Inter-Island Tunnel Water Quality Assessment

Technical Memo #3

Outfall #005 Dye Study

submitted to

Massachusetts Water Resources Authority

by

Drew L. McGillivary
E. Eric Adams

MIT Sea Grant College Program
and
Department of Civil & Environmental Engineering

Massachusetts Institute of Technology

Cambridge, MA 02139

April 1995

Table of Contents

Summary

Due to system modifications, treated effluent from the Deer Island treatment plant was discharged through the short emergency Outfall 005 during the period February 7 through 17. This offered the opportunity to study the potential effects of a future discharge through this outfall which might result during periods of high flow if the north and south system flows were to be treated at the new Deer Island Treatment Plant prior to the operation of the new tunneled outfall in Broad Sound. As part of this study, Rhodamine dye was released through the outfall during the period 14:00 to 16:00 on February 16 and surveyed over the following 24 hours (Battelle, 1994). The dye and salinity distributions were also modeled mathematically using initial mixing models and depth-averaged models of hydrodynamics and water quality. This report summarizes the comparison between modeled and measured dye concentrations and salinities. The chief conclusions are as follows.

Minimum initial dilutions computed from measured dye and salinity were about 2, which is similar to that predicted by initial mixing models described in Technical Memo 1.

Both dye and salinity measurements in the vicinity of the outfall showed significant vertical stratification, making it difficult to conduct a precise comparison with depth-averaged predictions. However, concentrations and salinities predicted shortly after the end of the dye release showed the same spatial trends as corresponding measurements and the predictions were generally within the range of observation. That is, observed dye concentrations were generally higher in the surface and lower at depth than corresponding predictions while observed salinities were generally lower at the surface and higher at depth than corresponding predictions.

Dye concentrations simulated one day after the dye release were reasonably uniform spatially and indicated a dilution of approximately 4000. For the most part, corresponding measured dye concentrations were even lower, although small pockets with concentrations up to ten times the predicted concentrations were observed. We suspect those pockets of high concentrations are not real but, even if they are, both model and measurement indicate that effluent discharged through Outfall 005 will receive substantial mixing despite the poor initial mixing and the short outfall length.

Introduction

The Massachusetts Water Resources Authority (MWRA) currently operates two primary wastewater treatment plants: the Nut Island facility treats South System flows and the Deer Island facility treats North System flows. For Deer Island, Outfalls 001 and 002 discharge average flows and operate essentially continuously; Outfall 004 is activated at high flows (approximately 2% of the time); Outfall 005 is activated during extremely high flows and during emergencies when the other outfalls cannot be used (005 was not operated during 1992 or 1993).

Deer Island Outfalls 001 and 002 are located offshore in President Roads and discharge effluent through a series of ports located along a diffuser[1]. Outfalls 004 and 005 are nearshore outfalls that discharge effluent through a single port and at a depth significantly shallower than the main outfalls. Deer Island Outfall 005 is shown in Figure ELA1 of Appendix A. The Nut Island outfall system is described in detail in Technical Memo 2.

In the future, South System flows will be routed to Deer Island via an Inter-Island Tunnel. The combined North and South System flows will be treated at a new facility on Deer Island which will discharge effluent via a tunnelled outfall into Broad Sound. It is possible that the Inter-Island Tunnel and the last two batteries of the new primary treatment plant at Deer Island will be operable before the new outfall tunnel is completed. During the period of time before the new outfall tunnel is completed, two interim scenarios are possible:

A. Do not operate the Inter-Island Tunnel: continue to treat the North and South flows separately (with new primary treatment for North System flows only) and discharge through the current outfall systems,

B. Operate the Inter-Island Tunnel: transfer the South System flows to Deer Island for treatment along with the North System flows and discharge the combined effluent through the current Deer Island outfall system.

The median daily flow of Deer and Nut Islands combined is approximately 340 MGD. The median flowrate of 340 MGD is distributed such that approximately 2/3 of the flow is treated at Deer Island and 1/3 is treated at Nut Island. However, during extreme events the combined flow can exceed 1000 MGD for a short time. Hence, transferring the South System flows to the new

[1]These two outfalls were reversed in Technical Memo 1: Outfall 002, the shorter and older of the two main outfalls, was mistakenly labeled as Outfall 001.

Deer Island primary treatment plant will increase the operation of the emergency outfalls that now exist at Deer Island. Specifically, Outfalls 005 and 004 will require operation during extreme events, depending upon tidal elevation and event duration.

This memo analyzes a dye study of the Outfall 005 plume that took place on February 16 and 17th of 1994. Analyses in this report qualitatively compare the data taken over the 24 hours following the dye release (Battelle, 1994) with that of model simulations.

Study Description

Outfall 005 was used as the single operable outfall from Deer Island from February 7 through February 17 due to system modifications. To take advantage of this situation, a dye study was conducted to help determine the water quality impacts of operating Outfall 005. Beginning at 14:00, February 16 and ending at 16:00 that same day, dye was released through Outfall 005 by combining it with the effluent. The middle of the dye release corresponded with high-tide, which occurred at approximately 14:45. A total of 29.9 kg of 20% dye solution was dispensed uniformly over the two hours. Therefore, 6 kg of pure dye was released and the mass load was approximately 0.83 grams/second. A complete description of the study and the data obtained are found in Battelle (1994), which has been reproduced as Appendix B of this memo.

Three tasks were performed based on the data obtained from the study. First, the minimum initial dilution was determined from known (discharged) and background dye concentrations. Second, the dispersion of the two-hour dye release was simulated using a circulation and transport model and compared with measured data collected shortly after release and additional data collected approximately one day later (Battelle, 1994). Lastly, the freshwater (treated effluent) released through Outfall 005 was simulated using the same models and the output was compared to the salinity measurements taken shortly after the dye release. Model results are included as Appendix A and the relevant data from the Battelle study are included in Appendix B.

Initial Dilution

The minimum initial dilution of Outfall 005 was determined from the known dye loading, background concentrations of dye, and the average flowrate over the two hours of dye release. The average hourly flows were recorded at the time of dye release: 236 MGD at 14:00, 240 MGD at 15:00, and 259 MGD at 16:00. Averaging these, a flowrate of 245 MGD over the two hours of dye release was assumed. The maximum concentration of dispensed dye (C_0) was, therefore, equal to the mass loading divided by the average flowrate, approximately 80 μg/L. Using this and the maximum concentration of dye found in the data collected (C_{max}), we can find the minimum initial dilution of Outfall 005. The maximum dye concentration occurred as the sampling vessel traversed the plume boil and was in the range of 35 to 40 μg/L. Two occurrences of this high concentration were observed at about 14:21 and about 14:25 on February 16 (Battelle Data Set 4), another observation was found at about 14:45 on February 16 (Data Set 6), and a final observation was found at about 15:00 on February 16 (Data Set 16). Using a basic equation to determine minimum initial dilution,

$$D_{min} = \frac{(C_o - C_b)}{(C_{max} - C_b)}$$

and assuming that the background concentration of dye, C_b, equals zero, we are able to find the range in minimum initial dilution for Outfall 005: D_{min} = 80/40 = 2.0 to 80/35 = 2.3. Results are equal (to one significant figure) to the theoretical initial dilution of 2 given for Outfall 005 in Technical Memo 1, Table 9 using the tidal current analysis and initial dilution models described in that document.

Similar calculations can also be made from the salinity measurements treating freshwater as the tracer. Corresponding to the three dye concentrations of about 40 μg/L were measured salinities of about 18, 12 and 14 PSU respectively. Assuming a background salinity of 31 PSU (as is assumed in the subsequent far field analysis), these low salinities correspond to dilutions of 31/(31-18), 31/(31-12), and 31/(31-14) or 2.4, 1.6 and 1.8 respectively. These are certainly in the same "ballpark" as the dye-derived initial dilutions and the slightly lower range of minimum dilutions for freshwater (1.6 to 2.4) versus dye (2.0 to 2.3) could reflect the greater build-up of freshwater due to the relatively long period of effluent discharge (compared with dye).

Simulated Dye Concentrations

The depth-averaged numerical models TEA and ELA (as described in Technical Memo 2) were used to simulate dye dispersion using a time step of 1/12 of a tidal cycle or approximately 1.03 hours. In the field study, dye was released at a rate of 3.0 kg/hour over a two hour period lasting from 14:00 through 16:00. Because high tide was at 14:45, the simulation assumed a release rate of 2.9 kg/hour over the 2.07 hour (2 time steps) interval of 14:45 to 16:49[2]. Spatial contour plots of modeled concentrations are shown in Appendix A for times of 16:49, 17:51, 18:53, 19:55, 20:57, 21:59, and 23:01 on February 16 and 00:03 and 01:05, on February 17. These nine figures are labeled ELA 2 through 10 in Appendix A. The times above were calculated from the number of timesteps following the beginning of dye release at "Hour 0". The label "Hours" in each of these figures actually refers to model timesteps, each of which is approximately 62 minutes.

These figures indicate that maximum resolvable concentrations of dye simulated by the model occur 1 to 2 hours after the beginning of the dye release and are equal to between 3 and 4 µg/L (ELA 2 and 3). Following the end of the release, the model indicates that concentrations between 0.1 and 0.5 µg/L are present until approximately 21:00 on February 16 (ELA 6) and, thereafter, between 0.05 and 0.1 µg/L through 01:00 the next day (ELA 7-10). The influence of tidal fluctuations upon dispersion can also be seen in the figures. ELA 2 indicates high concentrations to the west of Deer Island, ELA 3-7 indicate the outgoing tide as it disperses the dye, and ELA 8-10 indicate the return of the tide and substantially lower concentrations of dye.

By comparison, the 24-hour Battelle data set indicates a maximum measured concentration during the release of approximately 35-40 µg/L at the boil and between 0 and 15 µg/L away from the boil. After the end of the dye release, measured concentrations generally decline and by the next day concentrations of dye around Deer Island (including mid-Harbor and Broad Sound) are consistently between 0 and 0.2 µg/L.

