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6306 21st Ave. NE
Seattle, Washington 98115

A STUDY OF CURRENT PROPERTIES AND MIXING USING DROGUE MOVEMENTS OBSERVED DURING SUMMER AND WINTER IN CENTRAL PUGET SOUND, WASHINGTON

FINAL REPORT

by

Curtis C. Ebbesmeyer and Jonathan M. Helseth

for the

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Approved by:

Curtis C. Ebbesmeyer
Principal Investigator

ABSTRACT

As one of the Puget Sound Interim Studies, groups of drogues (i.e., current followers) were released over the West Point sewage outfall at depths of maximum effluent concentration. Through statistical analysis of subsequent drogue positions, the relative dilution of maximum concentration has been determined using an appropriate form of the Lagrangian diffusion equation during seven ebb, seven flood and two slack tidal phases in summer and winter.

By separating the eddy spectrum at the drogue group's effective diameter (average = 0.9 km) larger scale eddies appear as shear of the mean flow, whereas smaller scale eddies appear as turbulence characterized by an eddy diffusivity (average = 2.2×10^4 cm^2 s^{-1}). During established tidal currents the effluent is primarily stirred by the mean flow and large-scale eddies, thereby producing complex patterns of relatively concentrated filaments and patches. During slack tides, increased fluid accelerations rearrange and divide the larger eddies resulting in an increased supply of small-scale eddies, which more effectively disperse patches and filaments.

The net result is about a 1:10 dilution of maximum concentration over four hours during major flood or ebb tides compared with more rapid dilution proportional to t^{-x}, $x > 1.2$, during slack tides. Some effluent patches may retain their identity through several tidal phases as observed in photographs of dye injected into the Puget Sound Model. Those photographs also show an eddy in West Point's lee on selected flood tides as confirmed on two occasions by drogue trajectories.

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Cooperative Efforts

This work represents one of the Puget Sound Interim Studies initiated by the Municipality of Metropolitan Seattle (Metro). More specifically, this study is designed to provide a quantitative description of currents and mixing in support of a major dye study undertaken concurrently by the Applied Physics Laboratory (APL) at the University of Washington (UW). A closely related study of effluent dispersal using the Puget Sound Model of the UW Department of Oceanography provided supporting data for both studies.

Acknowledgements

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The drogues were constructed by Beth Chiodo and Dick Sylwester at Shoreline Community College. We are grateful to them and Jack Serwold, coordinator of the Marine Technician Program at Shoreline Community College for their fine work. Drogues were monitored from U.S. Geological Survey research vessel Hydor under the expert navigation of Bill Clique, and a National Oceanic and Atmospheric Administration survey vessel kindly supplied by Captain G.L. Short and navigated by Ray Schmidt. Sextant fixes were taken by Beth Chiodo, Joseph Glasscock, Lincoln Loehr, Jolene Patricelli and Dave Thomson. Joseph Glasscock, Jolene Patricelli and Darrell Terry plotted and digitized the fixes.

We are also grateful to Bill Bendiner and Richard D. Tomlinson for providing liaison with APL and Metro, respectively. Under separate contract John H. Lincoln at the UW Department of Oceanography took 16-mm film of the Puget Sound Model. With his guidance we reviewed that unique film and took pictures of selected frames.

We also wish to acknowledge the continued guidance of Professor Emeritus Clifford A. Barnes at the UW Department of Oceanography and Professor Akira Okubo at the Marine Sciences Research Center, State University of New York, Stony Brook, New York.

I. Summary

This study is designed to provide a quantitative description of currents and mixing in support of a comprehensive dye study undertaken concurrently by the Applied Physics Laboratory* (abbreviated APL). The objective of that study is to trace sewage effluent stained with a fluorescent dye as it flows away from the West Point outfall during the summer period 30 August-4 September 1974 and the winter period 25 February-4 March 1975 (Figure 1).

Methods and initial results of the summer drogue study were reported by Ebbesmeyer and Okubo (1974). The present study reports the winter observations with a reanalysis of the summer data. The observations of both summer and winter may be described briefly as follows: groups of drogues (usually seven) were released over the outfall during selected tidal phases at nominal depths of maximum dye concentration (50 m in summer; 20 m in winter). Drogue positions, obtained from two small craft using sextants at 5-15 minute intervals, were plotted and then processed on a high speed computer using statistical regression procedures and an appropriate form of the Lagrangian diffusion equation. Table 1 shows general information for releases of 16 drogue groups.

The analysis separates the eddy spectrum at the drogue group's effective diameter (average = 0.9 km) so that larger scale eddies appear as shear of the mean flow (see Table 2), and smaller scale eddies appear as turbulence characterized by an eddy diffusivity (Table 3: average = 2.2×10^4 cm^2 s^{-1}). During established tidal currents the effluent is

*At the University of Washington, Seattle, Washington.

primarily stirred by the mean flow and large-scale eddies, thereby producing complex patterns of concentrated filaments and patches. Maximum concentrations within patches require about four hours or five kilometers to achieve a 1:10 dilution.* After an initial interval of slower decay, maximum concentrations decay at the rate of approximately $t^{-1.2}$ (Figure 2*).

