the relatively distinct near-surface mixed layer whereas in southwest New Brunswick there is no well-defined surface mixed layer so the depth has been chosen to be consistent with the observed depth distributions of dye. The SEPA modeling does not include an Okubo type approach. Work is underway to begin evaluating the use of a more complex three-dimensional numerical water circulation model for southwest New Brunswick with an associated particle tracking transport and dispersal numerical model to simulate the release plumes. This approach includes spatial variations in bathymetry and coastlines and predicts the spatial and temporal variation in the advective flow field as well as variations in the density field and effective horizontal and vertical diffusivities.

Finally, as alluded to throughout the above sections, many factors are recognized as influencing the transport, dispersal and dilution of the pesticides used in the net-pen bath treatments. Table 6 summarizes many of these along with indications of the assumptions, variations and/or uncertainties associated with the simple models considered here.

Table 6: Summary of influencing factors, model assumptions and uncertainties related to the transport, dispersal and dilution of pesticides released from tarp and skirt bath treatments.

Influencing Factor	Assumptions, Variations and Uncertainties
Shape, size and volume of the bath treatment	This information is needed to set the initial conditions for the calculation and modeling efforts. **Assumptions**: A cylindrical bath treatment shape has been assumed. The cyclinder is assumed to be representative of tarped circular net-pen with a circumference of 120 m and a tarp depth, i.e., the cyclinder height, of 5 m (unless otherwise specified). **Uncertainties**: The majority of net-pens in the southwest New Brunswick area are circular in shape. The actual bath volume varies with the treatment due to variations in the shape of the tarp and the depth to which the nets have been pursed. These factors are estimated to result in a two-fold variation in the estimated bath volume (Table 1) and the concentration of pesticide within the bath at the time of release.
Pesticide type	The type of pesticide varies and is based in part on considerations of efficacy and potential to damage the fish being treated. In southwest New Brunswick, the industry has used mainly Salmosan and some trials with Alphamax in tarp treatments. In the tarp treatments analyzed, Salmosan was the dominant pesticide used. Alphamax was used in one treatment. The type of pesticide determines the mass of pesticide added to the treatment volume, the degree of dilution needed to reduce the pesticide concentration to below acceptable toxicity concentrations and the behaviour of the pesticide in the ambient receiving environment (e.g., stability and persistence of the pesticide in the treatment and ambient environment, degree to which the pesticide dissolves in seawater and binds to suspended particulates, etc.). **Assumptions**: A generic pesticide that does not decay with time or deviate in behaviour from that of the dye. **Uncertainties**: The type of pesticide is known for a particular treatment.
Mass of pesticide added and pesticide treatment concentration	The mass of pesticide initially added is determined by the type of pesticide and its product label directions as well as considerations of efficacy and risk of damage to the host fish. Knowledge of the mass is needed to estimate the concentration of the pesticide at the time of release. **Assumptions**: Health Canada target concentrations and amounts are assumed for typical bath volumes. **Uncertainties**: Concentrations resulting from current treatment procedures are considered to vary by plus or minus about 20% (M. Beattie, pers. comm.). The mass of pesticide added is guided by the product label instructions and varies to some unknown degree due to factors such as how the pesticide is packaged, whether the pesticide dose is fully dissolved in the mixing container before being introduced into the treatment volume, the estimated bath volume, water temperature, health status of the fish being treated, judgment of the overseeing veterinarian, procedures of the applicator and in the case of powdered pesticides the degree to which the pesticide has been dissolved into solution before being injected into the bath water.

Influencing Factor	Assumptions, Variations and Uncertainties
Pesticide behaviour	Specific pesticides will have specific behaviours (decay rates, absorption to organics, etc.) and these have the potential to influence the transport, dispersal and dilution rate of the pesticide. **Assumption**: In the present work the pesticide is assumed to behave like the dye. **Uncertainties**: Little is known about the behaviour of the pesticides in the circumstances studied here. However, similarities in the preliminary data concerning observed dilution rates of dye and chemicals suggests that for the order of magnitude of transport and dispersal rates considered here, the assumption that a generic pesticide behaves like the dye is reasonable. Specific detailed studies that are beyond the scope of this study, will be needed to define the behaviour of each pesticide.
Duration of the treatment	The duration of the treatment influences the degree to which the pesticide has been mixed throughout the treatment volume. Information on this is not explicitly needed for the calculations and models used here since an initial concentration is prescribed. **Assumptions**: The duration is sufficient to achieve mixing of the pesticide throughout the bath treatment volume. To date typical treatment durations range from ~ 20-40 minutes. **Uncertainties**: Treatment durations vary in association with factors such as the pesticide being used, the health status of the fish and water temperature. In some cases the treatment may need to be prematurely terminated, although this only occurs in less than 5% of the treatments (M. Beattie, pers. comm.). One of the factors influencing the duration of a treatment is the concentration of dissolved oxygen in the bath waters. If the oxygen concentration within the treatment volume drops below the critical level determined by the attending treatment supervisor, the planned treatment duration may be cut short. Mixing during the short treatments may be incomplete.
Pesticide concentration at the time of release into the ambient/receiving environment	This is needed to define the initial state at the time of release. **Assumptions**: For purposes of mathematical convenience a homogeneous distribution is assumed for Okubo based calculations and a Guassian distribution is assumed for Fickian calculations at the time of release. The concentration is assumed to be the target treatment concentration. **Uncertainties**: The calculations presented here suggest the concentration may vary by a factor of two due to uncertainties associated with the shape of the tarped volume. It has also been suggested that some of the pesticide may be absorbed onto the fish, although the magnitude of this potential is not known to us and is assumed to be insignificant. The present observations also suggest that the pesticide may not be completely mixed throughout the treatment volume at the time of release, although if strong gradients in concentration do exist at the time of release they will be quickly mixed.

Influencing Factor	Assumptions, Variations and Uncertainties
Farm infrastructure	Farm infrastructure has the potential to influence the release rate of the pesticide as well as the transport and dispersal of the pesticides once they have been advected from the treatment net-pen, by providing a semi-permeable barrier to the pesticide plume causing the plume to advect around, through and perhaps under net-pens. The calculations and models do not explicitly require information on this factor (the SEPA model does not include farm infrastructure interactions). **Assumptions**: The farm infrastructure does not influence the flow. **Uncertainties**: The assumption is unlikely to be true but the exact influence is unknown. The influence is related to the amount of drag generated by the net mesh and the degree of influence will depend upon the shape of the net-pen (e.g., circular or square), the size of the net-pen (width and depth of nets), the spacing between net-pens (varies with the grid layout pattern), the size of mesh on the net-pens and its degree of bio-fouling as well as the current speed.
Temporal sequence and duration of the release of the pesticide into the receiving environment	This information is required in models as part of defining the source function for the release into the receiving environment (also required in SEPA modeling). **Assumptions**: The models assume the release is instantaneous. **Uncertainties**: This is a convenient first approximation and is seldom the actual case. The observations indicate that the release or flushing from the treatment cage occurs over a period of minutes to hours. This means the behaviour of the released pesticide is actually somewhat like that of a discharge that is continuous over a finite period of time and has a discharge concentration that decreases with time. The flushing rate is likely to be associated with the specifics of the farm infrastructure and the number of experiments conducted to date is too low to quantify the frequency distribution of flushing times. In general a more protracted release means the plume is likely to be larger in spatial extent and the concentration of pesticide within the plume is likely to be less concentrated than if it had been released over a short period of time. This means protracted releases may result in longer exposures for non-target organisms but at lower concentrations.
The increase in the horizontal scale of the pesticide patch is proportional to the Okubo relationship	This functional relationship is required for Okubo based calculations and models (the SEPA model does not require Okubo relationships). **Assumptions**: The Okubo (1971, 1974) relationships. **Uncertainties**: The Okubo (1971, 1974) relationships were developed from data gathered in locations distant from the shoreline and away from obstacles. Hence they do not include the effects that coastlines and farm infrastructures may have on dispersal rates. Although the data presented here are insufficient to accurately quantify the effects of farm infrastructure and site specific coastline and bathymetric effects on dispersal, they do suggest that the Okubo relationships may sometimes under-estimate the dispersal rate.

Influencing Factor	Assumptions, Variations and Uncertainties
Rate of horizontal mixing in the receiving environment	This information is the basis of dilution; no mixing means no dilution. Hence it is required by models other than those based on the Okubo relationship to estimate the increase in patch size and dilution. Rates of horizontal dispersion in the coastal environment vary over several orders of magnitude and rates along the major axis of the flow are generally larger (~10-100x) than those in the cross-flow direction. This results in patch and plume shapes being elliptical or stretched along the axis of the major flow. Typical horizontal rates range from 1 to 0.1 m^2/s and typical vertical rates are smaller by an order of magnitude or more (the SEPA model also requires this). This means that horizontal mixing dominates the dilution process. **Assumptions**: Typical rates of horizontal diffusivity were assumed (e.g., K_x=K_y=0.1 m^2/s) for Fickian dispersal and the diffusivities implied by the Okubo (1971, 1974) relationships describing the increase in patch size. **Uncertainties**: The literature indicates that horizontal mixing rates, i.e., horizontal diffusivity rates, can vary by an order of magnitude or more due to changes in tidal state, wind speed and direction, local baroclinic processes, local bathymetry and random conditions. Hence, the model-based estimations of dilution must be viewed accordingly, since they are meant to provide only an order of magnitude estimate of the dilution.
Rate of horizontal advection in the receiving ambient environment	This information is required in order to make estimates of the horizontal distances released patches are likely to travel during specified periods of time (the SEPA model also requires this). **Assumptions**: A typical value of 0.1 m/s is used for illustrative purposes since it gives transport distances consistent with the mid-range of what was observed (Figure 11). **Uncertainties**: The rate of horizontal advection in the coastal zone of southwest New Brunswick, also referred to as the speed of drift, can vary spatially and temporally from zero to over one m/s. The advective velocities are typically dominated by tidal currents, although wind driven currents are significant in some areas and at some times. The dominant tidal cycle is 12.4 h, hence the tidal currents at any given location vary on time scales of minutes to hours. Although the amplitudes and phases of the currents are somewhat site specific, the amplitudes at each location vary by about 30% on a fortnightly basis. The specific rate of advection for a given treatment therefore depends to a large extent on the phase of the tide and the wind speed and direction and the site location. Bath treatments are usually planned for time periods when the water currents are weakest, i.e., slack water. This means the advective velocities pesticide plumes experience are biased toward the lower portion of the current range (~0.1 m/s). However, some treatment releases will likely occur at higher current speeds (>0.1 m/s). The sensitivity of pesticide dispersal to this factor has not been formally investigated; however, the evidence to date (Figure 11) suggests the distances travelled after two hours can vary by about an order of magnitude.