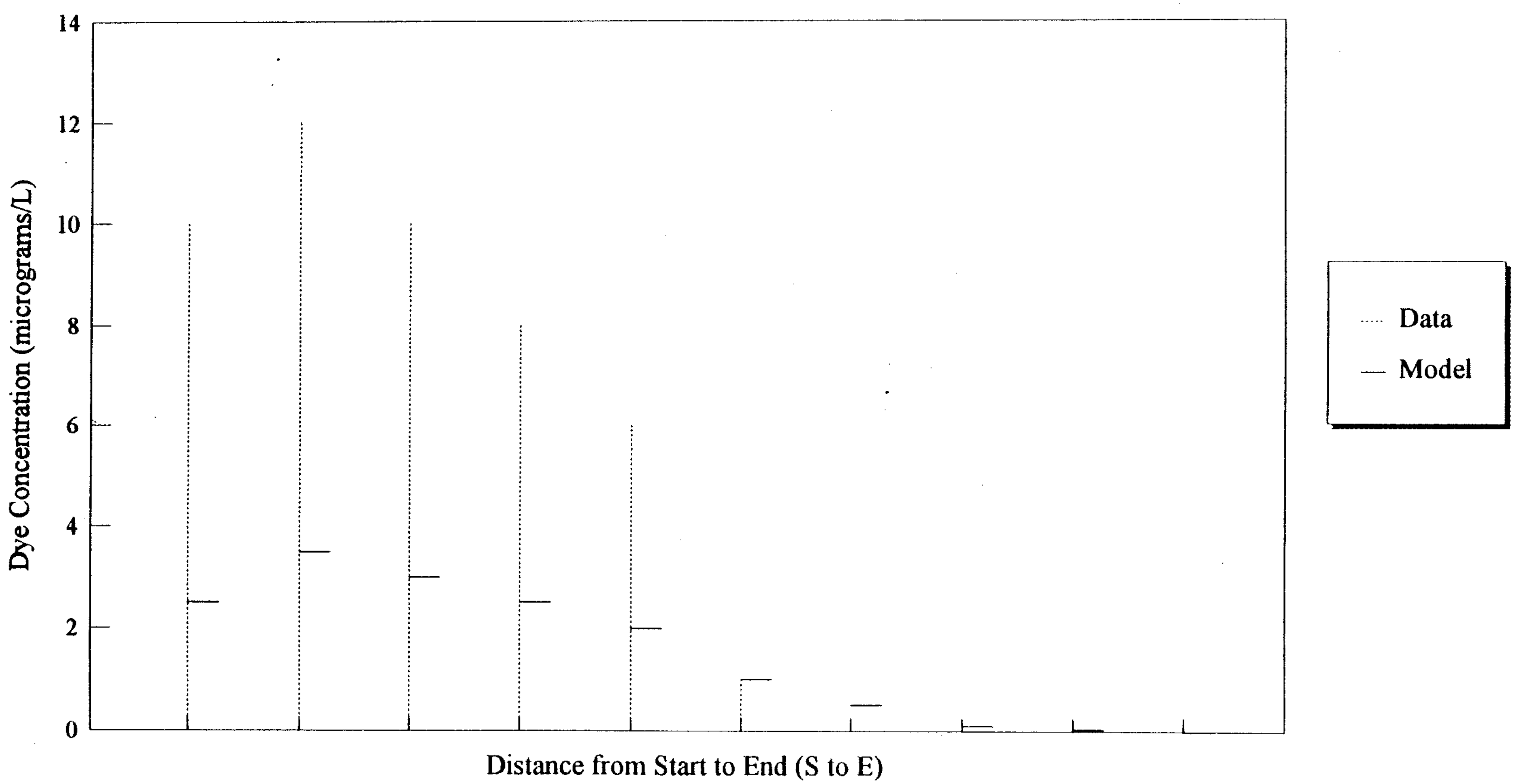
As discussed in the previous section on initial dilution, the maximum concentration found in the data set (35-40 µg/L) are directly over the discharge site and on the water surface whereas the model's maximum concentrations of 3-5 µg/L are depth-averaged and some distance away. The model's grid resolution is on the order of 100 meters and, therefore, care should be taken in the interpretation of spatial concentrations very near the outfall site.

Two analyses for comparing the measured and modeled far field dye concentrations were done. The first analysis used ELA 2 and data from Battelle Data Set 11 to compare dye concentrations immediately following the dye release on February 16th. Modeled concentrations at time 16:49 corresponding to the trackline of Data Set 11 have been plotted in Figure 1 by interpolation from ELA 2 and compared with the range of measurements presented in Data Set 11 (which correspond to times 16:12 to 16:54). A range was used because the measurements were taken in tow-yo fashion with the surface concentration exceeding the bottom concentrations by a

[2]This approximation was made because model simulations start at high tide.

Figure 1

Modeled versus measured dye concentrations along trajectory in Data Set 11 soon after dye release



Source: Data, Battelle Data Set 11; Model, ELA 2 considerable margin. The predictions show a similar trend as the data and fall in between the high and low values at each station.

The vertical stratification of dye is consistent with similar stratification of other discharge contaminants such as the volatile halogenated organic compounds (VHOCs) studied by Kossik et al (1986). While Kossik observed stratification of VHOCs near the main Deer Island outfalls in President Roads, concentrations were essentially well-mixed throughout most of the harbor west of the outfall, justifying use of the depth-averaging TEA/ELA models.

An attempt was also made to compare measured and modeled dye concentrations approximately one day after the dye release (there were no measurements between approximately 17:00 on February 16 and 09:00 on February 17). Data Sets 29, 30, 33, and 34 correspond to times 13:18 to 16:18 or about 24 hours after the start of dye release. These measurements show concentrations ranging generally between 0 and 0.05 μg/L except for an occasional spike such as the apparent peak of about 0.3 μg/L found in Data Set 30. Note that these peaks correspond with the peaks in the beam attenuation data. While an attempt was made to eliminate this correlation in the calibration of dye fluorescence (Battelle, 1994), we suspect that the dye peaks really reflect peaks in turbidity.

Alternatively, they could reflect residual dye which was somehow bleeding out of the system long after the dye release was officially stopped. In either case, it is doubtful that these peaks of relatively high concentrations could reflect dye which was discharged 24 hours earlier because the spatial concentration gradients are simply too great, especially considering the turbulent mixing that would have resulted from the continued discharge of effluent. Meanwhile model concentrations presented for similar times in ELA (plots not shown) range between 0.014 and 0.023 μg/L, which is roughly similar to the measurements.

Because of the low concentrations and the possible residual interference from beam attenuation, this agreement is more qualitative than quantitative. Nonetheless, the predicted dye concentrations of about 0.02 μg/L represent a dilution of about 4000 after only about two tidal cycles. And, for the most part, measured dye concentrations indicate even greater dilutions. Hence, both model and measurements are indicating substantial dilution, despite the poor initial dilution and the nearshore location of the outfall.

Simulated Salinity Concentrations

Salinity was modeled using TEA/ELA by treating freshwater effluent as a tracer and converting model concentrations to salinity (PSU) assuming a known background salinity of 31

PSU. The simulation began with the beginning of effluent release through Outfall 005 (February 7) and was continued through the duration of measurements on February 17. Thus Outfall 005 was in operation for about nine days prior to the dye release and near-field salinities were assumed to have approached steady-state within that time frame.

As with the dye simulation, the salinity simulation used a time step of 1/12 of a tidal cycle (approximately 62 minutes or 1.02 hours) and spatial contour plots of modeled salinities are shown in Appendix A at times of 15:47, 16:49, 17:51, 20:57, on February 16 and 00:03 and 17:37 on February 17. These six plots are indicated as ELA 11-16 and represent conditions 1, 2, 3, 6, 9, and 26 model time steps after the simulated start of dye release.

The comparison between modeled and measured salinity is shown in Figure 2 and corresponds to conditions approximately one hour after the beginning of dye release. Thus modeled salinities at time 16:49 corresponding to the trackline of Data Set 11 have been plotted in Figure 2 by interpolation from ELA 12 and compared with the range of measurements presented in Data Set 11. Again, a range of measurements was used because the sampling was conducted in tow-yo fashion with surface salinities being significantly lower than those measured at depths. As with the dye comparison, the predictions show a similar trend as the data and generally fall between the high and low values at each station.

Conclusions

The following conclusions can be drawn from this study.

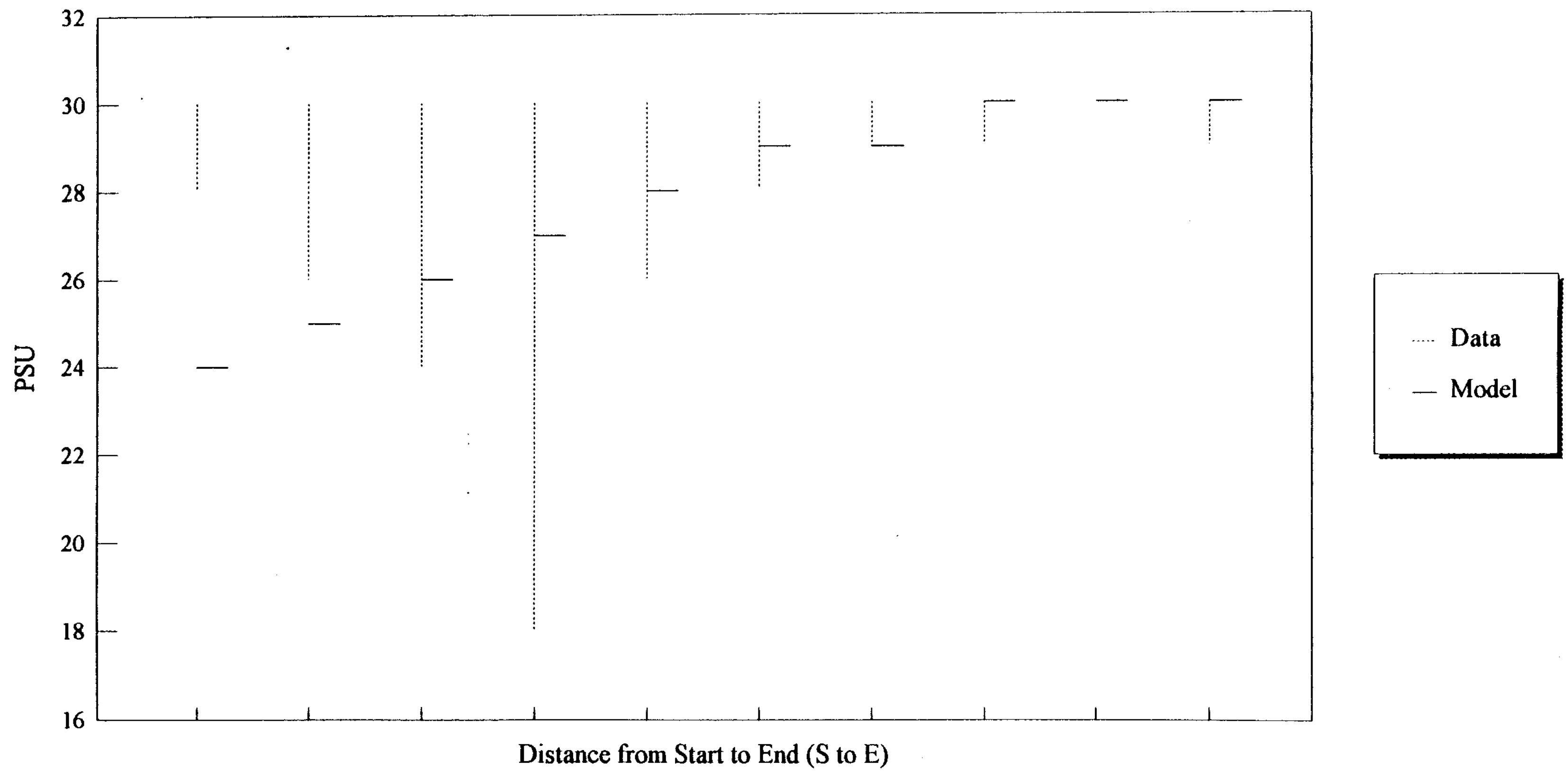
1) Minimum initial dilutions computed from measured dye and salinity were about 2, which is identical (to one significant figure) with the results of initial dilution calculations conducted for Outfall 005 in Technical Memo 1. ± 50%

2) Both dye and salinity measurements in the vicinity of the outfall show significant vertical variations which can not be represented by the depth-averaged TEA/ELA calculations. This stratification is similar to that observed with other effluent contaminants (e.g., the VHOCs measured by Kossik et al (1986) discharged through the main Deer Island Outfalls 001 and 002).