During slack tide, increased fluid accelerations rearrange and divide the larger eddies resulting in an increased supply of small-scale eddies. The result is an increased rate of dilution according to t^{-2} to t^{-4} for patches toward shore, while patches toward mid-channel may only experience decay rates moderately faster than $t^{-1.2}$.

Figure 3 shows drogue plumes for all releases. Superpositions of these on corresponding photographs of dye injected into the Puget Sound Model show that drogue plumes often approximate dye plumes (cf., Plates I,II). Deviations occur due to dye recirculated from previous tidal phases. Drogue trajectories tend to follow the more concentrated filaments and patches.

The photographs also indicate an asymmetrical distribution of patchiness between ebb and flood tides, possibly as a result of net freshwater accumulation flowing northward. During flood tides two types of patchiness are often evident: (1) effluent patches dispersed between mid-channel and Magnolia Bluff; (2) an eddy in West Point's lee circulating counterclockwise. Ebbs produce a characteristic filamentary dispersion sweeping northward around Meadow Point. Selected patches were observed to maintain their identity for up to 15 hours.

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*Because of assumptions basic to the Lagrangian diffusion equation these dilutions should be treated as estimates of maximum dilution.

Table 1. General information for summer and winter drogue studies.

Date	Tidal phase	Tidal range (m)	# drogues launched	Depth (m)	Hour first drogue launched	Hour last drogue retrieved	Elapsed time (h)
8-30-74	Flood	3.2	7	50	13.4	19.5	6.1
8-31-74	"	3.1	7	50	12.2	19.1	6.9
9- 1-74	"	3.0	7	50	11.5	17.6	6.1
9- 2-74	"	2.9	7	50	12.8	18.5	5.7
2-25-75	"	2.1	5	20	14.5	17.3	2.8
9- 3-74	Ebb	2.3	6	50	7.3	12.1	4.8
2-26-75	"	3.0	7	20	8.5	11.8	3.3
2-27-75	"	3.4	6	20	7.9	12.2	4.3
2-28-75	"	3.6	7	20	8.2	11.7	3.5
3- 1-75	"	3.7	7	20	8.7	14.7	6.0
3- 2-75	"	3.6	7	20	9.5	14.3	4.8
3- 3-75	"	3.4	7	20	9.5	15.4	5.9
9- 3-74	Slack		4	50	12.7	14.7	2.0
2-28-75	"		7	20	13.1	16.2	3.1
2-26-75	Shilshole flood	2.6	5	20	13.8	17.8	4.0
2-27-75	Flood eddy	2.9	6	20	14.2	18.7	4.5

Table 1 Cont'd.

Date	Tidal phase	Interval analyzed for current properties	Initial area of group (km^2)	Final area of group (km^2)	Average drogue speed ($cm\ s^{-1}$)	Average wind speed* (kn)
8-30-74	Flood	14.2-15.8	.741	.612	32.8	5.9
8-31-74	"	13.1-16.3	.366	8.75	18.1	5.3
9- 1-74	"	12.8-16.9	.816	4.99	19.1	6.7
9- 2-74	"	13.7-17.4	.288	3.42	23.4	7.0
2-25-75	"	14.8-16.8	.0644	.418	27.3	15.0
9- 3-74	Ebb	8.2- 9.5	.411	.501	29.0	7.8
2-26-75	"	9.0-11.2	.0775	.496	37.8	14.1
2-27-75	"	8.8-11.7	.0685	.254	36.7	5.7
2-28-75	"	8.8-11.2	.166	.471	42.9	12.4
3- 1-75	"	9.3-13.0	.124	2.49	36.1	7.7
3- 2-75	"	9.9-13.6	.340	.443	42.4	20.1
3- 3-75	"	9.8-15.0	.175	.621	46.9	16.9
9- 3-74	Slack	13.2-14.1	.256	.806	18.8	7.8
2-28-75	"	13.7-15.8	.137	.254	17.9	12.4
2-26-75	Shilshole flood	15.5-17.3	.0868	.241	17.0	14.1
2-27-75	Flood eddy	14.8-18.3	.0382	.206	13.5	5.7

* 24 hour averages. Summer values from Sea-Tac airport. Winter values from UW weather station at West Point (courtesy of E. E. Collias).

Table 2. Average centroid speed and properties of the mean flow and eddies larger than drogue groups.

Date	Tidal phase	Centroid speed ($cm\ s^{-1}$) mean	Centroid speed ($cm\ s^{-1}$) std. dev.	Horizontal divergence ($10^{-4}\ s^{-1}$) mean	Horizontal divergence ($10^{-4}\ s^{-1}$) std. dev.	Relative vorticity ($10^{-4}\ s^{-1}$) mean	Relative vorticity ($10^{-4}\ s^{-1}$) std. dev.
8-30-74	Flood	32.8	2.10	-.535	1.72	-4.33	.908
8-31-74	"	18.1	6.60	2.89	2.93	1.96	1.41
9-1 -74	"	19.1	3.39	1.21	.178	-.566	1.09
9-2 -74	"	23.4	6.91	1.29	1.81	1.52	.703
2-25-75	"	27.3	11.0	2.43	.739	1.04	1.48
9-3 -74	Ebb	29.0	3.26	.344	1.06	-1.81	.644
2-26-75	"	37.8	4.66	1.83	1.77	3.16	2.74
2-27-75	"	36.7	7.63	1.05	1.99	.877	1.72
2-28-75	"	42.9	1.04	1.05	1.13	.928	2.07
3-1 -75	"	36.1	4.09	2.17	1.13	-.833	.609
3-2 -75	"	42.4	1.37	.279	.989	-.747	.626
3-3 -75	"	46.9	7.18	.764	.858	-.290	.567
9-3 -74	Slack	18.8	2.15	4.96	2.38	1.72	1.84
2-28-75	"	17.9	8.05	.633	1.25	-2.58	1.89
2-26-75	Shilshole flood	17.0	6.06	1.52	3.55	-.924	2.38
2-27-75	Flood eddy	13.5	6.56	1.11	3.78	.144	2.88

Table 2. Cont'd.