Influencing Factor	Assumptions, Variations and Uncertainties
Vertical stratification and depth of mixing in the receiving ambient environment	This information is required for defining the depth distribution of the released pesticide (also required by SEPA model). In southwest New Brunswick the rate of vertical mixing is likely to vary over the tidal cycle in relation to variation in the tidal currents. **Assumptions**: In the model calculations presented here a surface mixed layer of about 5 m has generally been assumed (unless stated otherwise) since the majority of the dye seems to be found within this depth zone in most cases. **Uncertainties**: Vertical stratification in the coastal areas of southwest New Brunswick is generally not pronounced. In some areas and at some times, the density increases with depth in the upper 5-10 m by less than one sigma-t unit. In some unusual cases of high freshwater runoff there may be a strong pycnocline to a depth of less than 5 m. Although the vertical distribution of the dye and pesticide is not as well-known as the horizontal distribution, the variation in the vertical distribution over time is a factor of 2 or 3 whereas the variation in the horizontal is several orders of magnitude. Hence, estimates of pesticide dilution are dominated by horizontal spreading rather than vertical mixing. A doubling of the assumed depth results in a halving of the dye concentrations.
Interaction with the shoreline	The presence of a shoreline can influence the dispersal of a pesticide plume by restricting the horizontal and vertical dispersal processes. The potential for a plume to interact with the shoreline is site specific. For plumes of pesticides that are still toxic after a few hours of dilution, the length scale of the major axis of the plume is of the same magnitude or greater than the distances of southwest New Brunswick farms from shorelines (i.e., 100s -1000s of meters). Hence, there is potential for some shoreline interaction in this area. However, the realized potential for interaction is site and environmental condition specific. **Assumptions**: The existing models assume there is no interaction with the shoreline. The SEPA model assumes an idealized coastline that reflects the plume. **Uncertainties**: This assumption is not true for at least some farm sites. Interactions are expected based on the logic that the length scales of the plumes are of the same magnitude or greater than the distances of southwest New Brunswick farms from shorelines (i.e., 100s -1000s of meters) and on the empirical evidence. In the present set of tarp releases there was at least one release plume that interacted with the shoreline and in a previous set of releases at least one other plume contacted the shoreline (Ernst et al. 2001). The proportion of releases that might result in coastline interactions is unknown since this potential is site specific and depends upon the local water circulation at the time of the release.

Influencing Factor	Assumptions, Variations and Uncertainties
Interactions with the seabed	This information is not used explicitly in the calculations or models presented here. However, it is used in numerical circulation models (not discussed here) and in interpretation of the transport and dispersal results in the context of what habitats and organisms may be exposed to the released pesticide. **Assumptions:** The models used assume the pesticide is limited to a specified depth that is representative of what was observed in the dye concentrations. **Uncertainties**: Whether or not there is interaction between the plume of released pesticide and the seabed depends upon the rate of vertical mixing and the depth of the bottom in the treatment area. Many of the sites in southwest New Brunswick are located in areas within a few hundred meters of the shoreline and where the water depths are of order 20 m. The vertical profiles of dye examined to date indicate the dye remains for the most part in the upper 10 m, but in a few profiles from one site dye was detected near the bottom in water depths of about 15-20 m (data not shown). How prevalent interactions with the bottom will be depends upon the site specific situation.
Multiple Treatments	Multiple treatments are not explicitly considered in the calculations and models presented in this document. **Assumptions**: The modeling to date has assumed only one isolated treatment at a time. However, releases from multiple treatments can be treated as the summation, at specific points in space and time, of concentrations generated by individual releases. **Uncertainties**: It is often in the best interest of disease control to treat a farm as quickly as possible, hence several treatments a day may be conducted. Usually these treatments are conducted sequentially with about an hour between each treatment. However, in some cases the time between treatments may be less. The distance between the treatments may also vary depending upon the circumstances. Hence, release locations range from being spatially adjacent to being at opposite ends of the site. If the treatments occur during opposite phases of the tide, pesticide plumes will drift in opposite directions, whereas if the treatments occur on the same phase of the tide the pesticide plumes may overlap. The frequency and timing of treatments depends upon many factors including the weather, tidal currents, availability of equipment and staff as well as pesticide label limitations and the intensity of sea lice. The degree to which treatment plumes overlap depends upon the proximity of each treatment in time and space.

TRANSPORT AND DISPERSAL FROM WELL-BOATS

Well-boats operating within the southwest New Brunswick area of the Bay of Fundy are used to conduct therapeutant bath treatments for sea lice. There are three well-boats operating in southwest New Brunswick. Although the general principles of how each vessel is operated are similar, each vessel has some unique characteristics that influence the manner and rate in which therapeutants are mixed within the well and discharged into the environment.

Independent of the vessel, there are two fundamentally different flushing discharge scenarios; one in which the discharge is directed away from the side of the vessel and into ambient sea water (Figure 13, upper picture) and one in which the discharge is from the side of the ship adjacent to a fish cage (Figure 13, lower picture). The former discharge initially carries the therapeutant away from the well-boat and net-pens in a jet type flow and in most cases the near-field jet transitions into background type transport and dispersal. However, in certain circumstances the ambient flow field may carry the discharge back into the farm. In the latter discharge situation, the discharge jet is directed into and/or alongside the adjacent net-pen. Whether the majority of the discharge enters the adjacent net-pen or flows along the outside edge of the net-pen depends upon the position of the well-boat relative to the net-pen. This positioning varies slightly between and within treatments. The between treatment variation is associated with slight differences in the vessel mooring arrangement, whereas the within treatment variation arises from the pressure of the discharge jet causing the vessel to move relative to the net-pen. This latter dynamic seems to vary throughout the discharge period; the vessel initially moves in response to the discharge jet commencing and it moves again toward the end of the discharge as the jet flow reduces. Exploration and quantification of these latter dynamics and how they affect the transport and dispersal of the pesticides within the discharge jet are beyond the scope of the work being pursued here.

THE TREATMENT PROCESS

A typical well-boat bath treatment in southwest New Brunswick proceeds as follows. The well-boat fills its wells with ambient water while steaming to the fish farm site. Once at the site the vessel ties up to a net-pen and pumps the fish, previously pursed together and close to the vessel, into the wells. The water within the wells is continuously recirculated for as long as the fish are in the well by pumping water from one end of the well to the other. The fish are monitored visually through the well hatch and via real time underwater video cameras located at each end of the well. The concentrations of dissolved oxygen in the well are also continuously monitored by permanent sensors within the well and by hand held sensors lowered through the well's hatch. Oxygen is injected into the well if needed. Measurements of water temperature and salinity are also taken at the beginning of each treatment. The on-site fish health supervisor uses this information to help determine if the treatment should be undertaken, and if so what its duration should be. The choice of the concentration of the pesticide is guided by the Health Canada label for the pesticide being used.

At the beginning of each treatment the therapeutant is injected into one end of the well. This injection takes several minutes and it takes several more minutes for the therapeutant to become homogeneously mixed throughout the well. Once the desired treatment duration has occurred the water within the well is flushed from the well. This entails pumping water in and out of the well at equal rates so the volume of water within the well remains constant. The water pumped out of the well contains therapeutant while the water pumped into the well does not unless therapeutant from a previous treatment happens to be near the intake. The operational duration of the flushing is typically 15-25 minutes. Unlike the situation in Scotland or Norway, the vessel stays moored to the treatment cage during this process. This is to avoid the vessel having to travel significant distances (~1-10 km) in order to be able to discharge in an area away from fish farms. The discharge from one side of the vessel flows away from the cages and that from the other side flows toward and into the cages (Figure 13). In both cases the subsequent transport and dispersal is controlled by the ambient environmental conditions, with the dispersal in the latter situation being highly influenced by the presence of the farm infrastructure. Once the wells have been flushed, the fish are pumped back into an adjacent fish cage. Any residual therapeutant in the well water is discharged into the environment at this time.

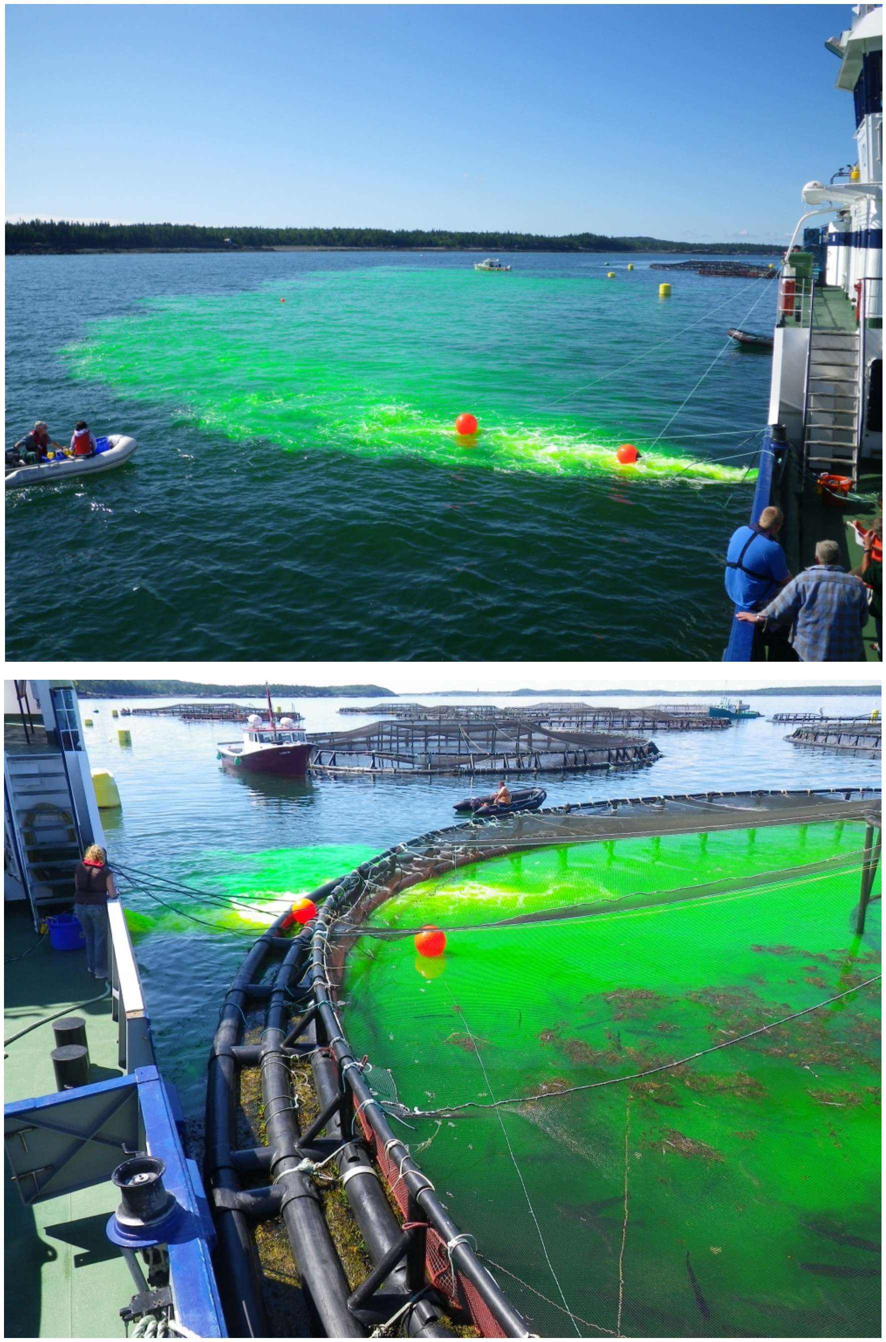


Figure 13: Photographs of a flushing discharge directed away from the net-pens (top photo) and one directed into a net-pen (bottom photo).