3) Dye concentrations predicted shortly after dye release for a trajectory extending away from the outfall (Data Set 11) were between the maximum measured dye concentrations (on the surface) and the minimum measured dye concentrations (at depths). Similarly, modeled salinities were

Figure 2

Modeled versus measured salinity along trajectory in Data Set 11 approx. one week after beginning of effluent release



Source: Data, Battelle Data Set 11; Model, ELA 12 generally between the minimum measured salinity (on the surface) and the maximum measured salinity (at depths). While the vertical stratification in the measured concentrations makes a precise comparison with depth-averaged model predictions difficult, the comparisons show that the model is able to predict the correct range of depth-averaged concentrations.

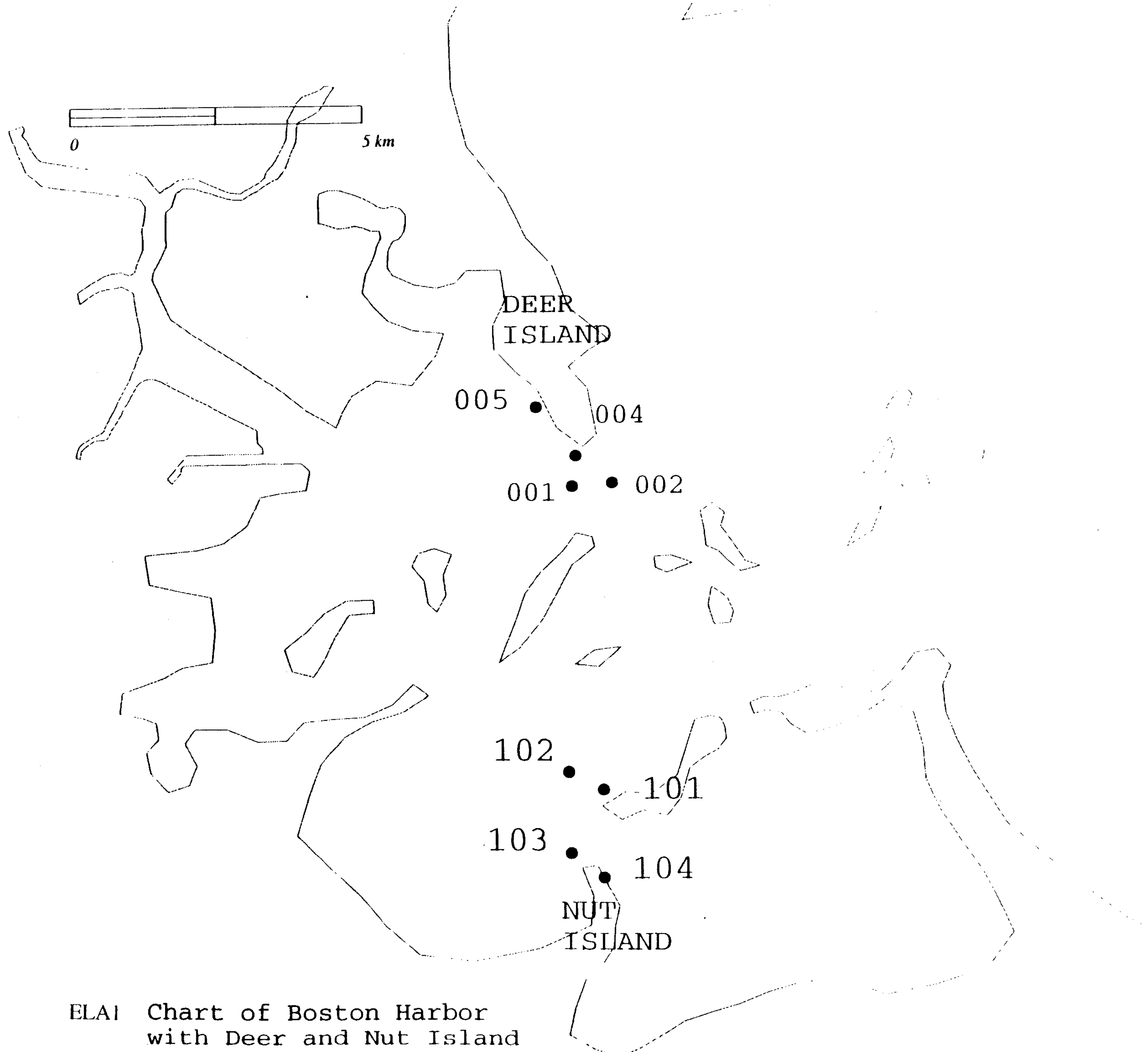
4) Simulations one day after the dye release suggest a reasonably uniform spatial distribution of dye concentrations in the vicinity of the outfall. Compared with the initial (discharged) dye concentrations, these concentrations reflect a dilution of about 4000. For the most part, corresponding measurements suggest even lower concentrations, although small pockets with concentrations up to ten times the predicted concentrations are observed. We suspect these pockets of high concentration are not real but, even if they are, both model and measurement indicate that effluent discharged through Outfall 005 will receive substantial far field mixing despite the poor initial mixing and the short outfall length.

References

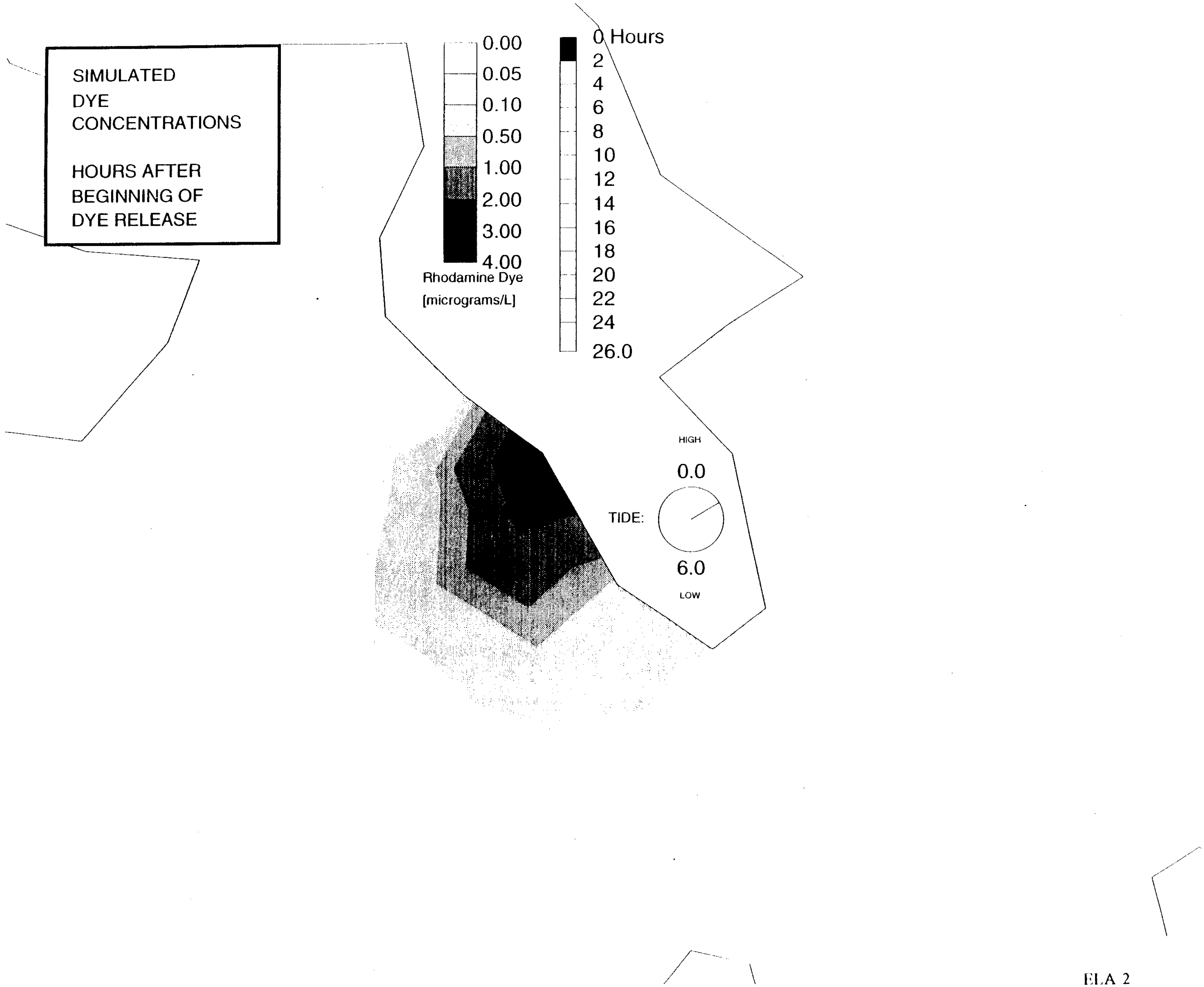
Battelle Ocean Sciences. 1994. Deer Island Dye Plume Tracking Survey Report. Prepared for the MWRA, Environmental Quality Dept., Boston, MA.

Kossik, R.F., P.S. Gschwend and E.E. Adams. 1986. Tracing and Modeling Pollutant Transport in Boston Harbor. MIT Sea Grant Report No. 86-016.