Date	Tidal phase	Stretching deformation (10^{-4} s^{-1}) mean	Stretching deformation (10^{-4} s^{-1}) std. dev.	Shearing deformation (10^{-4} s^{-1}) mean	Shearing deformation (10^{-4} s^{-1}) std. dev.	No. of data points
8-30-74	Flood	-.474	1.52	-.724	.928	13
8-31-74	"	-.309	3.30	-.876	1.07	29
9-1 -74	"	.748	.538	-.240	1.30	38
9-2 -74	"	.0781	1.93	-.116	1.17	34
2-25-75	"	.115	2.15	.326	1.26	17
9-3 -74	Ebb	.484	.354	-3.70	.755	10
2-26-75	"	4.40	2.88	1.07	1.56	19
2-27-75	"	1.14	3.98	1.52	2.64	26
2-28-75	"	-.767	2.79	-1.67	2.18	21
3-1 -75	"	.0881	.361	.531	.357	34
3-2 -75	"	.554	.920	.675	1.09	34
3-3 -75	"	.419	.591	-.282	1.57	51
9-3 -74	Slack	-.756	1.44	-1.76	2.75	6
2-28-75	"	-.566	.838	.972	1.57	18
	Shilshole					
2-26-75	Flood	-1.80	3.33	2.49	2.96	15
2-27-75	Flood eddy	-1.17	6.56	.123	2.72	32

Table 3. Horizontal eddy diffusivity and mean division between large and small scale eddies.

Date	Tidal phase	Horizontal eddy diffusivity (10^4 cm^2 s^{-1})	Mean division* between large and small scale eddies (km)	No. of data points
8-30-74	Flood	.711	.836	13
8-31-74	"	9.23	1.63	29
9-1 -74	"	4.78	1.64	38
9-2 -74	"	5.58	1.38	34
2-25-75	"	.208	.516	17
9-3 -74	Ebb	.799	.824	10
2-26-75	"	2.08	.680	19
2-27-75	"	.386	.400	26
2-28-75	"	.289	.576	21
3-1 -75	"	.445	1.16	34
3-2 -75	"	.904	.692	34
3-3 -75	"	.494	.584	51
9-3 -74	Slack	2.03	.728	6
2-28-75	"	.221	.472	18
2-26-75	Shilshole Flood	.852	.616	15
2-27-75	Flood eddy	.156	.360	32

*Diameter of drogue group.