The volume of the treatment well and the biomass of fish to be treated determine the number of treatments that are required in order to treat all of the fish within a net-pen. Typically a well-boat treatment will require about four wells to treat the number of fish in a fully stocked net-pen. This therefore results in multiple consecutive treatments for a single net-pen, which may result in overlapping discharge patches. The volume of a single treatment well in southwest New Brunswick is 330 m^3 meaning the volume of water needed to conduct four treatments is about 1320 m^3. The estimated volume of a 100-m tarped net-pen ranges between 3100 m^3 –

6000 m^3. Hence, the well-boat treatment uses a smaller overall volume of water than the tarp treatments and assuming the same concentration of pesticide is used in both approaches, the total mass of pesticide used in a well-boat treatment is considerably less than that used in a tarp treatment.

INITIAL THERAPEUTANT DISTRIBUTION WITHIN THE WELL

An analysis of the transport and dispersal of therapeutant released into the environment as a result of well-boat bath treatments must first consider the concentration of the therapeutant within the well at the time of flushing. As described above, the concentration is not constant over time. Initially there is no therapeutant in the well and the concentration is zero. Once the therapeutant is injected into the well, the concentration varies in time and space within the well until it is homogeneously mixed. The well mixed concentration (C_0) can be estimated as the mass of therapeutant (M) divided by the volume (V) of the well (i.e., M/V).

Once flushing of the well begins the therapeutant concentration within the well decreases with time until the flushing is stopped or the therapeutant is completely flushed from the well. This decrease can be approximated by equation 20.

$$C = C_0 exp\left(-\frac{Qt}{V}\right) \qquad 20$$

In this equation Q is the rate at which water is pumped into and out of the well (Vesilind et al. 2010). The ratio V/Q is the e-folding time scale (t_{flush}) or the time needed for 63% of the therapeutant in the well to be flushed from the well. Eighty–six percent of the therapeutant is flushed in $2t_{flush}$ and 95% is flushed in $3t_{flush}$. The equation assumes the pesticide is always instantaneously well-mixed and of course this is not true; the mixing takes time (see below). Despite this, equation 20 often provides a useful first approximation to the concentration within the well during flushing (see below).

If for some reason the well was not rapidly mixed, the ambient water might be considered to enter the well as a plug that moves toward the discharge location. Assuming the discharge is drawn from the end of the well opposite to that of the inflow, the time (t_{pl}) needed for the plug to flow through the well and exit the well is called the hydraulic retention time. In this type of flow the time to remove the therapeutant from the well is also estimated as $t_{pl} = V/Q$ (Vesilind et al. 2010) but the concentration in the flushing discharge would be equal to C_0 from the time flushing began until t_{flush} and then it would immediately drop to zero. The V/Q ratio can also be thought of as the time needed to fill or empty the well when water is pumped in (or out) at a rate of Q. The design of the well-boats is such that plug flow is not desired and plug flow has not been observed to date.

Example of Mixing within Well-Boat Wells

In order to determine what type of mixing actually occurs in well-boats a series of dye experiments have been conducted on each of the well-boats. Although each experiment had its challenges and resulted in individual variations, the general characteristics were similar. For this report, the results of the dye study conducted on 14th December 2010, on well-boat C, a vessel owned and operated by Cooke Aquaculture, are described.

Well-boat C has two wells – a starboard and port well. Each well contains about 330 m^3 of water when filled to operational bath treatment standards. The volume is slightly less when fish are in the well because the fish displace some of the water. Fish were not in the well for the

December 14th experiment. Once the wells were filled with water, the external water intake was closed, and the water was continuously recirculated within the well with the water being pumped from the stern to the bow at an unknown rate. While the water was being recirculated, 50 g of powdered fluorescein dye was introduced into the vessel's therapeutant mixing tank. This procedure is consistent with commercial therapeutant treatments that use powdered chemicals such as Salmosan. The mixing tank holds 400-500 L of water. The dye was mechanically mixed with the water with a bladed stirring rod for two sequential periods of 4 minutes, i.e., a total mixing time of 8 minutes. The mixture was injected into one well at a time in a two-step process. In the initial step the full volume was pumped into the designated well. In the second step the mixing tank was flushed with 50 L of water and this was also then pumped into the designated well. The process was repeated for the each well. The estimated concentration of dye in each well, assuming it was homogenously mixed throughout the well, was 151 µg/L (M/V with M=50 g and V=330 m^3), i.e., mass of therapeutant added divided by the assumed volume of water in the well.

Once the dye was injected into the well, the water and dye was recirculated and mixed for a 20 minute time period. This simulated the time when fish would be exposed to therapeutant. Once this recirculation period was completed, the dye was flushed from the well by pumping water out of the well while clean water was pumped into the well at the same rate so the volume of water remained more or less constant within the well. The water within the wells continued to be recirculated during this flushing period. Once flushing was completed the trial was ended. When fish are in the well and flushing is completed, the water in the well continues to be recirculated until the fish are ready to be pumped back into a net-pen.

Prior to the filling of the wells with sea water, a series of four Turner Designs Cyclops-7® fluorescein sensors were hung within the wells. The sensors were hung near the stern, about one third of the way toward the bow, two thirds of the way from the stern (≅one third of the way from the bow) and near the bow of the well. A fifth sensor was deployed through the well hatch cover at various times to obtain additional readings of dye concentration at several depths within the well. The hatch was located near the centre of the well.

Figure 14 shows the results recorded by the fluorometers. The concentration of dye inside the well varied over time. Initially there was no dye in the well. Once the dye was injected the concentration increased rapidly. This rate of increase varied with location in the well. In some locations the concentration increased and then decreased to a more or less constant concentration. In other locations the concentration increased steadily to a constant concentration. In all locations the concentration became constant after about 10 to15 minutes. The concentration did not generally achieve the expected homogeneous value of 151 µg/L. Although this may suggest that mixing may have been incomplete, it is more likely that it is due to measurement error associated with air bubbles sticking to the optical sensor of the fluorometers. This was suggested by the fact that when the sensors were shaken the concentration values increased, and by some of the sudden increases in concentration seen in the time series data. Unfortunately, in this case, only the mid-bow sensor could be shaken vigorously and this resulted in the concentration reading just prior to flushing rising to the expected 151 µg/L. This interpretation is consistent with the fact the mid-bow readings are similar to the values obtained through the well hatch. These latter readings are believed to be affected by bubbles to a much lesser extent since the sensor is constantly being moved up and down in the water column.

Once flushing began the dye concentration recorded by all sensors decreased with time (Figure 14). This decrease is replotted in Figure 15 by standardizing ($C(t)/C_0$), the concentration ($C(t)$) to the concentration (C_0) observed just prior to the commencement of flushing. This helps to compensate for the assumed effect of bubbles on the concentrations. The plots indicate that the concentration of dye or therapeutant within the well is reduced by an order of magnitude within about 30 minutes. The plots also show expected rates of decrease based on the volume of the well (V=330 m^3), several estimates of pumping rates (Q) and the relationship described above in which $C(t) = C_0 \exp(-Qt/V)$. Although the pumping rate for any given flushing event is not well known, the maximum pumping rate the pumps are rated for, is about 3000 m^3/hour (M. Szemerda, Cooke Aquaculture, pers. comm.). The pumping rate during a flushing event is often less than this since the pumps are not run to full capacity (F. Page, pers. comm.). The curves on the plot assumed a maximum pumping rate of 3500 m^3/hour. The 30% of maximum pumping rate curve corresponds to a pumping rate of 1050 m^3/hour and an e-folding flushing time of 19 minutes. The 50% pumping rate is 1750 m^3/hour and an e-folding flushing time of 11 minutes.

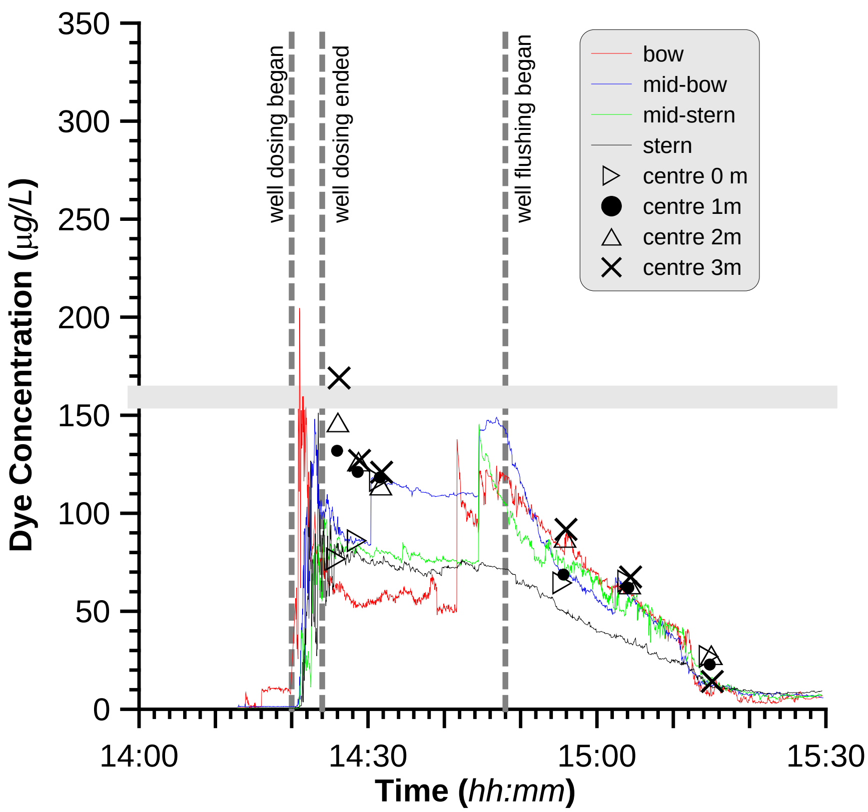


Figure 14: The time series of dye concentration within the starboard well of well-boat C as measured by Cyclops 7 fluorometers suspended within the well on December 14th, 2010. The time series from fluorometers suspended at four locations (bow, mid-bow, mid-stern, stern) within the well are shown as solid lines. Point source fluorometry readings at four depths (0, 1, 2 and 3 m) within the centre of the well are shown as symbols. The amount of dye added to the well was 50 g so the homogeneous concentration would have been 151 µg/L[1].

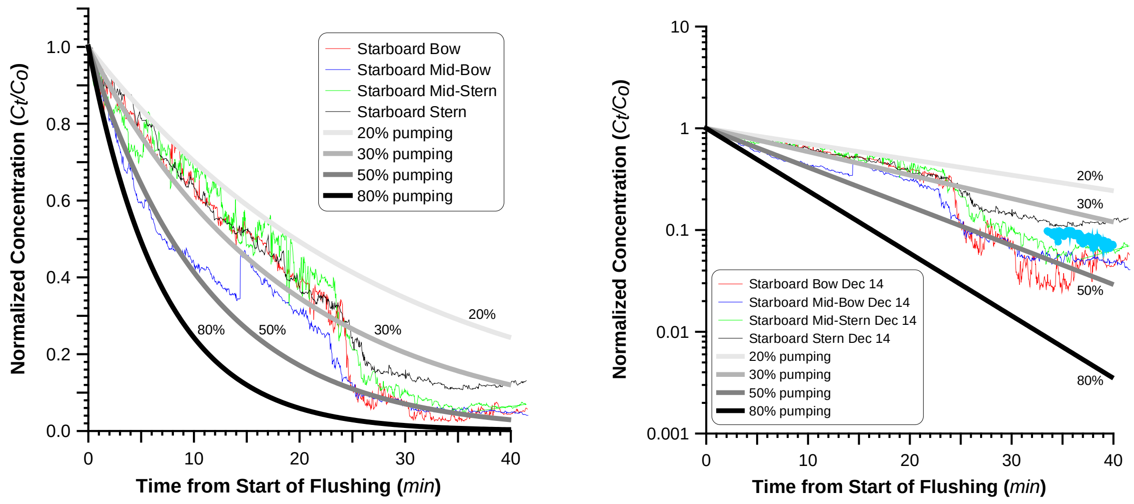


Figure 15: The time series of normalized dye concentration within the starboard well of well-boat C during the flushing period conducted during the dye experiment conducted on December 14th, 2010. The two figures show the same data as in Figure 14. The data in the left panel are plotted on an arithmetic scale that in the right panel on a logarithmic scale.