APPENDIX A: ELA MODEL RESULTS

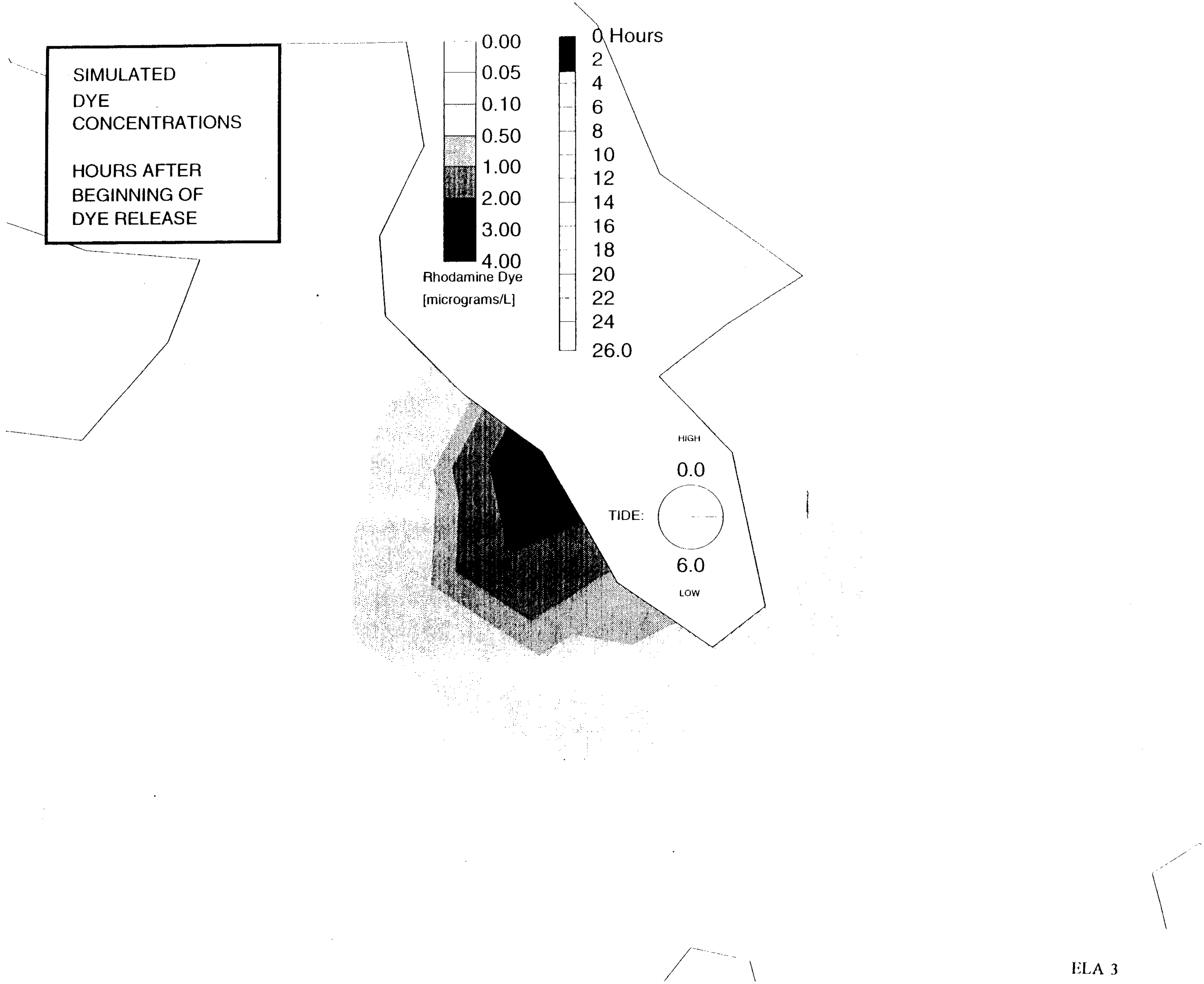


ELA1 Chart of Boston Harbor with Deer and Nut Island outfall locations

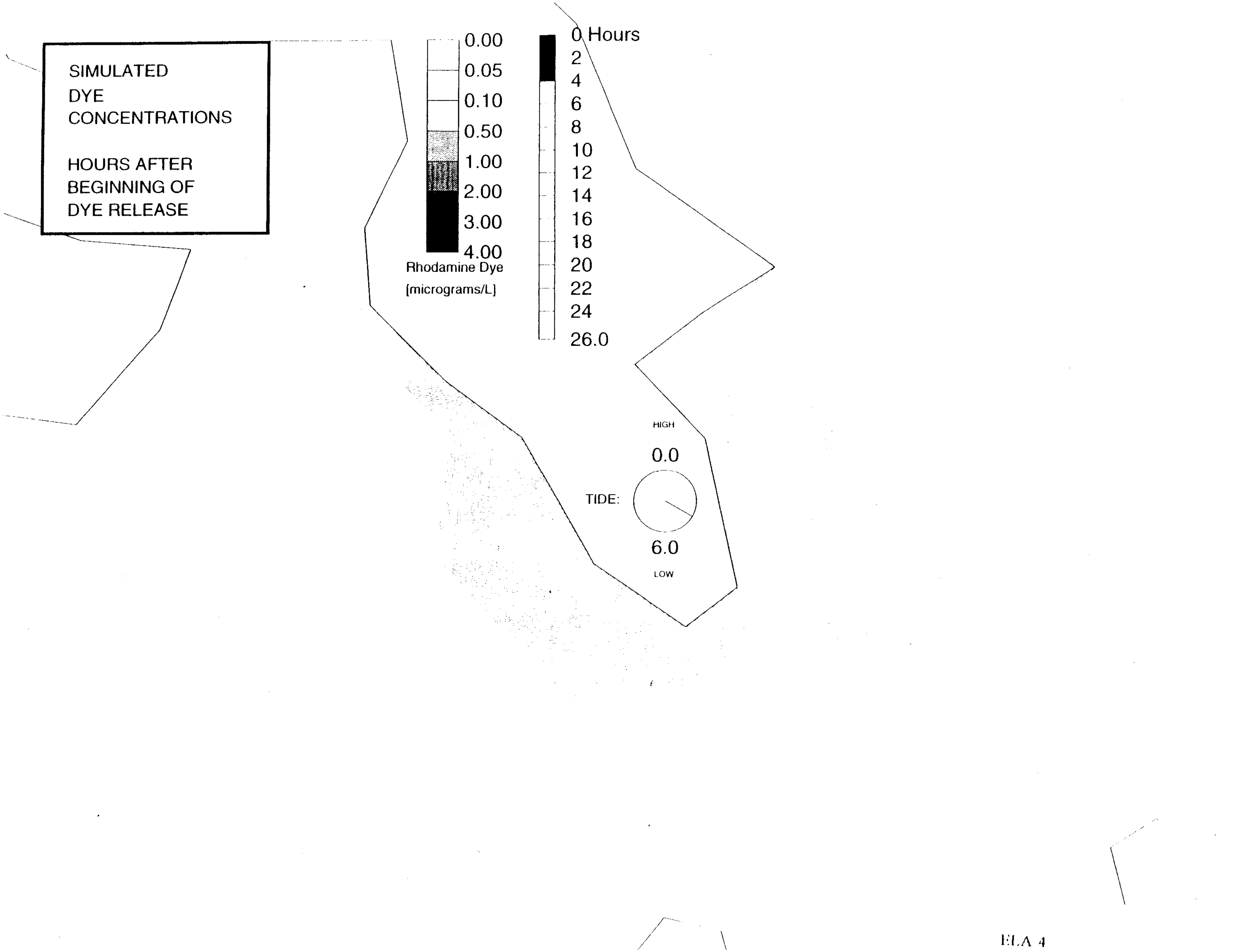


SIMULATED
DYE
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0.00
0.05
0.10
0.50
1.00
2.00
3.00
4.00
Rhodamine Dye
[micrograms/L]
0 Hours
2
4
6
8
10
12
14
16
18
20
22
24
26.0
HIGH
0.0
TIDE:
6.0
LOW

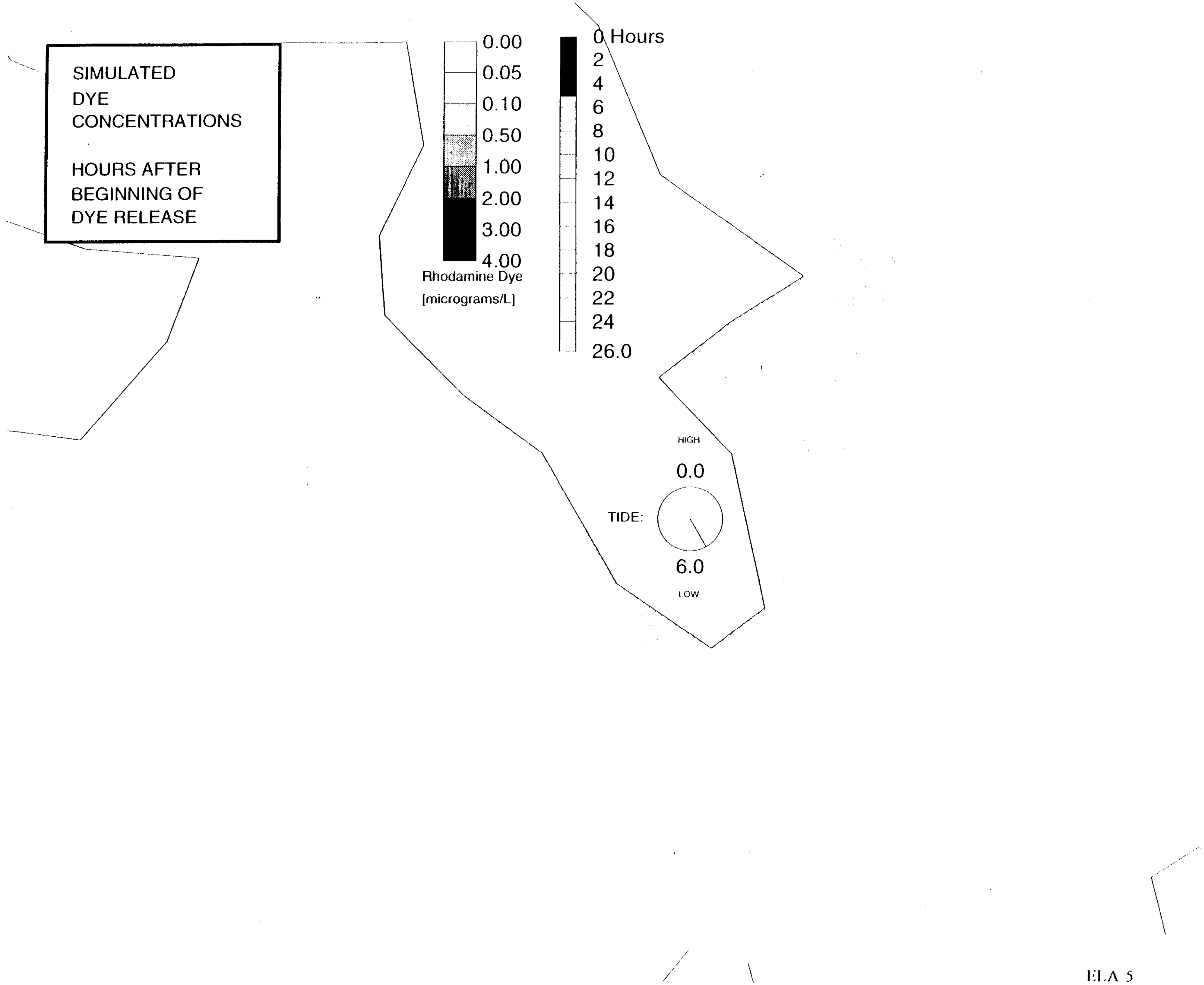
ELA 2


SIMULATED
DYE
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0.00
0.05
0.10
0.50
1.00
2.00
3.00
4.00
Rhodamine Dye
[micrograms/L]
0 Hours
2
4
6
8
10
12
14
16
18
20
22
24
26.0
TIDE:
HIGH
0.0
6.0
LOW