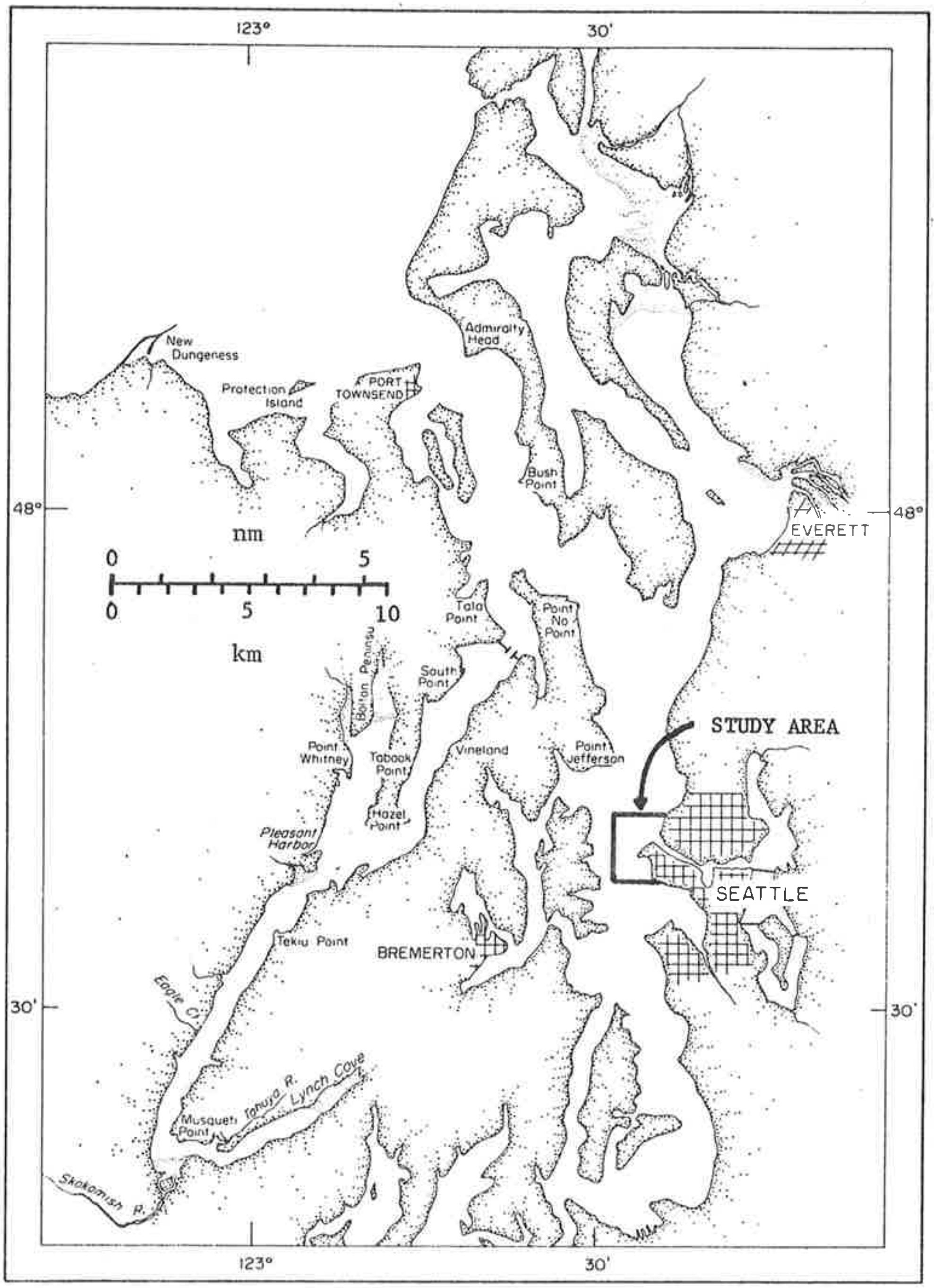

Figure 1. Puget Sound and study area.

Plate I. Photograph of dye injected into Puget Sound Model during flood tide of 27 February 1975. Note eddy in West Point's lee and three patches between Magnolia Bluff and mid-channel. For comparison with corresponding drogue plume and trajectories see Figures 3a3 and 8a3, respectively.

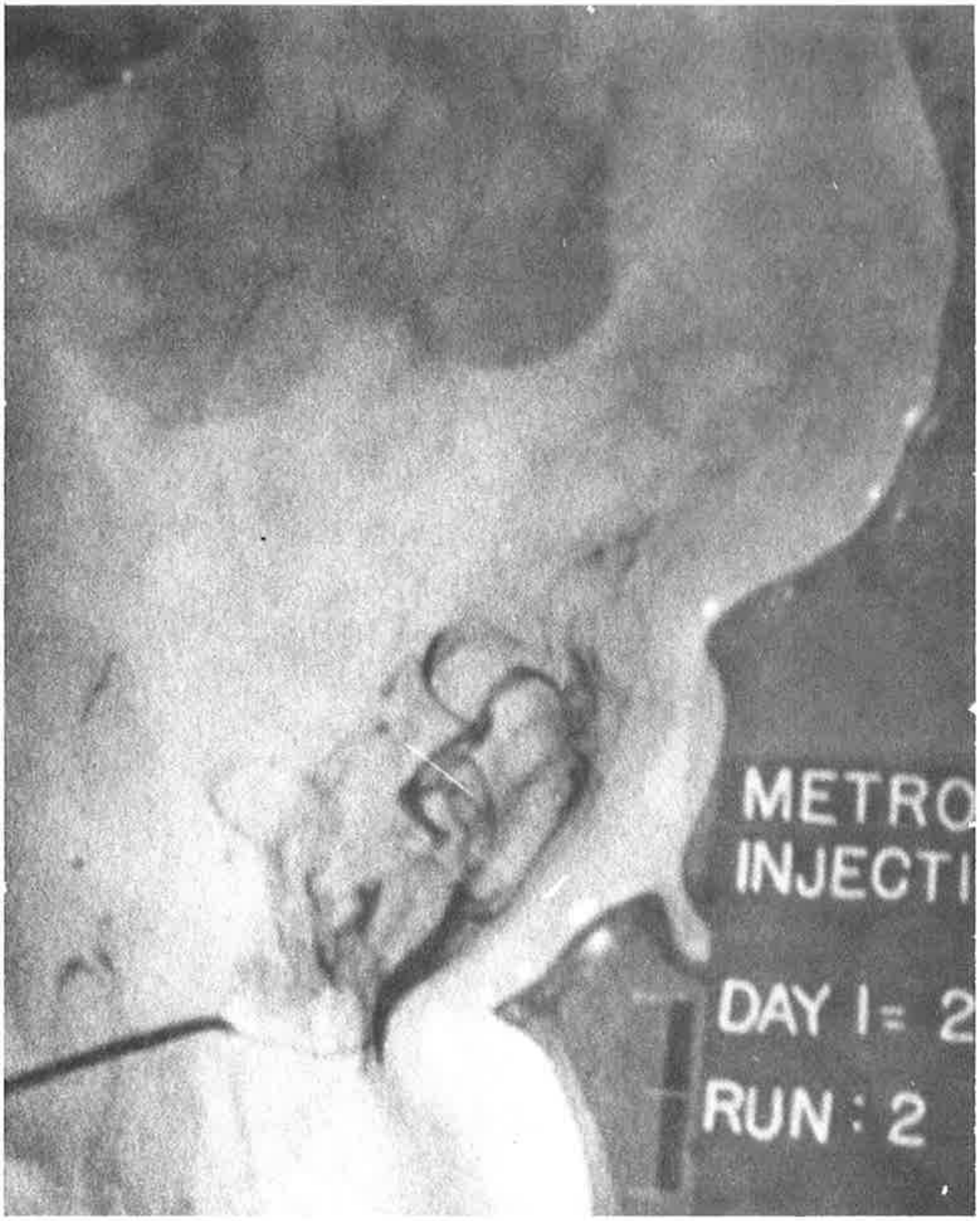

Plate II. Photograph of dye injected into Puget Sound Model during ebb tide of 1 March 1975. For comparison with corresponding drogue plume and trajectories see Figures 3b4 and 8b4, respectively.