TRANSPORT AND DISPERSAL ONCE RELEASED INTO THE RECEIVING ENVIRONMENT

As described above, well-boats discharge therapeutant solutions into the ambient receiving water by mechanically pumping the bath treatment water through a circular pipe that exits the side of the vessel at an angle normal to the vessel hull. The discharge solution therefore has momentum and it intrudes into the receiving water. The flow induced by this type of discharge is termed jet flow (Fischer et al. 1979, Cushman-Roisin 2011). The water exiting the discharge pipe has a velocity and a density and the receiving water has its own characteristic velocity and density. When the density of the discharge water is greater than or less than the density of the ambient receiving water the jet is termed a buoyant jet and the discharge tends to rise toward the surface or sink toward the bottom. Bouyant or sinking jets are not discussed here since it is assumed the water from most well-boat discharges has a density equal to that of the receiving waters.

The neutrally buoyant jet flows have a characteristic cone shape near the discharge source. The cone has a diameter equal to that of the discharge source at the point of discharge. The cone widens and the shape becomes less distinct due to currents and eddy processes in the receiving waters as the distance from the source increases. Typically, however, the cone transitions into an elongated tear-drop shaped plume that is curved in the direction of the ambient flow. Once the discharge has ended the plume evolves into an elliptical patch that is transported and dispersed by ambient processes. This transition is not discussed further in this report. However, it is hoped that future work will provide some data suitable for a better characterization.

One of the distinguishing features of jet flows is that as the jet exits into, and flows through the receiving waters, ambient water is entrained into the jet. This entrainment helps dissipate the momentum of the jet and dilute the therapeutant contained in the discharged water. When the jet is perturbed by structures within the flow regime, the jet dynamic and entrainment process may be affected. Presumably the jet velocity is reduced or dissipated to some degree by the presence of the net-pen mesh and hence entrainment is likely to be reduced. Because of this it may be reasonable to think, at least initially, of the discharge into an adjacent net-pen as a tarp type release in which the initial concentration within the tarp is the mass of pesticide added to the well-boat treatment well divided by some assumed volume of treatment water within the adjacent net-pen. However, what this volume should be and what these dynamics are, are not understood and are not considered in what follows.

For circular discharge pipes discharging below the water surface and into unobstructed ambient waters, the steady state velocity $u(x,r)$ parallel to the main axis of the jet may be approximated by equation 21 (Cushman-Roisin 2014).

$$u(x,r) = u_{max}(x) exp\left(-\frac{50r^2}{x^2}\right) \quad (21)$$

In this equation x is the distance from the infinitely small or virtual jet source along the main axis of the jet and r is the radial distance perpendicular to the main axis. The velocity at distance x along the centre of the jet ($r = 0$) is defined as equation 22

$$u_{max} = \frac{5d}{x} U \quad (22)$$

where d is the diameter of the discharge pipe, and U is the cross-sectional average of the exit velocity of the water at the end of the discharge pipe (Cushman-Roisin 2014). The axial velocity therefore decreases with distance from the discharge origin such that when $u_{max} = 0.1U$, $x = 50d$ and when $u_{max} = 0.01U$, $x = 500d$. Commensurate with the decrease in axial velocity with increasing distance from the discharge point, is an increase in the width or radius (R) of the jet. The effective radius is approximated as $R = 0.2x$ (Cushman-Roisin 2014).

The above equations use a distance x that is from a virtual infinitely small diameter discharge pipe. The distance at the end of the actual discharge pipe that has a specific diameter is given by $x = 5d/2$ where d is the diameter of the actual discharge pipe. For practical purposes the distance from the mouth or end of the actual discharge pipe is therefore given by $x' = x - 5d/2$.

In addition to the velocity, the steady-state concentration of a substance, $c(x,r)$, within a jet has also been approximated and is given by equation 23 (Cushman-Roisin 2014).

$$c(x,r) = C_{max}(x) exp\left(-\frac{50r^2}{x^2}\right) \quad (23)$$

The concentration of therapeutant at any given distance along the axis of the jet is a maximum when $r = 0$. This concentration (C_{max}) is given by equation 24

$$C_{max} = \frac{5d}{x} C_0 \quad (24)$$

in which Co is the concentration constantly leaving the discharge pipe.

In order to apply the above relationships to discharges from well-boats, the diameter of the discharge pipe and the flow rate of water through the pipe must be known. Measurements of the diameter of the discharge pipes on the well-boats used in the present study indicate a typical diameter for the discharge pipe is approximately 0.5 m. Discussions with the well-boat Captains indicated that the discharge pumping rates were typically about 3000 $m^{/}s$. Under these assumptions x=1.25 m. When u_{max}=0.1U, x=25 m and R=5 m. When u_{max}=0.01U, x=1.25 m and R=5 m. Although discharge velocities are not well known for the well-boats examined, it may be reasonable to assume they are of order U=1 m/s. Under this assumption u_{max} is of order 0.1 m/s (≡10 cm/s) at x=25 m and 0.01 m/s (≡1 cm/s) at x=250 m.

These calculations suggest that discharges directed vertically downward from a well-boat can be expected to interact with the seafloor when the vertically discharging well-boats are operating in waters of less than depths in the order of 100 m. For vessels that direct the discharge down at a 45^o angle to the sea surface the depth of penetration for u_{max}=0.1U is 18 m and for u_{max}=0.01U is 180 m. This also suggests that predictions of the transport of therapeutants discharged from well-boats must take into consideration the water velocities generated by the discharge jet as well as those in the receiving waters. Tidal velocities in the vicinity of fish farms in the coastal waters of southwest New Brunswick typically range from 0 to 1 m/s. Hence, the velocities associated with well-boat flushing discharge jets can be expected to rival or exceed those of the tidal currents within 25-250 m of a well-boat.

From a dilution of therapeutant perspective, the concentration equations suggest that for the same diameter discharge pipe as above, the concentration of therapeutant exiting the discharge pipe will be reduced by a factor of ten when x = 25 m (i.e., $c_{\max} = 0.1C_0$ and $x = 50d$), by a factor of 100 when $x = 250$ m (i.e., $c_{\max} = 0.01C_0$ and $x = 500d$) and by a factor of 1000 when $x = 2500$ m (i.e., $c_{\max} = 0.001C_0$ and $x = 500d$). In general, the distance at which the concentration will be equal to a specified value ($c_{threshold}$), such as an LC_{50}, is estimated as $x = 5dC_0/ c_{threshold}$ (Cushman-Roisin 2014). It should be noted that the distance is dependent only on the discharge concentration and not the discharge velocity and that the distances are overestimates since the effect of ambient turbulence is not taken into consideration.

Although the above solutions are steady state solutions, a quasi-time dependent concentration within the discharge jet might be approximated by equation 25 which was derived by replacing C_0 in equation 24 with $C_0(t) = (M/V)\exp(-Qt/V)$ so that

$$C_{max} = \frac{5d}{x}(M/V)\exp(-Qt/V) \qquad 25$$

At the time of this writing a true time dependent solution had not been found.

From a dispersion perspective, Cushman-Roisin (2014) indicate that the above relationships correspond to an effective rate of cross-axis dispersion that is approximated as $D = 0.0125dU$. The effective rate of cross-axis dispersion associated with the above discharge characteristics is therefore 0.006 m^2/s ($D = 0.0125dU$ (0.5 m)(1 m/s). This is about an order of magnitude less than a typical rate of cross-flow eddy dispersion and similar to typical rates of vertical eddy dispersion. Therefore the estimated reductions in concentration due to cross-flow dispersion are underestimates since the mixing processes in the receiving waters will enhance the dispersion generated by the jet.

Although the above theory gives some insight into the magnitudes of jet velocities, magnitudes of concentration dilutions and the length scales of jet influence, it should be noted that the dilution rates are likely underestimates of dilution since the ambient eddy diffusivities in the receiving waters are not included in the calculations. It should also be noted that in one of the well-boats the discharge is at a height of a few centimetres above the sea surface. The effluent therefore needs to fall into the sea before the jet is established. This dynamic is not accounted for in the above equations since they assume the discharge is completely submerged and unaffected by boundaries.

Although the above equations refer to the steady-state situation, the spin up time for the jet, particularly in the near-field, is short, on the order of a minute, and the observations on dye concentration shown below (Figure 17) indicate that the equations give a reasonable first approximation to the observed concentrations of dye within the jet.

Examples: Well-boat C (release on 5 August 2011)

On August 5, 2011 a dye release was conducted from the well-boat C. In this release, 1.5 kg of dye was injected into the well. A larger mass of dye was added than in the previous example to facilitate the tracking of the dye in the discharge jet and beyond. As with the case of the lower dose of dye described in the previous example, the time series of the concentration of dye inside the well showed that prior to dye injection there was no appreciable concentration of dye in the well (Figure 16). Once the dye was injected (t = -20) a rapid increase in concentration was recorded until the upper threshold of the fluorometer was exceeded. However, unlike the previous example, the temporal evolution of the dye concentration within the well could not be followed since the concentration quickly exceeded the fluorometer maximums (approximately 316 µg/L). The calculated average dye concentration within the well, after it was well mixed was 4545 µg/L (M/V = 1.5 kg/330 m^3).

Flushing began 20 minutes after the dye injection. A decrease in dye concentration was not detected until 10-15 minutes after the commencement of the flushing (t = 0); it took this long for the concentration to be reduced below the upper threshold (316 µg/L) of the instrument. The decrease continued exponentially until flushing was stopped 55 minutes after it began. The concentration had been reduced by a factor of 0.01 (i.e., 100 times less concentrated) after 30 minutes of flushing. When the flushing was stopped after 55 minutes the dye concentration within the well was 0.003 times the initially well mixed concentration (i.e., almost 1000 times less concentrated).

The concentration within the flushing discharge jet during the treatment is shown in Figure 16 for a depth of 0.5 m and a distance of approximately 6 m from the point of discharge along the major axis of the discharge jet. The concentrations for the first ten minutes or so after the commencement of flushing are higher than the upper threshold (~395 µg/L) of the instrument (note: this was not the same instrument as was used inside the well and as such has a unique upper threshold); after this the concentration decreased with time. The concentration was always less than that measured inside the well at a comparable time. The scatter or high frequency variation in the concentration within the discharge jet is assumed to be evidence of the entrainment of ambient water into the jet. This variation was considerably greater than that recorded inside the well where ambient water was not available for entrainment.