ELA 3


SIMULATED
DYE
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0.00
0.05
0.10
0.50
1.00
2.00
3.00
4.00
Rhodamine Dye
[micrograms/L]
0 Hours
2
4
6
8
10
12
14
16
18
20
22
24
26.0
HIGH
0.0
TIDE:
6.0
LOW

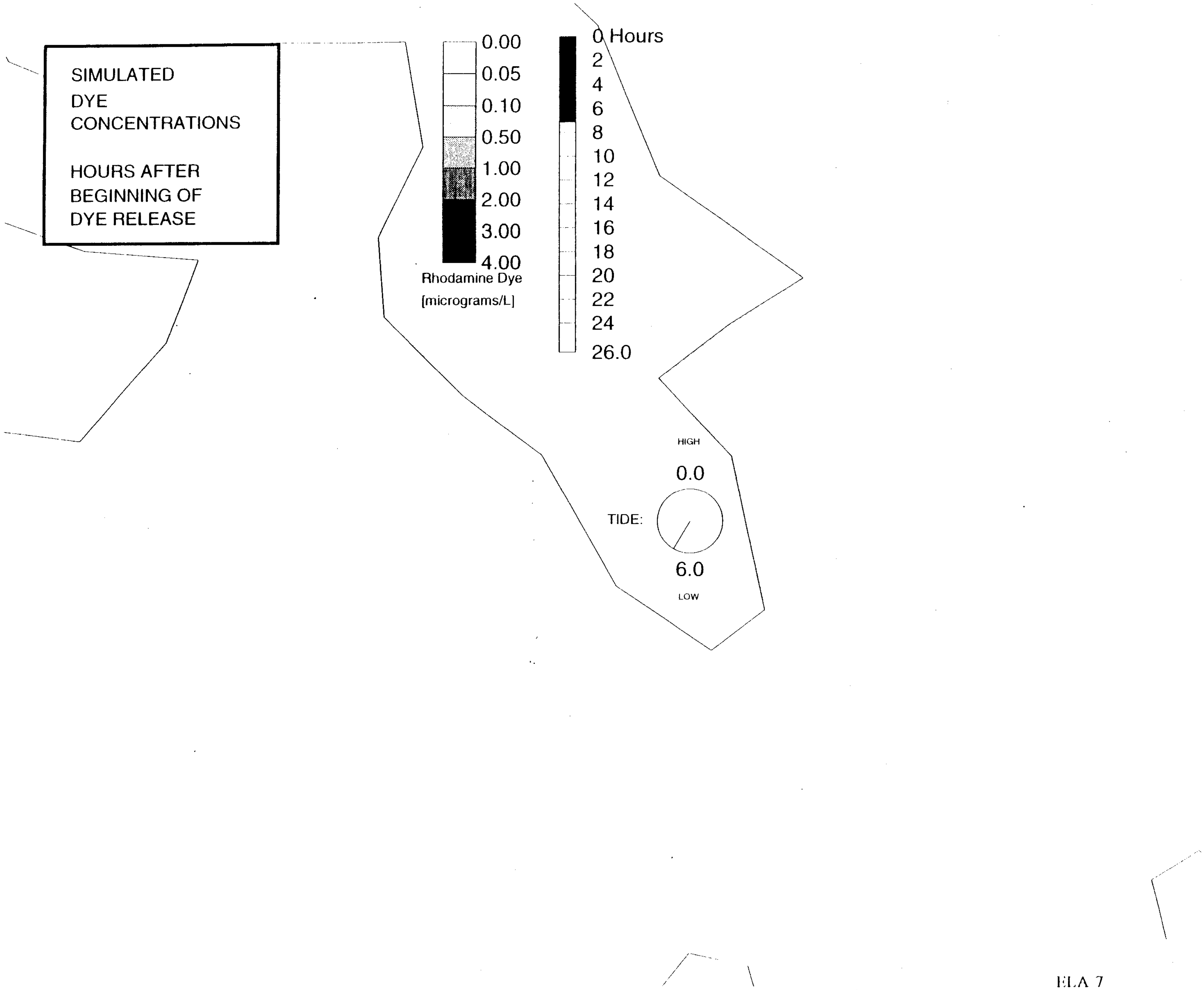
ELA 4


SIMULATED
DYE
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0.00
0.05
0.10
0.50
1.00
2.00
3.00
4.00
Rhodamine Dye
[micrograms/L]
0 Hours
2
4
6
8
10
12
14
16
18
20
22
24
26.0
TIDE:
HIGH
0.0
6.0
LOW