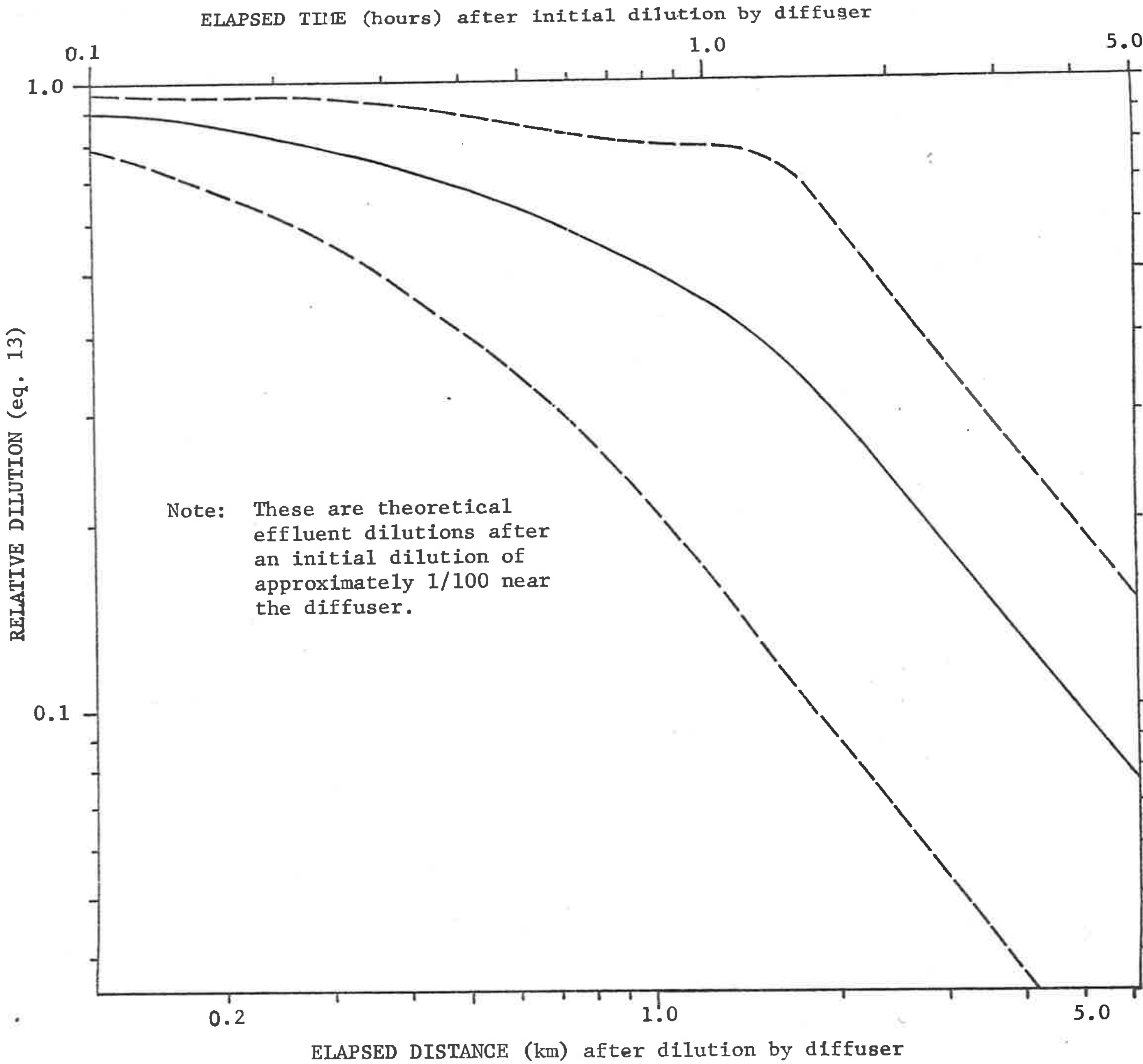

Figure 2a. Average and limits of relative dilution of maximum concentration. Average consists of five flood and seven ebb tides listed in Tables 1-3.