The reduction in concentration inside the discharge jet relative to that inside the well is consistent with the expectation generated by applying a dilution factor to the time series of the smoothed concentration observed within the well during the flushing time period (Figure 16). The dilution factor (d_f) was based on the assumption that the dilution is caused by the entrainment of ambient water into the discharge and that this could be approximated by $d_f = c_{max}/C_0 = 5d/x$. For the data discussed here the dilution factor was 0.46 since the distance (x) from the discharge point was 6 m and the diameter of the discharge pipe was 0.56 m.

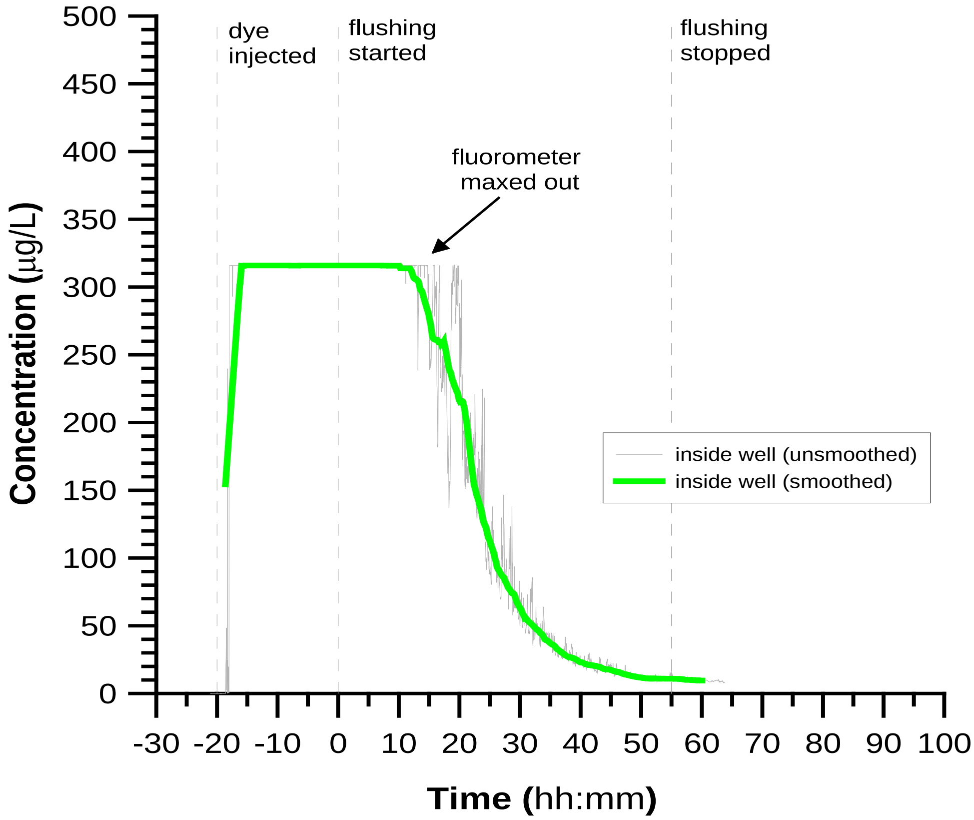


Figure 16: The time series of dye concentration within the starboard well of the Well-boat C as measured by a Turner Designs Cyclops 7 fluorometer hung through the well hatch on August 5, 2011. The grey line is the unsmoothed data and the green line is the data smoothed by a 5 minute running mean. The amount of dye added to the well was 1.5 kg so the estimated homogeneous concentration would have been 4545 µg/L, a value well above the upper detection limit of the fluorometer.

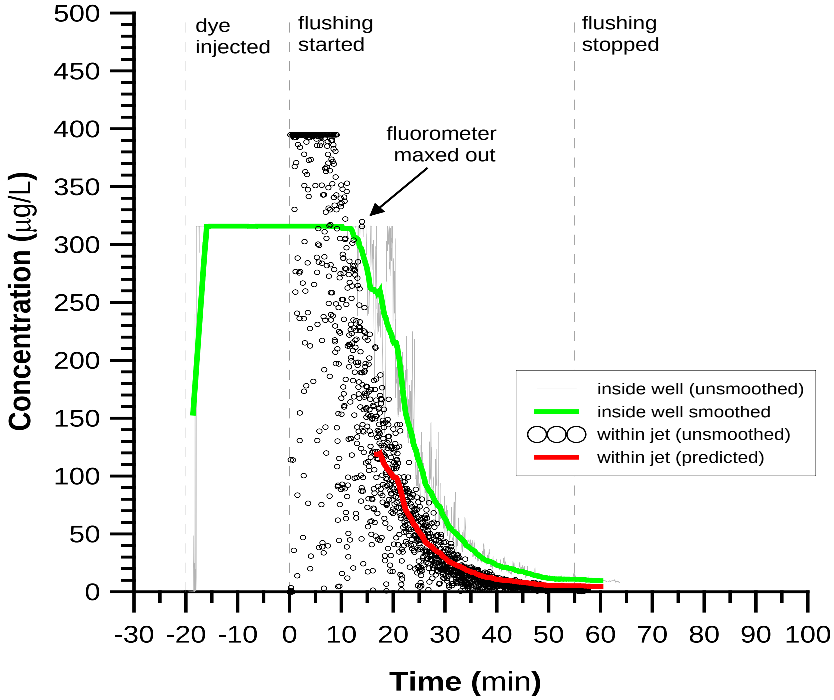


Figure 17: The time series of dye concentration within the well and flushing discharge jet associated with the starboard well dye treatment conducted on the well-boat C on August 5, 2011. The open black symbols are the unsmoothed time series of dye concentration at depth of 0.5 m and a distance of 6 m from the point of discharge. The heavy red line is the predicted time series of concentration (equation 24, see text for details). The thin grey and heavy green lines are the concentrations within the well and are the same as those shown in the previous Figure 16.

The maximum concentration inside the discharge jet is also consistent with that predicted by the relationship $C_{max} = 5dM/Vx \exp(-Qt/V)$, when the pumping rate (Q) was assumed to be 2400 m^3/h, i.e., about 80% of the maximum rate (of 3000 m^3/h) estimated for the ships discharge pumping system (Figure 18). A pumping rate of 3000 m^3/h tended to underestimate the concentrations (Figure 18). The predicted concentrations do not equal the homogeneous concentration at the time of flushing initiation because they represent the concentrations at a distance from the discharge. The prediction for a distance of zero ($x = 0$), i.e., the mouth of the discharge, at the time of discharge initiation would be equal to the homogeneous concentrations.

The predicted dilution factor, equal to the ratio of the predicted concentration to the homogeneous concentration within the well just prior to discharge, as a function of time after the beginning of flushing discharge and distance from the mouth of the discharge pipe is shown in Figure 19. After about 20 minutes the concentration of therapeutant within 10-50 m of the discharge pipe is between 100 and 1000 times less concentrated than within the well at the time of flushing initiation.

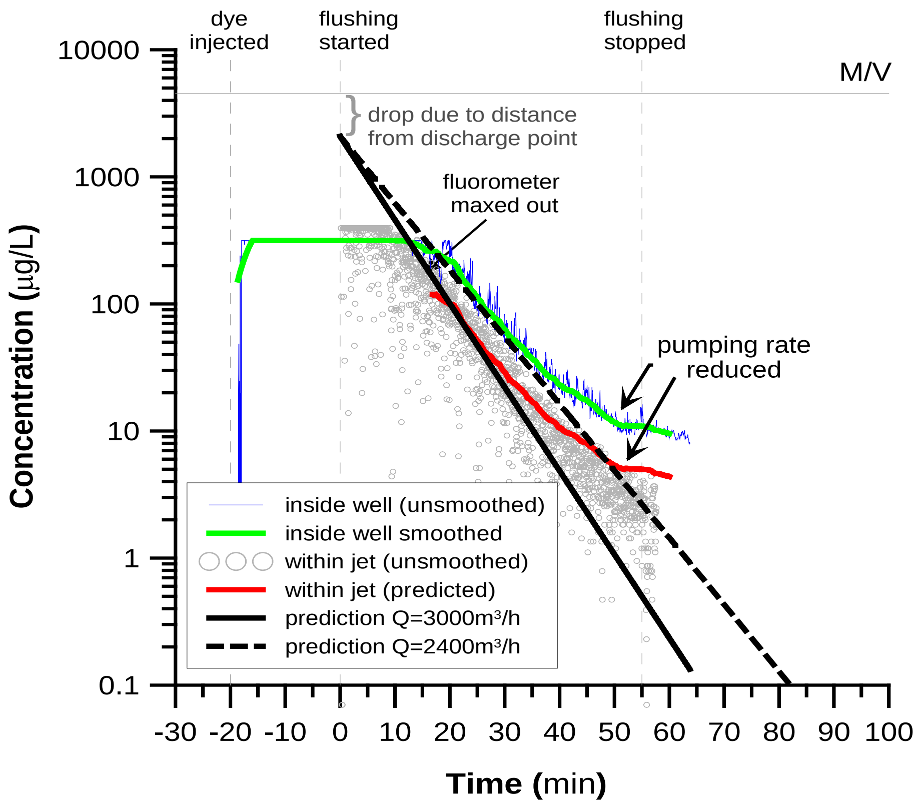


Figure 18: The time series of observed and predicted dye concentrations within the well and flushing discharge jet at a distance of 6 m from the discharge pipe. The observations are associated with the starboard well dye treatment conducted on the well-boat C on August 5, 2011. The straight line predictions (heavy black lines) are based on the equation 25. The heavy red line prediction is a scaled version of the smoothed observations taken from inside the well (green line). The blue line is the time series of observations taken from within the well. The open grey symbols are the unsmoothed time series of dye concentration at depth of 0.5 m and a distance of ~6 m from the point of discharge.

Figure 19 uses the above equations to illustrate the decrease in therapeutant concentration within the discharge jet as a function of time since flushing begins and distance from the point of discharge. The plot suggests that after twenty minutes the therapeutant concentration at a distance of 50 m from the vessel is reduced by two to three orders of magnitude.