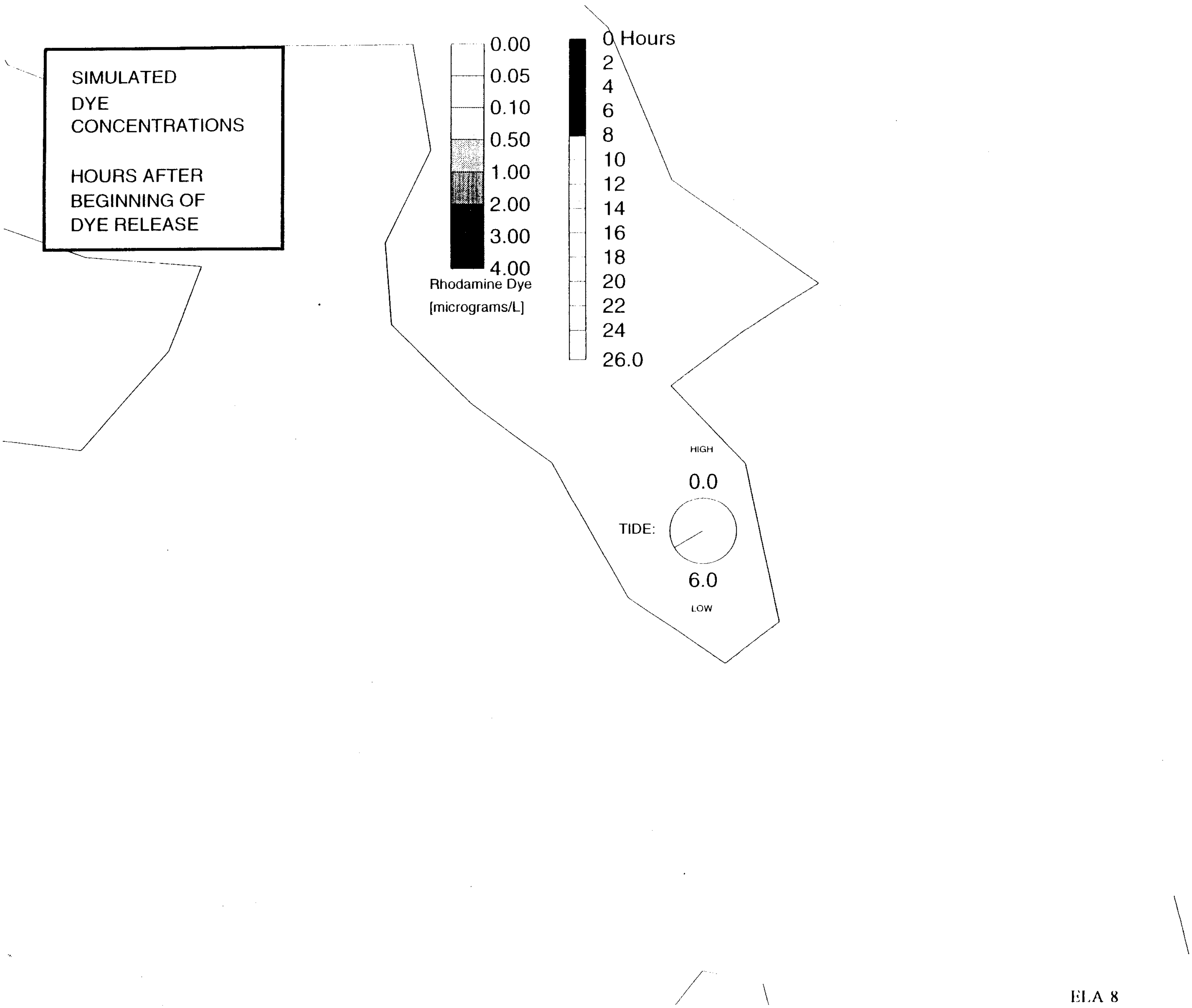
ELA 5

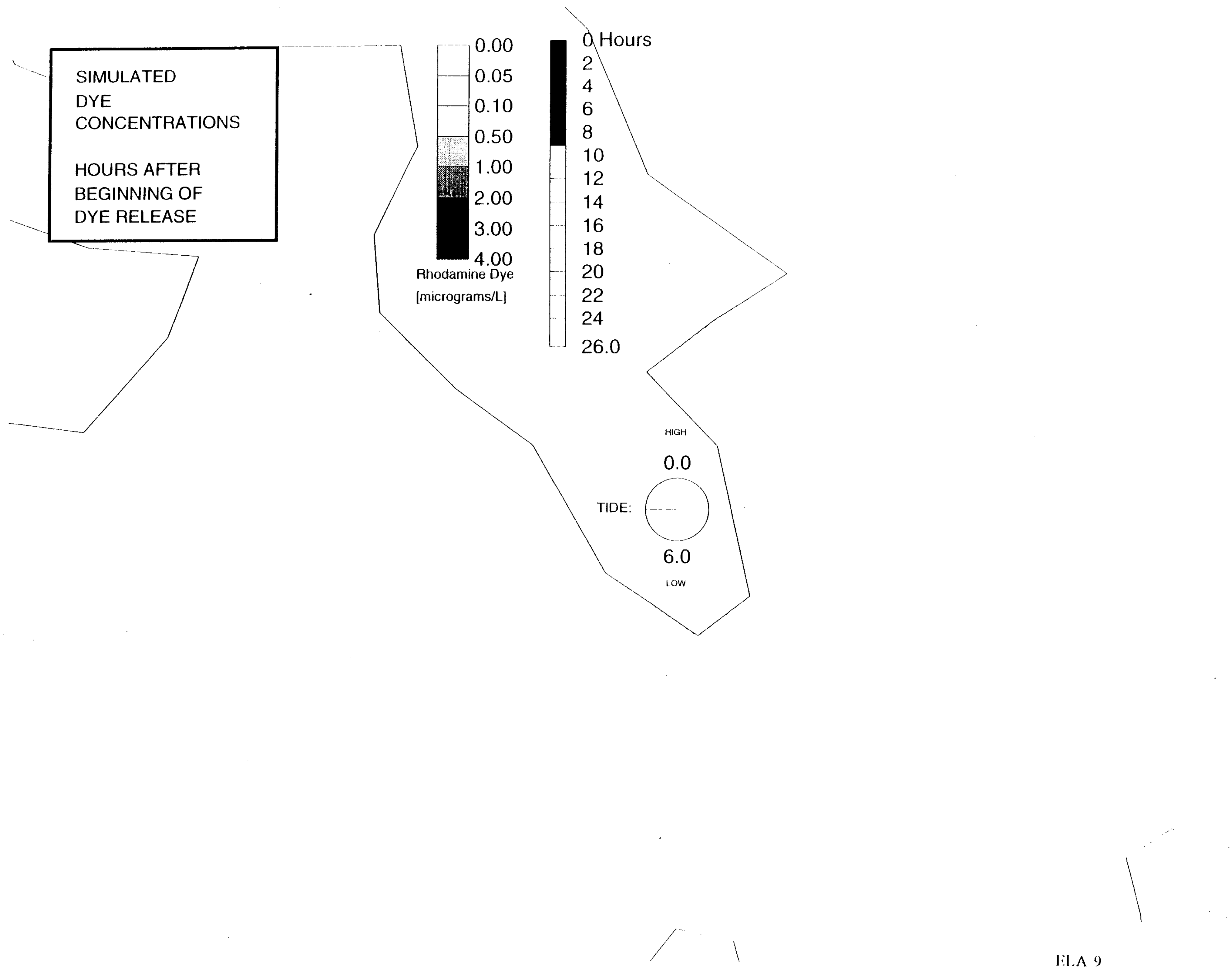
SIMULATED
DYE
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0.00
0.05
0.10
0.50
1.00
2.00
3.00
4.00
Rhodamine Dye
[micrograms/L]
0 Hours
2
4
6
8
10
12
14
16
18
20
22
24
26.0
HIGH
0.0
TIDE:
6.0
LOW

ELA 6

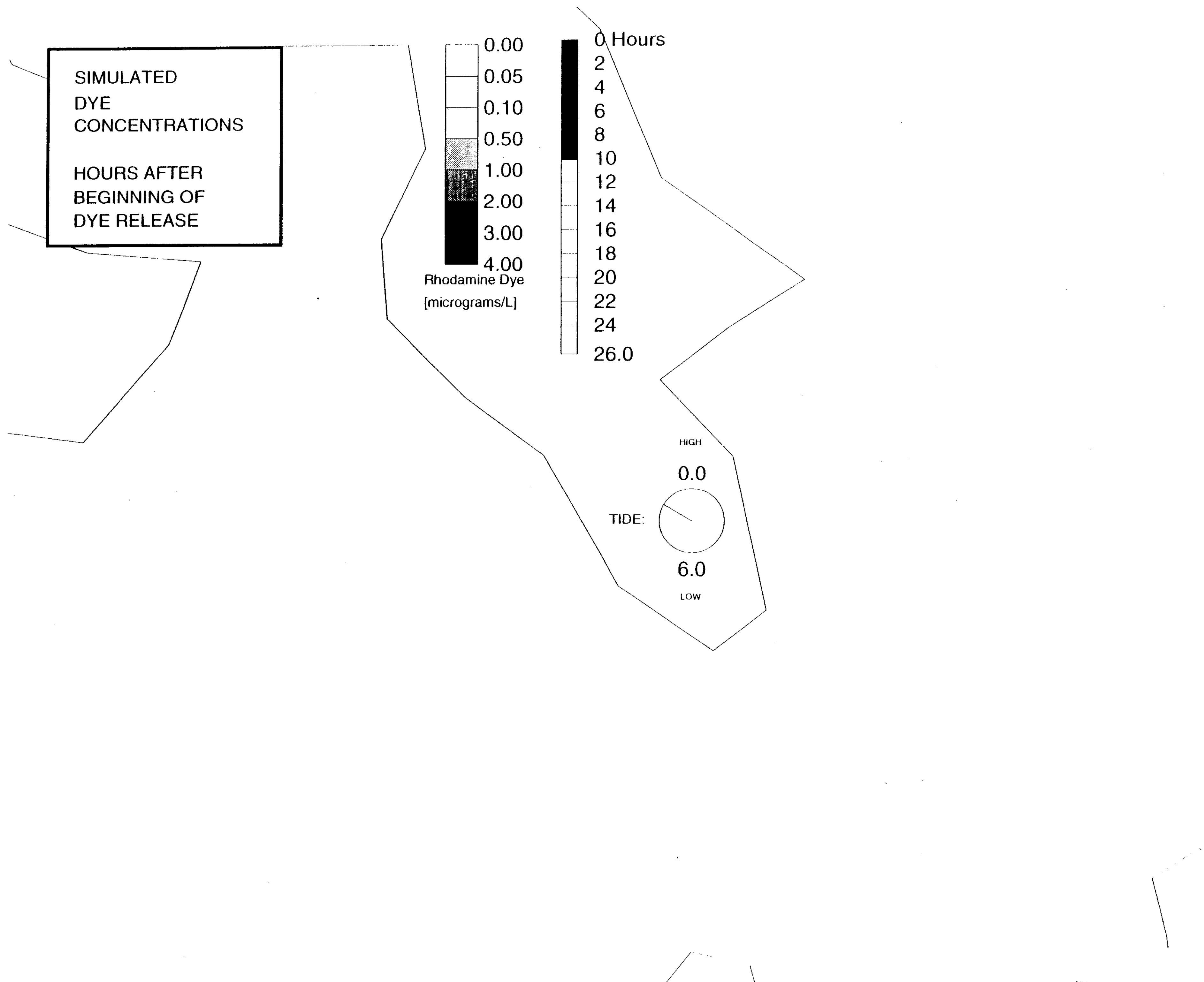

SIMULATED
DYE
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0.00
0.05
0.10
0.50
1.00
2.00
3.00
4.00
Rhodamine Dye
[micrograms/L]
0 Hours
2
4
6
8
10
12
14
16
18
20
22
24
26.0
TIDE:
HIGH
0.0
6.0
LOW

ELA 7

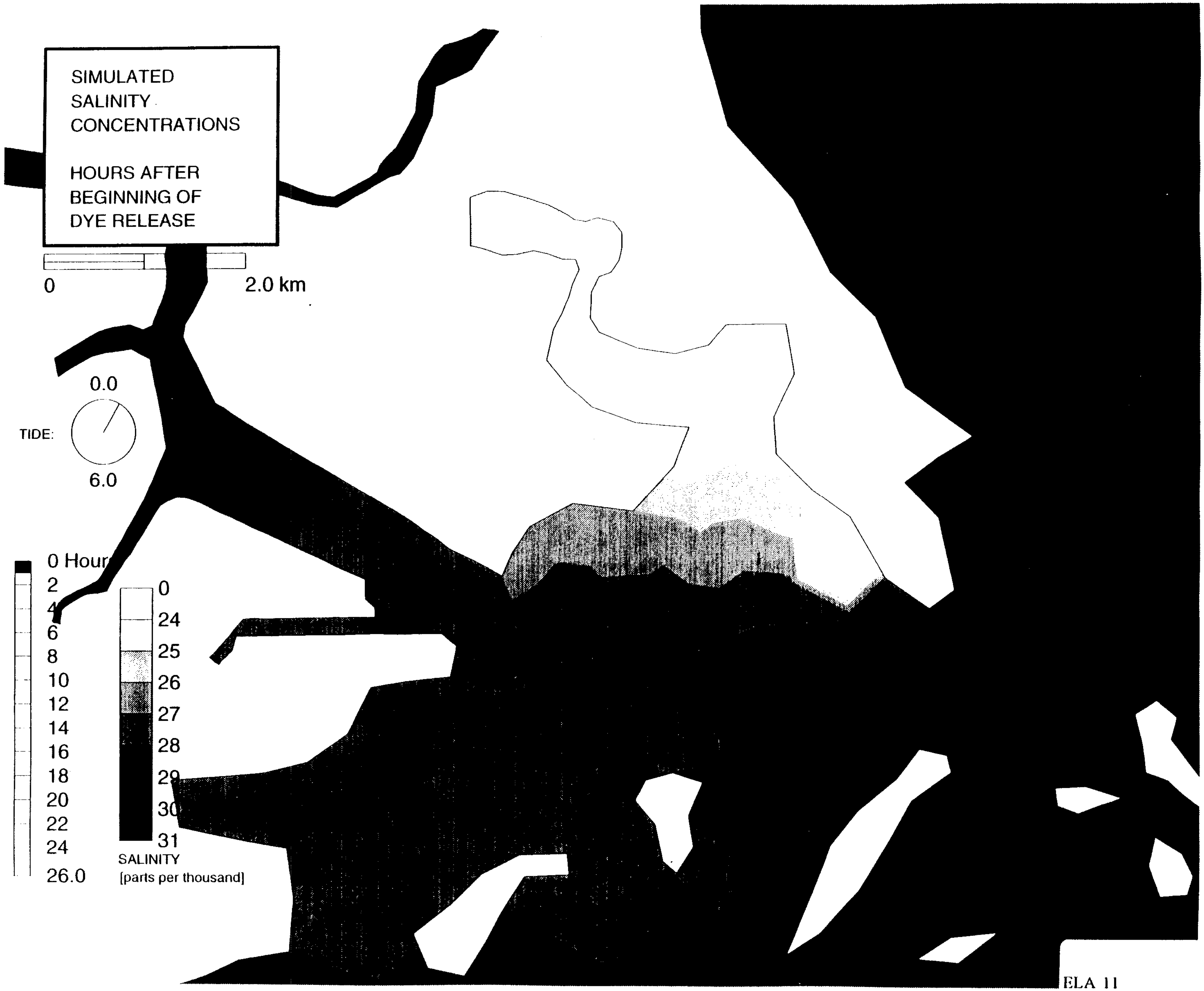

SIMULATED
DYE
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0.00
0.05
0.10
0.50
1.00
2.00
3.00
4.00
Rhodamine Dye
[micrograms/L]
0 Hours
2
4
6
8
10
12
14
16
18
20
22
24
26.0
TIDE:
HIGH
0.0
6.0
LOW