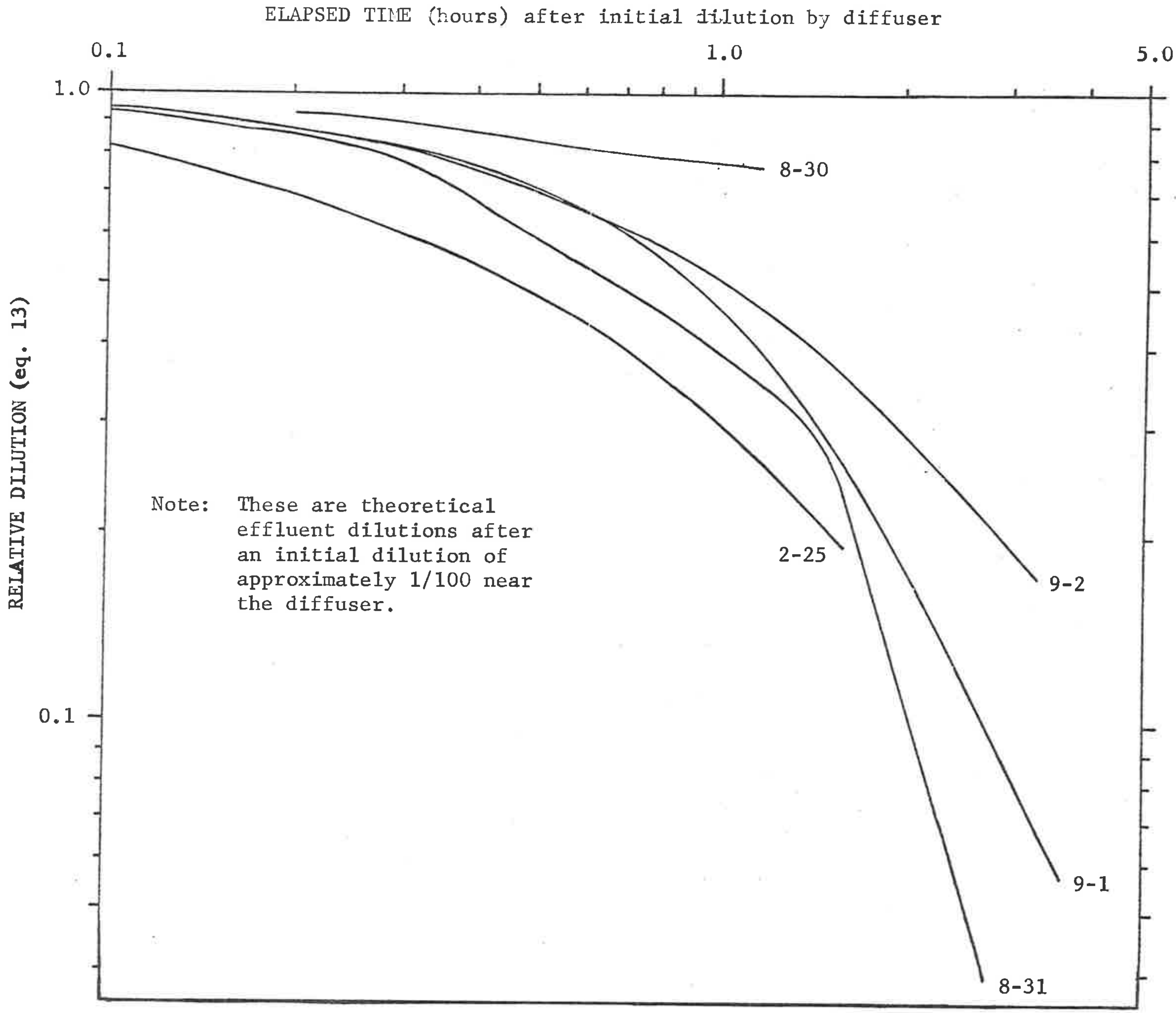

Figure 2b1. Relative dilution of maximum concentration for flood tides versus elapsed time.

ELAPSED DISTANCE (km) after initial dilution by diffuser

Figure 2b1. Relative dilution of maximum concentration for flood
tides versus elapsed time.