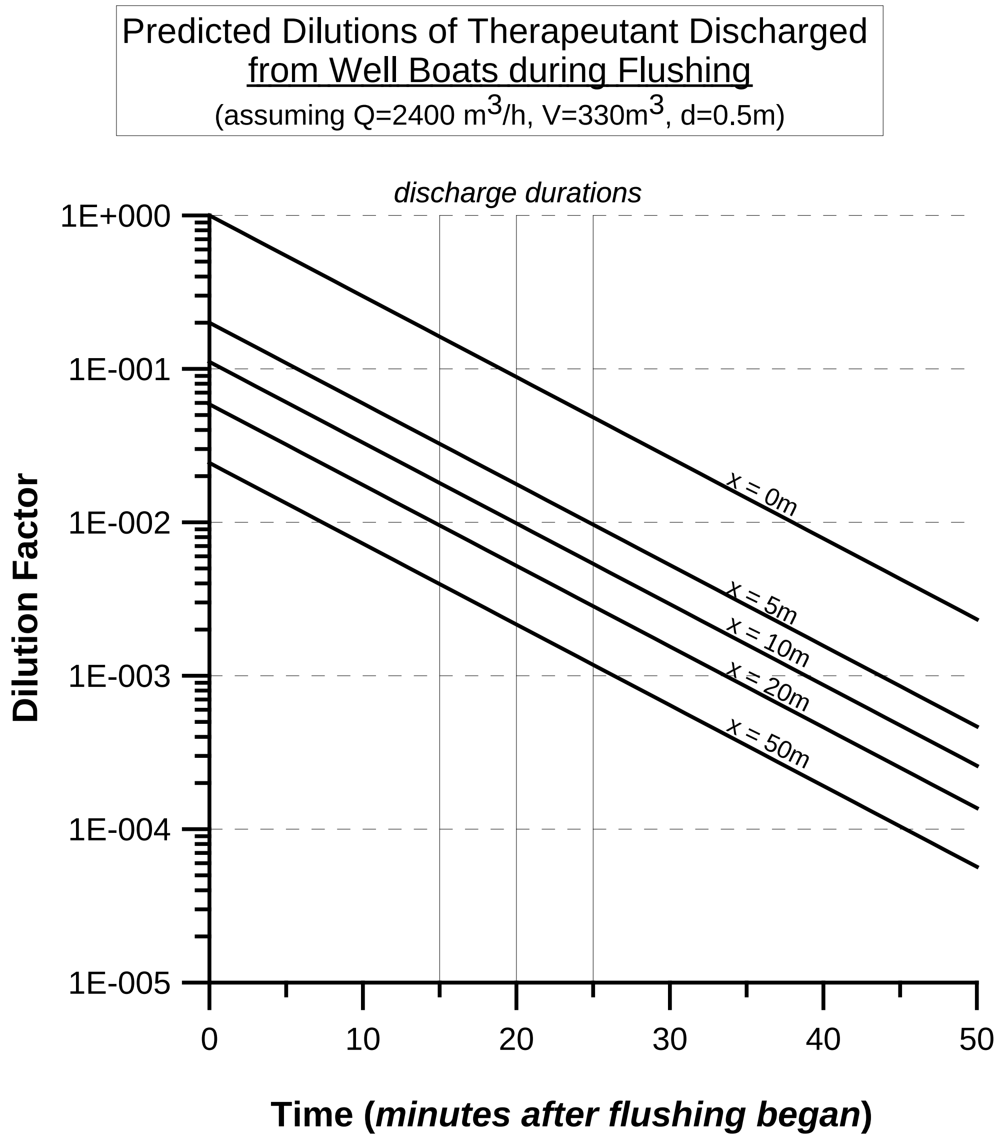


Figure 19: Predictions of pesticide dilution as a function of time and distance (x) from the mouth of the discharge pipe. The predictions are based on equation 25.

WELL-BOAT: SUMMARY

As in the case of net-pens, the above section presents a summary of the well-boat bath treatment process, a brief overview of some classical mixing and jet dynamic models and a brief overview of the dye release work that has been conducted during the first year of a recent two year DFO research project. To our knowledge this is first work of its kind and it is in its infancy still in progress and evolving, especially as industry practices and circumstances evolve.

The well-boat approach to bath treatments is new to southwestern New Brunswick and to Canada and our examination of the characteristics of the transport and dispersal of well-boat treatment discharges is in its early stages and is being conducted during a time when the industry is on a steep learning curve for conducting well-boat treatments and is evolving. Hence many experiments that have been conducted have not been reported since they focused purely on mixing within the wells, were part of the industry and science learning process and did not represent, what will hopefully become a more consistent treatment process.

Despite the limited experience to date, the perspective and information gained does indicate that there are some commonalities between well-boat treatments as well as some characteristics that are unique to each well-boat that should be considered when estimating the transport and dispersal aspects.

There are two major observation categories to date. One of these is the existence of differences in the location and angle of the discharge pipes between well-boats; two vessels discharge from the side of the vessel and a third vessel discharges from under the well-boat. In the horizontal discharging vessels the discharge is from pipes that are near or just below the water line and one of these discharges at an angle almost parallel to the sea surface whereas the other discharges at 45 degrees to the vertical. The vessel with the underneath discharge may potentially direct its discharge vertically downward. The other is that no matter which well-boat is used the treatment procedure of conducting the treatment, whilst the well-boat is alongside a net-pen, results in one discharge that is directed away from the vessel and net-pens and another that is directed into or adjacent to the net-pen being treated. In the case of fish farms with more than two rows of net-pens, both discharges are of necessity directed toward adjacent net-pens.

The well-boat observations presented here are based mainly on those obtained from the vessel that discharges horizontally and mainly on the discharges that are directed away from the net-pens. This is because it is easiest to study the vessel with the near-surface horizontal discharge, since the discharge plume can be seen and hence measurements are more apt to be taken in appropriate positions. The discharge plume from the vessel with a 45 degree discharge is to a large extent below the surface and hence harder to locate for sampling. The discharge from the vessel that discharges underneath its hull could not be adequately sampled with the present capability since the discharge could not be seen unless it happened to come to the surface somewhere. The bias toward discharges directed away from net-pens is because the deployment of the equipment and the gathering of data are not hindered by the presence of farm infrastructure.

Within the limitations expressed above, the results to date suggest that mixing of pesticides within well-boat wells is quite consistent between boats and treatments; that simple models seem to provide a reasonable first approximation to the concentration emerging from the discharge pipes and that, in the case of near-surface horizontal discharges directed away from the net-pens, the simple steady-state jet model seems to provide a reasonable prediction of pesticide concentration in the discharge jet within the first ten meters or so of the well-boat. The dilution at distances greater than a few tens of meters away from the well-boat and from sub-surface discharges is not yet well characterised.

Finally, as alluded to throughout the above sections and as in the case of tarp and skirt treatments, many factors are recognized as influencing the transport, dispersal and dilution of the pesticides used in the well-boat bath treatments. Table 7 summarizes many of these along with indications of the assumptions, variations and/or uncertainties associated with the simple models considered here.

Table 7: Summary of factors influencing the transport, dispersal and dilution of pesticides releases from well-boat bath treatments.

Influencing Factors	Variation and Uncertainty in Factor
Shape, size and volume of the bath treatment	This information is needed to set the initial conditions for the calculation and modeling efforts. **Assumptions**: A rectangular well-boat well shape has been assumed. The well is assumed to have a volume of 330 m^3. **Uncertainties**: All three of the well-boats operating in the southwest New Brunswick area have a volume similar to the assumed volume. The volume may vary by a few percent due to slight variations between vessels, vessel Captain's and operating procedures.
Pesticide type	The type of pesticide varies and is based in part on considerations of efficacy and risk of damage to the host fish. In southwest New Brunswick, the industry has used mainly hydrogen peroxide and perhaps some Salmosan in well-boat treatments. In the treatments considered here hydrogen peroxide has been the only well-boat treatment pesticide used. The pesticide type determines the mass of pesticide added to the treatment volume, the degree of dilution needed to reduce the pesticide concentration to below acceptable toxicity concentrations and the behaviour of the pesticide in the ambient receiving environment (e.g., stability and persistence of the pesticide in the treatment and ambient environment, degree to which the pesticide dissolves in seawater and binds to suspended particulates, etc.). **Assumptions**: A generic pesticide that does not decay with time or deviate in behaviour from that of the dye. **Uncertainties**: The type of pesticide is known for a particular treatment. However, specific pesticides will have specific behaviours (decay rates, absorption to organics, etc.), and little is known about these in the circumstances studied here. Specific detailed studies that are beyond the scope of this study will be needed to define the behaviour of each pesticide. In the case of hydrogen peroxide, the addition of fluorescein dye to the treatment interferes with fluorescence based measurements of hydrogen peroxide concentration and therefore limits the ability to gather data on *in situ* peroxide concentrations.
Mass of pesticide added and pesticide treatment concentration	The mass of pesticide initially added is determined by the type of pesticide and its product label directions as well as considerations of efficacy and risk of damage to the host fish. Knowledge of the mass is needed to estimate the concentration of the pesticide at the time of release. **Assumptions**: Health Canada target concentrations and amounts are assumed for typical bath volumes. **Uncertainties**: Concentrations resulting from current treatment procedures are considered to be quite accurate. Data quantifying the variability are not available to us at this time.

Influencing Factors	Variation and Uncertainty in Factor
Pesticide behaviour	Specific pesticides will have specific behaviours (decay rates, absorption to organics, etc.) and these have the potential to influence the transport, dispersal and dilution rate of the pesticide. **Assumption**: In the present work the pesticide is assumed to behave like the dye. **Uncertainties**: Little is known about the behaviour of the pesticides in the circumstances studied here. However, similarities in the preliminary data concerning observed dilution rates of dye and chemicals suggests that for the order of magnitude transport and dispersal rates considered here, the assumption of a generic pesticide that behaves like the dye is reasonable. Specific detailed studies that are beyond the scope of this study, will be needed to define the behaviour of each pesticide.
Duration of the treatment	The duration of the treatment influences the degree to which the pesticide has been mixed throughout the treatment volume. Information on this is not explicitly needed for the calculations and models used here since an initial concentration is prescribed. **Assumptions**: The duration is sufficient to achieve mixing of the pesticide throughout the bath treatment volume. To date typical treatment durations range from ~ 20-40 minutes. **Uncertainties**: Although treatment durations vary in association with factors such as the pesticide being used, the health status of the fish and water temperature, the assumption of the pesticide being initially well mixed throughout the treatment volume is generally reasonable. In some cases the treatment may need to be prematurely terminated, although this only occurs in less than 5% of the treatments (M. Beattie, pers. comm.). One of the factors influencing the duration of a treatment is the concentration of dissolved oxygen in the bath waters. If the oxygen concentration within the treatment volume drops below the critical level determined by the attending treatment supervisor, the planned treatment duration may be cut short. Mixing during the very-short treatments (<10 minutes) may be incomplete.
Mixing within a well	**Assumption**: well mixed at the time of discharge. **Uncertainties**: There is relatively low uncertainty associated with this assumption. Many measurements of hydrogen peroxide concentration taken from many locations within the well as part of treatment system testing, as well as many measurements of dye taken during well mixing experiments conducted as part of the research effort described here, have shown that the water within the well treatment volume is generally homogenously mixed by the end of a typical treatment period of approximately 20-40 minutes. The models assume that the clean ambient water brought into the well, to replace treatment water pumped out during flushing, is instantaneously mixed with the treated water remaining in the well. This assumption is not an exact representation of the real situation since the observed mixing time scale (reported in the text) is about ten minutes. However, the assumption provides a convenient first approximation that seems to be reasonable given the favourable comparisons between predicted and observed concentrations of dye in the discharge plume near the point of discharge.