SIMULATED
DYE
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0.00
0.05
0.10
0.50
1.00
2.00
3.00
4.00
Rhodamine Dye
[micrograms/L]
0 Hours
2
4
6
8
10
12
14
16
18
20
22
24
26.0
HIGH
0.0
TIDE:
6.0
LOW

ELA 9

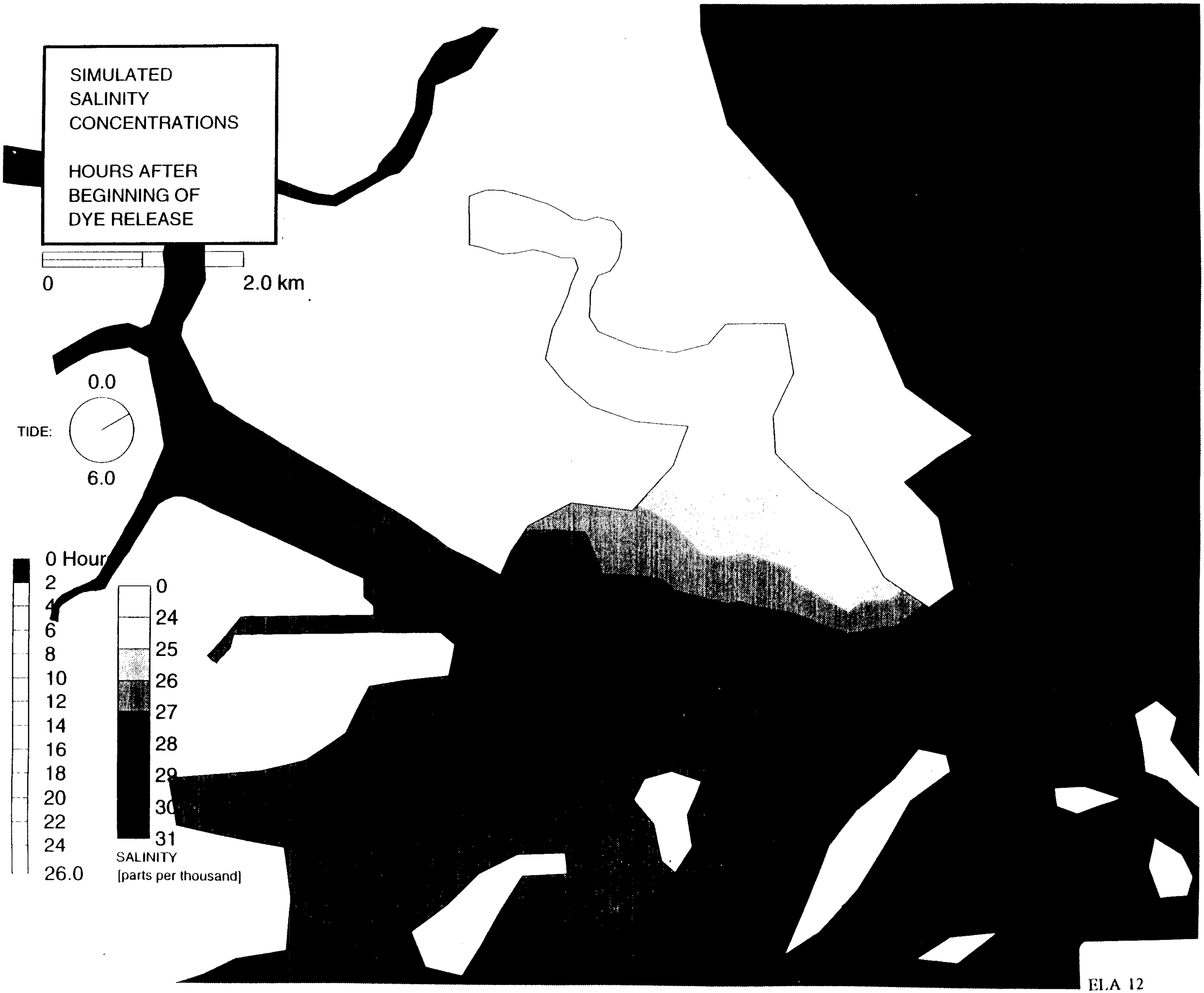

SIMULATED
DYE
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0.00
0.05
0.10
0.50
1.00
2.00
3.00
4.00
Rhodamine Dye
[micrograms/L]
0 Hours
2
4
6
8
10
12
14
16
18
20
22
24
26.0
HIGH
0.0
TIDE:
6.0
LOW

ELA 10

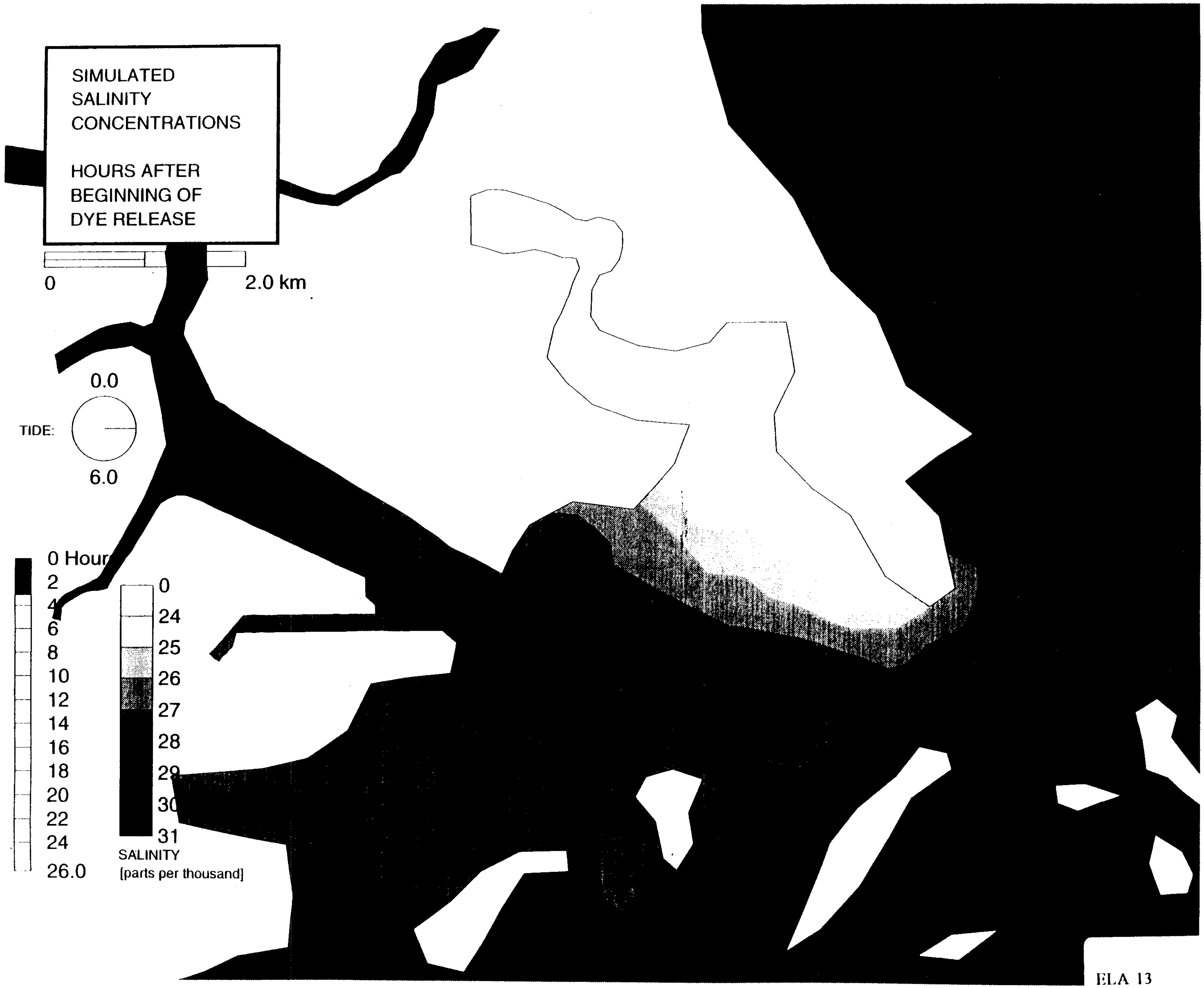


SIMULATED
SALINITY
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0
2.0 km
TIDE:
0.0
6.0
0 Hours
2
4
6
8
10
12
14
16
18
20
22
24
26.0
0
24
25
26
27
28
29
30
31
SALINITY
[parts per thousand]