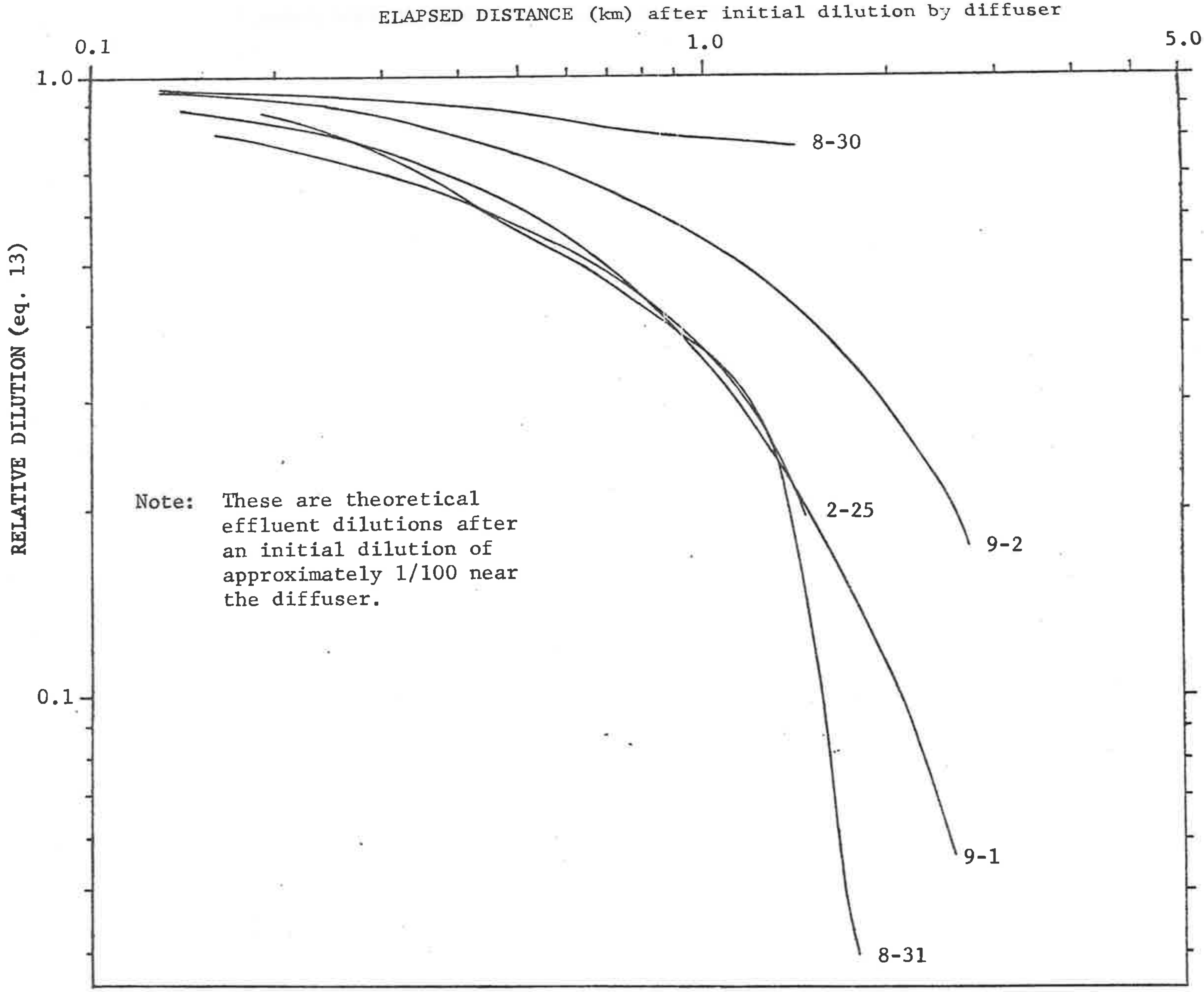

Figure 2b2. Relative dilution of maximum concentration for flood tides versus elapsed distance.