Influencing Factors	Variation and Uncertainty in Factor
Temporal sequence and duration of the release of the pesticide into the receiving environment	This is needed to define the initial state at the time of release. **Assumptions**: The release is assumed to occur over a finite period of time and the concentrations during the discharge period are assumed to be time varying. The concentration at the beginning of the discharge is assumed to be the target treatment concentration. The concentration is subsequently assumed to decrease exponentially according to the mixing model (Equation 20). **Uncertainties**: The above assumptions seem to be qualitatively quite reasonable for the first approximations considered here. No formal efforts have been made to quantify the variability in these time-varying initial concentrations. However, the concentrations within the discharge jet are sensitive to the discharge pumping rate such that slower pumping rates mean higher concentrations of pesticide in the effluent at any given time and a longer time needed to completely flush the well. Since in practice, flushing durations are truncated before flushing is complete, slower pumping rates mean higher concentrations of pesticide remain in the well at the end of the treatment and are pumped into the net-pen receiving the treated fish. Therefore slower pumping effectively means higher concentrations within the effluent plumes and patches.
Discharge location, angle and rate	The discharge location, angle and rate influence the direction, length and degree of entrainment within the jet flow. **Assumptions**: The discharge jet is from the side of the well-boat, near the water level, directed parallel to the sea surface, radially symmetric and discharged at rate of about 3000 m^3/h. **Uncertainties**: The assumption of a radially symmetric discharge jet is not entirely true for the case of a jet discharged at the sea surface since part of the jet is bounded by the sea surface. However, the consistency between the observations and model predictions considered here suggest that this is not a severe limitation of the approach. The rate of discharge is based on engineering specifications provided by the vessel Captains. However, the pumps driving the discharge are variable speed pumps, the pumps are not run at full speed and the pumping rate is not electronically monitored. Hence rates are somewhat uncertain and vary between operators. The rates used here are informed guesses that appear to provide predictions consistent with the observations.
Farm infrastructure	Farm infrastructure has the potential to influence (perturb) the flow within the discharge jet as well as the transport and dispersal of the pesticides if the discharge encounters the farm infrastructure. **Assumptions**: The farm infrastructure does not influence the flow. **Uncertainties**: The assumption only applies to about 50% of the releases since 50% of the discharges occur in directions away from the infrastructure and 50% are directed into the infrastructure. The model predictions given should only be applied to the discharges directed away from the net-pens.

Influencing Factors	Variation and Uncertainty in Factor
The increase in the horizontal scale of the pesticide patch	**Assumptions**: The near-field scale of the discharge patch or plume is initially assumed to be defined by the jet dynamics. The scales of the plumes or patches have not been considered beyond this. **Uncertainties**: The observations indicate qualitatively that this is a reasonable assumption for the first few minutes of the discharge. However, subsequent to this, the scale of the patch or plume is controlled by the combination of jet dynamics, ambient advection and dispersal processes as well as a temporally decreasing discharge concentration. These dynamics have yet to be considered.
Rate of horizontal mixing in the receiving environment	This information is required by models other than those based on the Okubo relationship to estimate the increase in patch size and dilution.Rates of horizontal dispersion in the coastal environment vary over several orders of magnitude and rates along the major axis of the flow are generally larger (~10-100x) than those in the cross-flow direction. This results in patch and plume shapes being elliptical or stretched along the axis of the major flow. Typical horizontal rates range from 1 to 0.1 m^2/s and typical vertical rates are smaller by an order of magnitude or more. In the case of jet flows the horizontal ambient rates are augmented by the entrainment processes associated with the jet flow. **Assumptions**: The horizontal mixing is only that generated by the jet flow. **Uncertainties**: The above assumption is likely to underestimate the dispersal of the pesticide since ambient mixing processes will act to augment the jet dilution. The influence of the ambient mixing is expected to increase relative to that of the jet entrainment as the distance from the source increases. The literature indicates that horizontal mixing rates, i.e., horizontal diffusivity rates, can vary by an order of magnitude or more due to changes in tidal state, wind speed and direction, local baroclinic processes, local bathymetry and random conditions. Hence, the model based estimations of dilution must be viewed accordingly, since they are meant to provide only an order of magnitude estimate of the dilution.

Influencing Factors	Variation and Uncertainty in Factor
Rate of horizontal advection in the receiving ambient environment	This information is required in order to make estimates of the horizontal distances released patches are likely to travel during specified periods of time. The advective velocities of the water, i.e., the speed of the water movement dictates how fast the pesticide will move downstream and how far the pesticide will travel within a given period of time. In the southwest New Brunswick area, the advective velocities are typically dominated by tidal currents although wind driven currents are significant in some areas and at some times. The currents typically range from zero to 0.5 m/s. The dominant tidal cycle is 12.4 h; hence, the tidal currents at any given location vary on time scales of minutes to hours. Although the amplitudes and phases of the currents are somewhat site specific the amplitudes at each location vary by about 30% on a fortnightly basis. **Assumptions**: The horizontal advection has been assumed to be zero for the near-field considerations discussed here. **Uncertainties**: The rate of horizontal advection in the coastal zone of southwest New Brunswick, also referred to as the speed of drift, can vary spatially and temporally from zero to over 1 m/s. The advective velocities are typically dominated by tidal currents, although wind driven currents are significant in some areas and at some times. The dominant tidal cycle is 12.4 h; hence the tidal currents at any given location vary on time scales of minutes to hours. Although the amplitudes and phases of the currents are somewhat site specific the amplitudes at each location vary by about 30% on a fortnightly basis. The specific rate of advection for a given treatment therefore depends to a large extent on the phase of the tide and the wind speed and direction and the site location. Well-boat treatments are not as restricted by ambient current speeds as tarp treatments and hence they occur over a larger range of current speeds and directions. The sensitivity of pesticide dispersal to this factor has not formally investigated, although the visual observations indicate the currents certainly affect the direction in which the jet bends as it leaves the vicinity of the vessel and the direction and rate at which the discharge plume moves.

Influencing Factors	Variation and Uncertainty in Factor
Vertical stratification and the depth of mixing	This information is required for defining the depth distribution of the released pesticide. The degree of stratification influences the vertical mixing of the pesticide. In southwest New Brunswick, vertical stratification varies with location but is typically weak, with a gradual increase in density over the top ten meters or so and no distinct upper mixed layer. On atypical occasions, such as during periods of high freshwater runoff, stratification can be considerably stronger. In the case of the horizontally discharging well-boat the pesticide is discharged into the upper few meters and hence into the near-surface pycnocline whereas in another well-boat the discharge is below the water surface and potentially below the pycnocline. In the third well-boat, the pesticide discharge is into the pycnocline but it is angled downward. **Assumptions**: In the model calculations presented here no explicit assumptions about water column stratification or the depth distribution of the discharge needed to be made, other than the fact that the results refer mainly to a near-surface (i.e., upper few meters) discharge plume. However, if the jet dynamics are merged with the ambient Okubo type dynamics in some way, then assumptions about depth distributions will need to be made. Also if the jet characteristics presented here are assumed to apply to the well-boats that discharge downward or at an angle of 45 degrees, the length scale of the jet may indicate the initial depth penetration of the discharge. **Uncertainties**: Vertical stratification in the coastal areas of southwest New Brunswick is generally not pronounced. In some areas and at some times, the density increases with depth in the upper 5-10 m by less than one sigma-t unit. In some unusual cases of high freshwater runoff there may be a strong pycnocline to a depth of less than 5 m.
Proximity of shoreline	The presence of a shoreline can influence the dispersal of a pesticide plume by restricting the horizontal and vertical dispersal processes. The potential for a plume to interact with the shoreline is site specific. For plumes of pesticides that are still toxic after a few hours of dilution, the length scale of the major axis of the plume is of the same magnitude or greater than the distances of southwest New Brunswick farms from shorelines (i.e., 100s -1000s of meters). Hence, there is potential for some shoreline interaction in this area. However, the realized potential for interaction is site and environmental condition specific. **Assumptions**: The existing models assume there is no interaction with the shoreline. **Uncertainties**: This is unlikely to true for at least some farm sites, and the proportion of releases that might result in coastline interactions is unknown since this potential is site specific, depends upon the local water circulation at the time of the drift and the nature of the discharge release. The short time scales considered for the well-boat discharge described above are insufficient for horizontal plume lengths and drift distances to be long enough to interact with shorelines. However, some interactions are expected based on longer time scales since the length scales of the plumes will increase with time to distances sufficient to reach shorelines (i.e., 100s -1000s of meters) in some locations. Also some of the preliminary observations (not presented) from at least one of the well-boat treatments conducted in shallow waters, i.e., on the order of 10 m, indicated that the discharge plume reached the bottom.

Influencing Factors	Variation and Uncertainty in Factor
Multiple Treatments	Multiple treatments are not explicitly considered in the calculations and models presented in this document. To date it has been typical for two net-pens to be treated per day on a single farm by a well-boat. There are two discharges per treatment – one from each side of the well-boat such that one discharge is directed toward and the other away from the net-pens. Hence there are typically four plumes per day per site. The degree to which treatment plumes overlap depends upon the proximity of each plume in time and space. Since the well-boats can treat two wells at a time, the plumes from each well are discharged from opposite sides of the vessel within minutes of each other the direction of the ambient flow dictates whether the two plumes will interact. Treatments of different net-pens on a single farm within the same day are typically separated in time by hours. These treatments may occur in adjacent net-pens or in net-pens distant from each other within the same net-pen grid. If the treatments occur during opposite phases of the tide, the pesticide plumes will drift in opposite directions whereas if the treatments occur on the same phase of the tide the pesticide plumes may overlap. The frequency and timing of treatments depends upon many factors including the weather, tidal currents, availability of equipment and staff as well as pesticide label limitations and the intensity of sea lice infections on net-pens. **Assumptions**: The modeling to date has assumed only one isolated treatment at a time. **Uncertainties**: Releases from multiple treatments can be treated as the summation, at specific points in space and time, of concentrations generated by individual releases. It is often in the best interest of pest control to treat a farm as quickly as possible, hence several treatments a day may be conducted. Usually these treatments are conducted sequentially with about an hour between each treatment. However, in some cases the time between treatments may be less and the treatments may be more numerous. The distance between the treatments may also vary such depending upon the circumstances. Hence, release locations range from being spatially adjacent to being at opposite ends of the site. If the treatments occur during opposite phases of the tide, pesticide plumes will drift in opposite directions, whereas if the treatments occur on the same phase of the tide the pesticide plumes may overlap. The frequency and timing of treatments depends upon many factors including the weather, tidal currents, availability of equipment and staff as well as pesticide label limitations and the intensity of sea lice infections on fish in net-pens. The degree to which treatment plumes overlap depends upon the proximity of each treatment in time and space. A worst case scenario may be that the plumes occur simultaneously and on top of each other. In this extreme case the concentrations produced by a single release would be multiplied by the number of releases.

OVERALL SUMMARY AND CONCLUSIONS

The theory and observations presented above give some insight into the nature of the observations that are being gathered and the theories and models that are being pursued as part of the effort to better understand the transport and dispersal of therapeutants being released into the ambient environment from tarping, skirting and well-boat bath treatments. The data gathered are sufficient to provide a good indication of the horizontal shape of the patches and plumes but insufficient data could be gathered to provide comparable insight into the shape in the vertical dimension. This would have required the towing of multiple fluorometers at difference depths or the use of a rapidly vertically undulating towed fluorometer, a capability that was not available to us. Hence, the plumes and patches have been conceptually assumed to be slabs with an irregular horizontal perimeter and a constant depth. Furthermore, since the modeling work has been limited to considerations of relatively simple analytical solutions to help develop understanding and give some order of magnitude insights into the transport and dilution processes, the shapes are simplified into horizontal discs or ellipsoids with constant depths. These generally assume horizontally and vertically, and at times temporally, homogeneous concentrations within the plume boundaries which is an oversimplification of most real world situations. More complex numerical modeling is being undertaken that includes spatial variation in three dimensions as well as temporal variations.