ELA 11

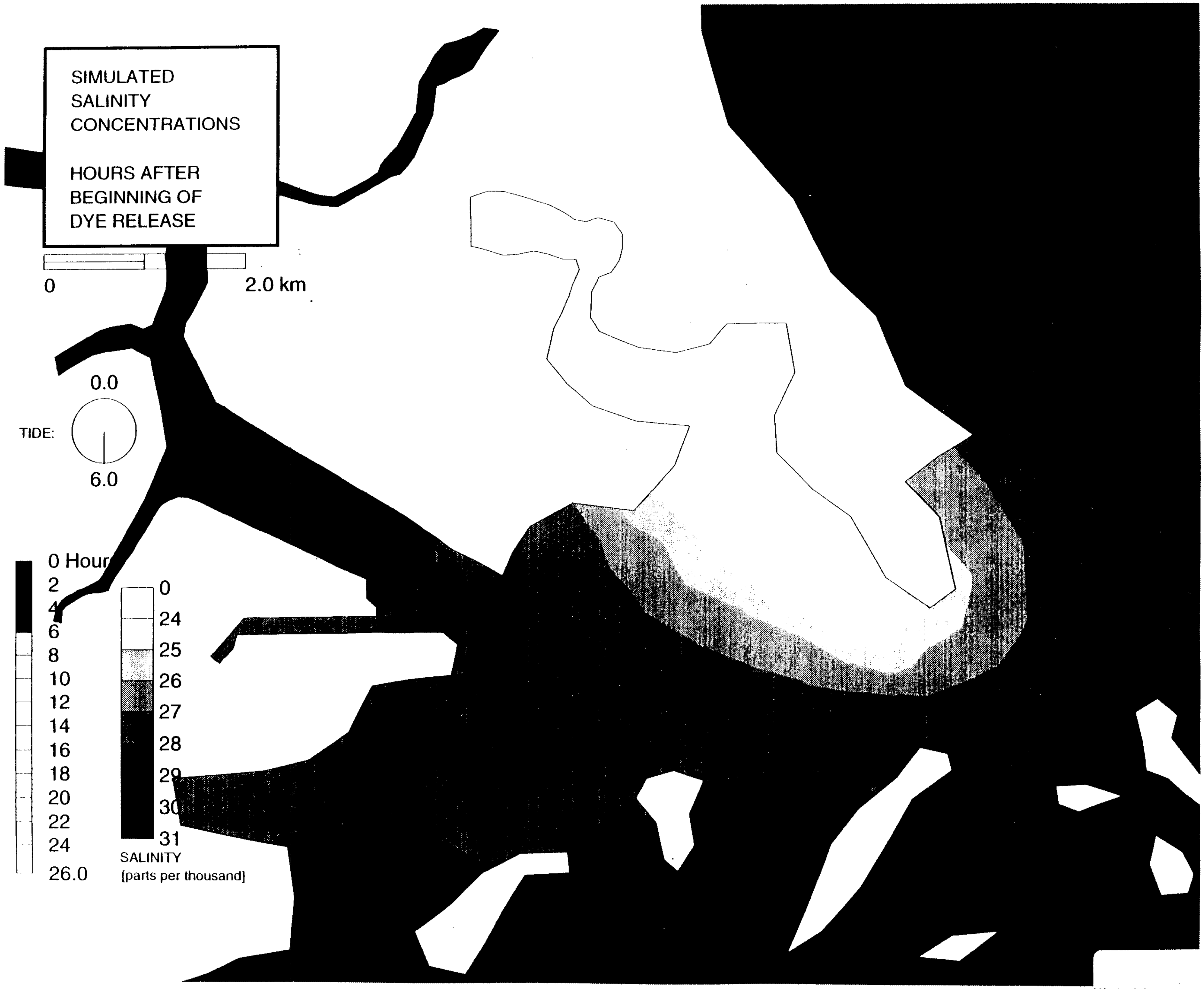

SIMULATED
SALINITY
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0
2.0 km
0.0
TIDE:
6.0
0 Hour
2
4
6
8
10
12
14
16
18
20
22
24
26.0
0
24
25
26
27
28
29
30
31
SALINITY
[parts per thousand]

ELA 12



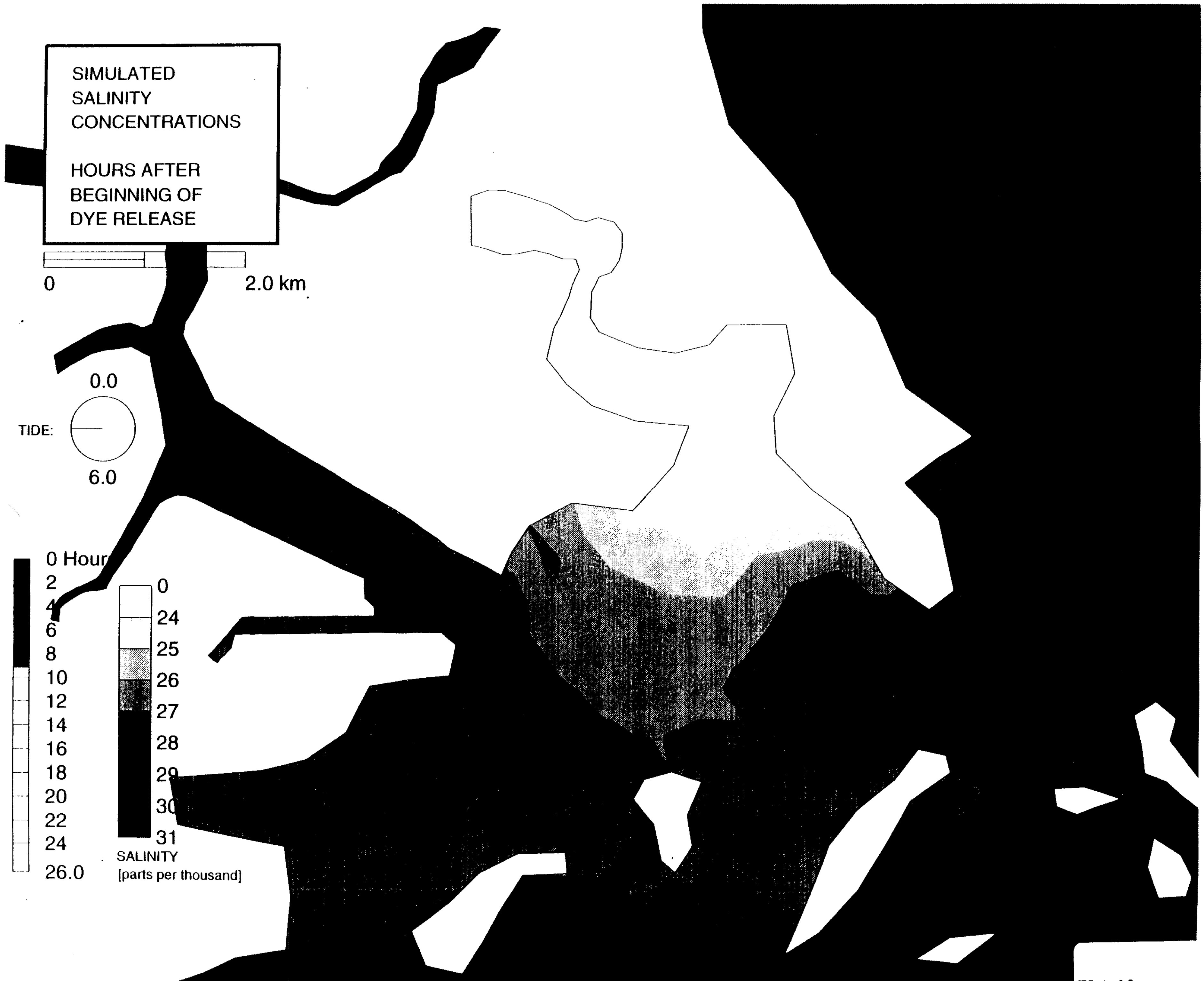
SIMULATED
SALINITY
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0
2.0 km
0.0
TIDE:
6.0
0 Hour
2
4
6
8
10
12
14
16
18
20
22
24
26.0
0
24
25
26
27
28
29
30
31
SALINITY
[parts per thousand]

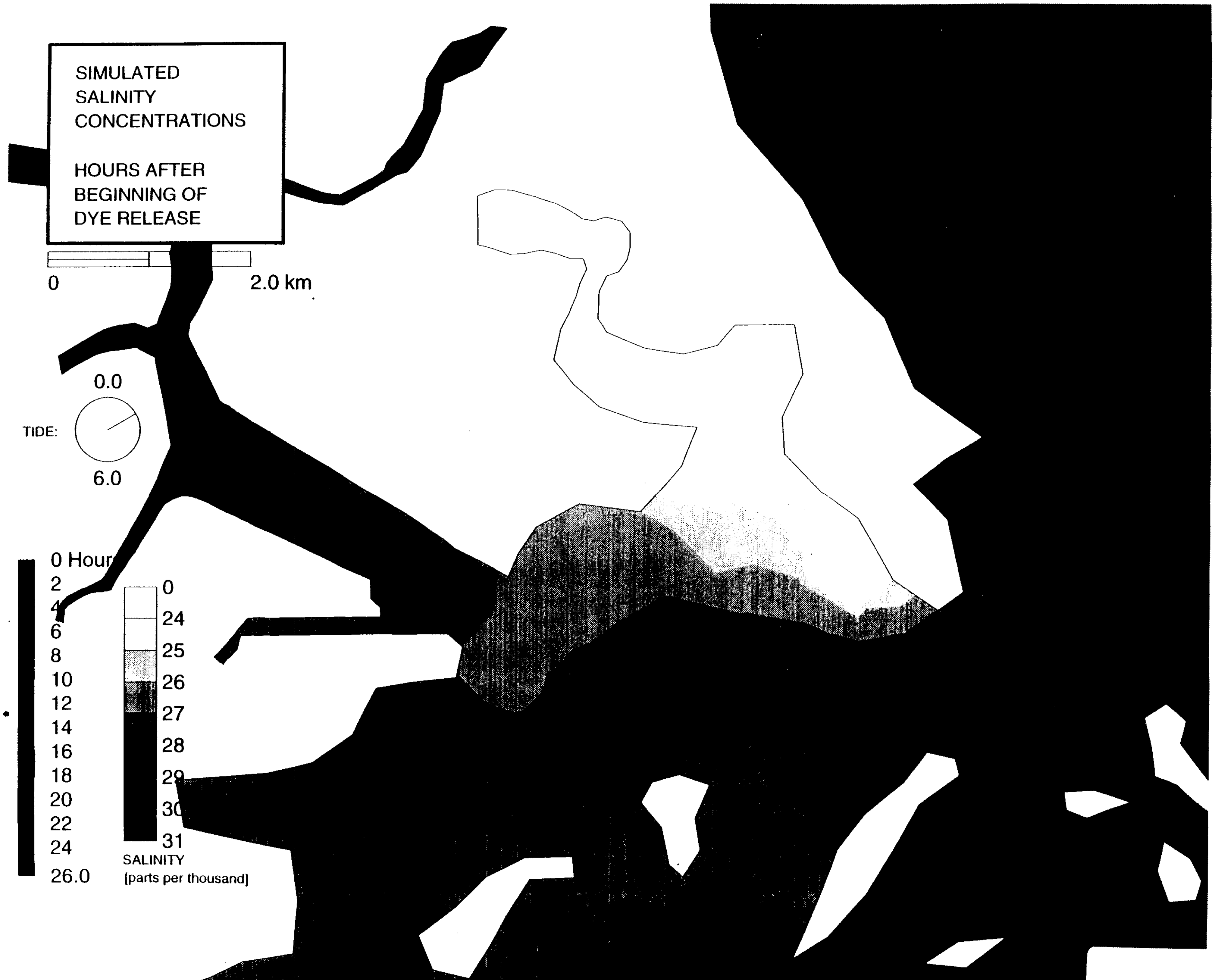
ELA 13



SIMULATED
SALINITY
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0
2.0 km
TIDE:
0.0
6.0
0 Hour
2
4
6
8
10
12
14
16
18
20
22
24
26.0
0
24
25
26
27
28
29
30
31
SALINITY
[parts per thousand]

ELA 14


SIMULATED
SALINITY
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0
2.0 km
TIDE:
0.0
6.0
0 Hour
2
4
6
8
10
12
14
16
18
20
22
24
26.0
0
24
25
26
27
28
29
30
31
SALINITY
[parts per thousand]


SIMULATED
SALINITY
CONCENTRATIONS
HOURS AFTER
BEGINNING OF
DYE RELEASE
0
2.0 km
TIDE:
0.0
6.0
0 Hour
2
4
6
8
10
12
14
16
18
20
22
24
26.0
0
24
25
26
27
28
29
30
31
SALINITY
[parts per thousand]

ELA 16

APPENDIX B: BATTELLE REPORT