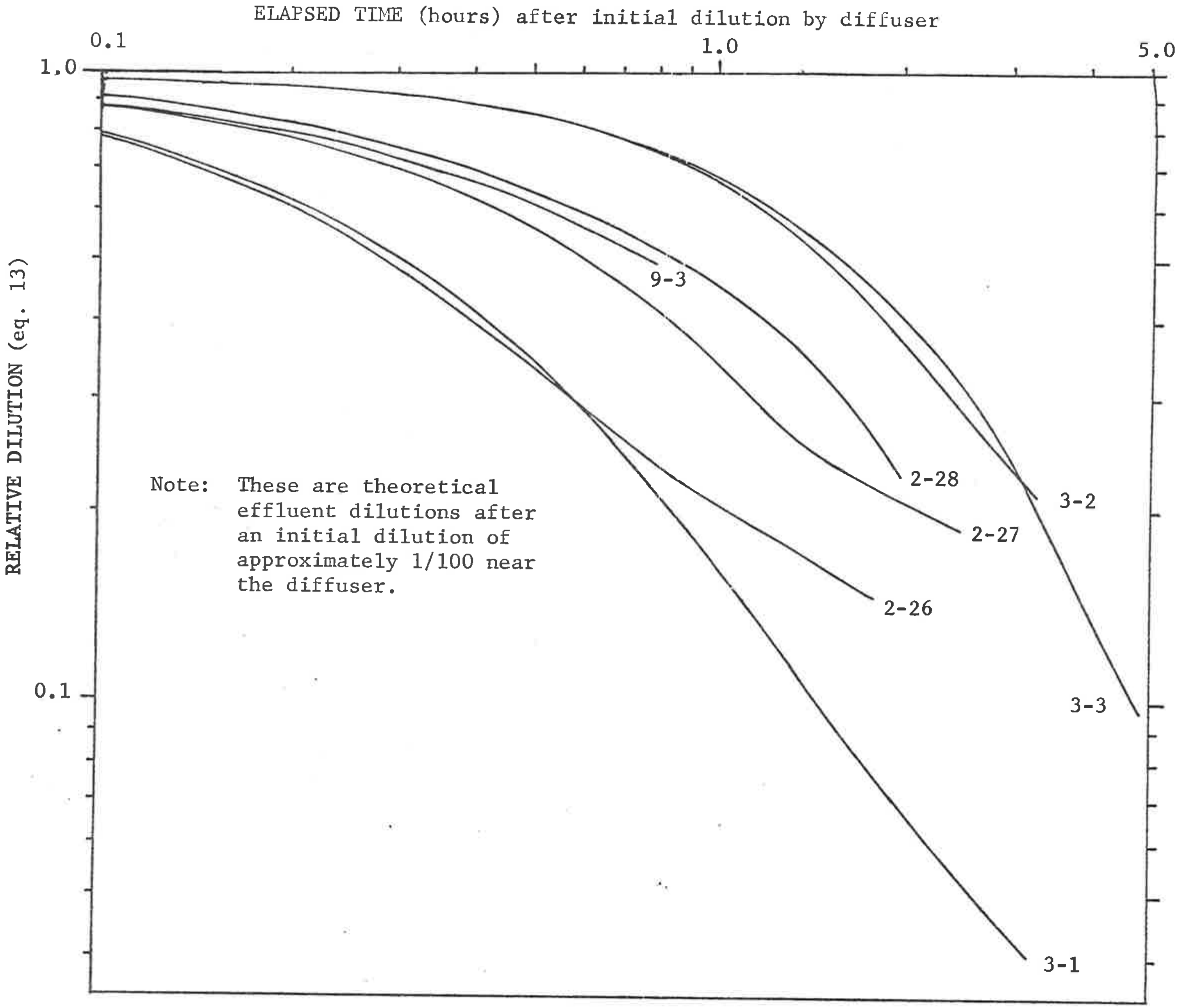

Figure 2c1. Relative dilution of maximum concentration for ebb tides versus elapsed time.

ELAPSED DISTANCE(km) after initial dilution by diffuser

1.0

10.0

Figure 2c1. Relative dilution of maximum concentration for ebb tides versus elapsed time.

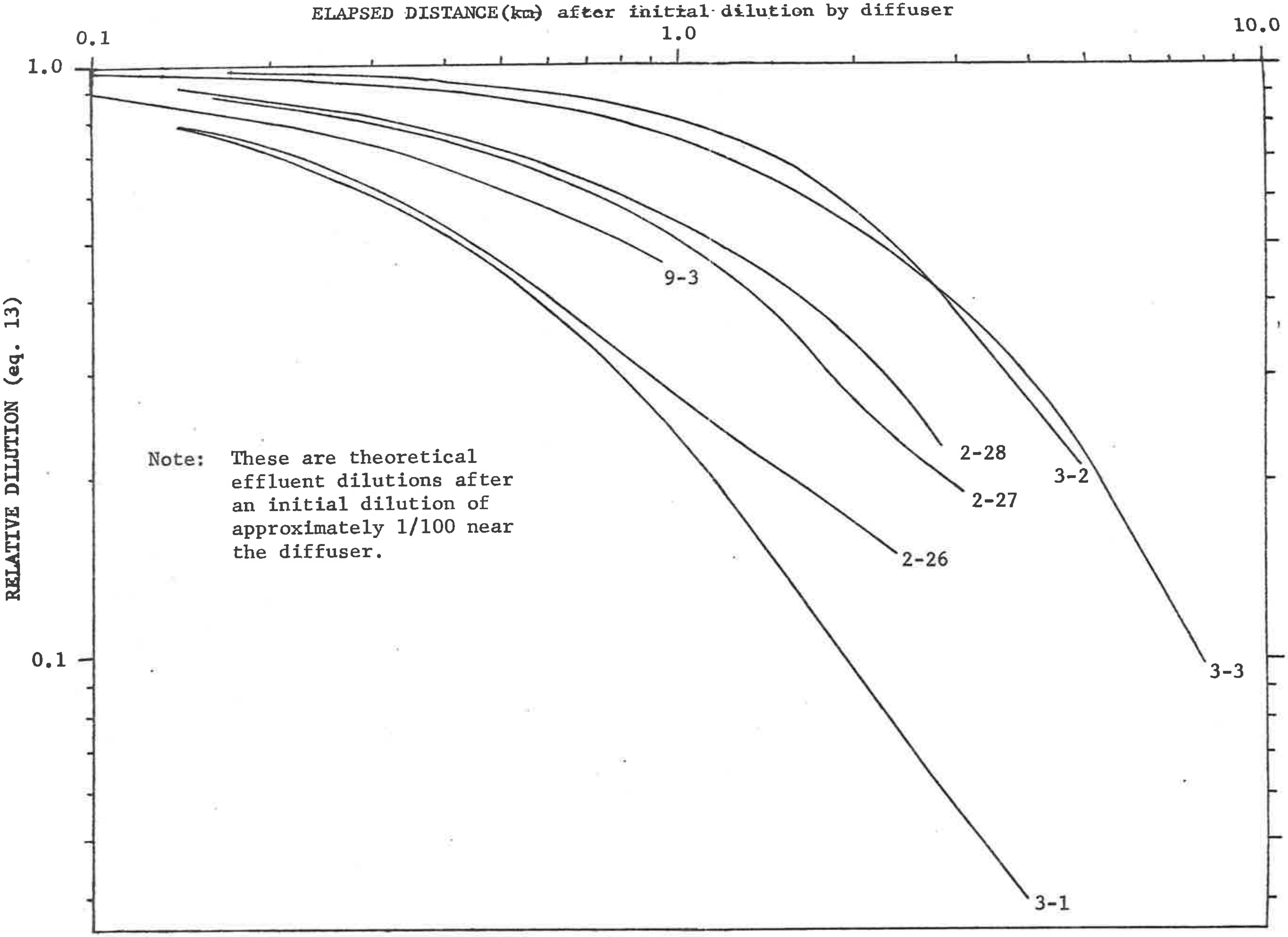

Figure 2c2. Relative dilution of maximum concentration for ebb tides versus elapsed distance.