The information presented focuses on the transport, dispersal and dilution of dye rather than the pesticides that are of ultimate concern. This is a common assumption in this type of modeling since it is much easier and cost effective to track dye than the invisible pesticides. It is also the assumption made in SEPA models. Considerable additional work would be needed on each pesticide to determine its behaviour in the environmental conditions being examined here and such work is beyond the scope of the present program. Nevertheless, it should be recognized that the potential exists for dispersal rates of dye and a pesticide to differ. For example, the degradation rates of dye and pesticide may differ, fluorescein dye is known to be susceptible to degradation by light, and the pesticides may bind to organics in the water column. In a general effort to account for these, the dye was mixed with the pesticide prior to injection into the bath volume and a series of water samples were taken from within the bath treatment volume, as well as from within and outside the visible dye plume, for chemical and dye analyses so the relationships between dye and pesticide concentrations could be empirically determined. The chemical analyses are not yet available to fully examine the relationships. However, a preliminary examination indicates that dye and pesticide concentrations seem to be related, at least to the extent that the dilution rate of dye seems to be indicative of the order of magnitude dilution rate of pesticide over the short time scales considered here. On longer time scales, chemical behaviour may play a more important role.

INFLUENCING FACTORS

Also of importance is the reiteration that the near-shore coastal marine environment, where net-pen aquaculture occurs, is not static and has a high degree of site specificity; conditions vary continuously with the potential to result in a wide range of drift and dilution scenarios. This is reflected in the variation seen in the observations presented here. The rates of dye dilution, speed and direction of drift, size of the area covered by the released bath treatment plume and depth to which the bath solution penetrates, all vary in time within and between treatments and all are influenced by many factors, most of which are not under the control of the applicator. A list of the major factors that influence the nature of the transport and dispersal of therapeutants from tarped fish cages and well-boats has been included in Tables 6 and 7, along with the assumptions made in the present analyses and the uncertainties associated with these. A brief listing of the major factors is repeated below in bulleted form.

The factors that influence tarp bath treatments include fixed and natural factors such as the:

- shape and scale of the tarped cage (diameter, volume)
- mixing of pesticide within the tarped volume prior to release
- absorption of pesticide to organics
- duration of the treatment and duration of the flushing from the net-pen
- farm layout
- rates of mixing in the horizontal (x,y) and vertical dimensions

- proximity of vertical boundaries in relation to vertical stratification, the sea bottom and inter-tidal zones
- proximity of horizontal boundaries such as the shoreline, bottom and pycnocline
- proximity of other cages and other farm infrastructure
- advective current velocities, i.e., the transportation of the patch
- weather, wind and waves
- chemical behaviour of the therapeutant in the ambient water

and operational or husbandry factors such as the:

- mass of therapeutant introduced into tarped volume, i.e., concentration of source
- removal of tarp, e.g., quickly removed or slowly removed
- porosity of the treated cage net, i.e., mesh size and bio-fouling
- degree of bio-fouling on adjacent fish cages
- premature termination of the tarping process due to factors such as low oxygen and fish health
- dropping of the pursed net, i.e., are fish retained near surface or allowed to swim throughout full volume of cage.

The factors that influence well-boat bath treatments include fixed and natural factors such as the:

- volume of well
- mixing time within the well
- angle of discharge, i.e., horizontal, vertical or at some other angle
- diameter of the discharge pipe
- depth or height of the discharge pipe below (above) the sea surface
- rate of discharge flow, i.e., pumping capacity
- rates of horizontal mixing in the receiving environment
- rates of ambient horizontal and vertical mixing in the receiving environment
- proximity of vertical boundaries in relation to vertical stratification, the sea bottom and inter-tidal zones
- proximity of horizontal boundaries such as the shoreline, bottom and pycnocline
- proximity of other cages and other farm infrastructure
- degree of bio-fouling on adjacent fish cages
- advective current velocities, i.e., the transportation of the patch
- weather, wind and waves
- chemical behaviour of the therapeutant in the ambient water

and operational factors such as the:

- mass of therapeutant introduced into well, i.e., concentration of source
- density of the discharge solution – this is usually the same as the ambient water
- velocity of discharge, i.e., the operator can vary this
- direction of the discharge, i.e., into cages or away from cages
- farm layout
- duration of the discharge; this is under the control of the operator and supervising fish health specialist.

Once the plume is some distance from the well-boat and the farm infrastructure, the factors that affect its transport and dispersal are the same as those for tarp treatments, i.e., the factors that influence rates of transport and dispersal in the ambient environment.

CONCLUSIONS

Although all of the above factors and limitations must be kept in mind when using the above information, the information is believed to lead to some at least preliminary conclusions and to give an initial order of magnitude estimate of dilution rate, drift speed and the spatial extent (area) of effluent releases, particularly from tarps, that can be used to generate an initial estimate of exposure potential (Page and Burridge 2014). A bulleted list of the conclusions reached to date is given below.

TARP TREATMENTS

- Cage tarp treatments are restricted to periods of the tidal cycle with relatively weak currents. This is because site crews are unable to easily tarp the cages in strong currents and want to avoid the billowing of tarps since this will trap the fish in small pockets of water. They are also limited by weather conditions such as wind and waves.
- Releases from tarped fish cages are finite size releases.
- Releases may be near instantaneous or spread out over tens of minutes to a few hours.
- The observed increase in the scale of the dispersing patches from tarp treatments appears to be in general agreement with predictions based on the Okubo mixing. The rate of increase is suggested to agree more closely when the patches are not influenced by cage infrastructure. When cage infrastructure is involved, the scale of the patch seems to undergo a more rapid increase than predicted by the Okubio relationship. However, after the first hour, observations follow the Okubo rate of increase in patch size.
- Pesticides released following tarp treatments may be diluted by several orders of magnitude over a few hour period.
- Releases from tarp treatments may be advected up to 1-2 kilometers within a couple of hours after release.
- The shape of the advecting pesticide patch or plume tends to become elliptical with the major axis in the direction of the dominant water flow. The area within this patch is similar to or greater than that predicted by the Okubo relationship.

WELL-BOATS

- Well-boats can conduct treatments at most, if not all, phases of the tide and in a wide range of weather conditions.
- Flushing discharges have a finite initial size, a continuous flow for a limited period of time and a concentration of pesticides in the flow that decreases with time.
- The characteristics of each well-boat discharge is different due to variations in the concentration within the discharge, as well as variations in the pumping rates and durations, the angle and direction of the discharge pipe and the receiving environments.
- Fifty percent (50%) of well-boat flushing discharges in southwest New Brunswick are directed away from the farm infrastructure and 50% are directed into fish pens. These two discharge types need to be treated differently. Some theory exists to help with the former type but no theory exists for the latter.
- To a first approximation, observed dye concentrations obtained from within a well during the flushing discharge jet agree well with concentrations predicted from simple completely mixed wells.
- The observations and mixing theories appear to be in general agreement when the flushing discharges are treated as jet discharges.

- Well-boat treatments use significantly less pesticide than tarp treatments and the pesticide that is used in well-boat treatments appears to be diluted more quickly than following tarp treatments due to the inclusion of mechanical mixing within the well during flushing of the pesticide from the treatment well and the entrainment induced dilution associated with the discharge jet.

COMMON TO BOTH TARP AND WELL-BOAT TREATMENTS

- Fish cage infrastructure definitely influences the transport and dispersal of the dye, and by inference, the chemical therapeutant. This influence is complex, not well understood and varies with site design and location.
- No robust theory or prediction capability for the transport and dispersal of therapeutants accounts for the influence of fish cage and farm infrastructure.
- Each treatment, whether from a well-boat or tarped cage is unique to some degree.
- It appears possible to establish general scales of therapeutant transport and dispersal.
- Efforts to model of the full spatial and temporal evolution of the transport and dispersal of well-boat flushing discharges is still underway.
- The shape of the released pesticide patch or plume may influence the ability of organisms to avoid the patch. For example, patches and plumes that completely encompass the width of an inlet prevent or have a spatial scale that exceeds the excursion range of the organism may expose more non-target organisms than long narrow plumes.

FUTURE WORK

Although the above information represents a significant amount of work and the observations presented are consistent with existing general theories and empirical relationships, the sample size is small and the models examined do not predict the direction or rate of drift of the plume nor its shape. For example, the observed plumes resulting from tarp treatments are elliptical in shape and the Okubo model deals only with the area of the plume. The Fickian model can generate an elliptical plume but estimates of the along-flow and cross-flow rates of horizontal diffusivity are required. The work to date in relation to releases from well-boat treatments has focused on the initial conditions of the release and the near-field concentrations or dilution factors; observations on the resulting plumes are still sparse. Circulation modeling work that is underway will hopefully provide some detailed insight into the transport aspects. Hence, more work is needed to develop a more complete and robust understanding of the transport and dispersal processes and their predictability.

The following list therefore includes a range of potential work themes that will provide information considered useful for improving knowledge of the variations in pesticide exposure profiles and the capabilities to predict the transport, dispersal and dilution of pesticides released into the ambient environment as a result of tarp, skirt or well-boat bath treatments. Most of the work is of a medium to long term nature since significant improvements to measurement methodology and modeling capabilities are required. The items are not necessarily in order of importance.

Tarp and Skirt Treatments

- Develop an operational mechanism for establishing and maintaining a consistent shape and volume of tarped and skirted bath waters during the bath treatment period.

- Develop a robust standard operating procedure for the dissolving and mixing of pesticides prior to injection into the tarp or skirt bath volume.

- Develop a robust mechanism and standard operating procedure for quickly and thoroughly mixing pesticide within a tarped or skirted bath volume.
- Develop a better understanding and quantification of the degrees of influence farm infrastructure (cage size, number of cages, mesh size, position of cages relative to each other, i.e., farm layout) and bio-fouling has on cage flushing rates and subsequent transport and dispersal rates and directions of pesticides.
- Explore and/or develop models of transport and dispersal that incorporate a temporal aspect to the concentration of pesticide being discharged from a treated cage and compare these with models that assume an instantaneous release.
- Explore the ability of an existing southwest New Brunswick circulation model to simulate observed patterns of dye and pesticide transport and dispersal patterns.
- Develop a better quantification of the ability to predict the probability of non-target exposure to pesticide releases from tarps and skirts.
- Obtain additional observations on the transport, dispersal and dilution rates and processes of pesticides released from a wide range of farm configurations and geographic locations and times representing a broad range of the operational and environmental conditions that influence pesticide transport and dispersal processes associated with tarp and skirt bath treatments.

Well-Boat Treatments

- For pesticides that are initially mixing in the mixing tank of well-boats, develop a testing procedure and measure concentrations of pesticide in the well-boat mixing tank just prior to injection into the well bath volume to determine if the pesticide is fully dissolved and mixed in the mixing tank.
- Develop a more detailed and quantitative understanding of near surface well-boat discharge points on entrainment and dilution dynamics.
- Develop a better understanding and quantification of the degrees of influence farm infrastructure (cage size, number of cages, mesh size, position of cages relative to each other, i.e., farm layout) and bio-fouling has on the transport and dispersal rates of flushing discharges directed into the farm array.
- Develop an improved understanding and quantification of the time-dependent dilution rates associated with the initial jet discharge dynamics of pesticide discharges from well-boats.
- Develop an improved understanding and quantification of the transition between the initial dilution generated by jet dynamics and the subsequent transport and dispersal of the released pesticide in the ambient receiving waters.
- Develop a better quantification of the ability to predict the probability of non-target exposure to pesticide releases from well-boat discharges.
- Obtain additional observations on the transport, dispersal and dilution rates and processes of pesticides released from the full range of well-boat configurations being used or considered for use in Canada as well as data from the operation of these configurations in representative suite of geographic locations and times representing a broad range of the operational and environmental conditions that influence pesticide transport and dispersal processes associated with well-boat discharges.

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