

## CHAPTER 138

### Experimental Studies of Tidal Flow and Diffusion in the Seto Inland Sea

by

Haruo Higuchi,<sup>1</sup> Tamotsu Fukuda,<sup>2</sup> Hiroshi Ihara,<sup>2</sup> Norio Hayakawa<sup>2</sup>

#### Abstract

The paper describes the environmental problem of the Seto Inland Sea of Japan. A number of model studies of tidal flow and effluent diffusion of this sea are presented. In particular the similarity law that has been developed to model turbulent diffusion is delineated.

#### Introduction

During the post-war period, Japan has achieved a rapid industrialization which brought her prosperity as well as extensive environmental pollution problems. The Seto Inland Sea is one of the scenic areas of the country suffering from environmental pollution due to tremendous urbanization and industrialization of the surrounding region. In order to study water pollution of this sea, the senior author has undertaken two hydraulic model studies. On the basis of these studies, a model similarity law of turbulent diffusion has been established and an enormous hydraulic model of the entire sea was constructed.

#### The Seto Inland Sea

The Seto Inland Sea is a narrow passage of approximately 500 km long and 60 km wide and is squeezed by three major islands of Japan (Fig. 1). It is a shallow sea, most of the area less than 60 meters deep, and is sprinkled with more than 5000 islands. It covers the area of about 21,400 square kilometers and has three openings to the outside oceans. The surrounding area supports about 30 million people and the coastal region is heavily industrialized. Fig. 2 gives surface

---

1. Ehime University, Matsuyama, Japan.

2. Chugoku Institute of Industrial Technology, Hiromachi, Kure, Japan

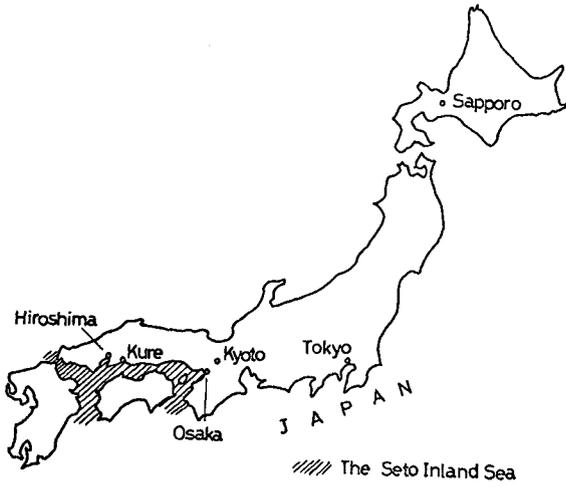


Fig. 1. Japan Islands and the Seto Inland Sea.

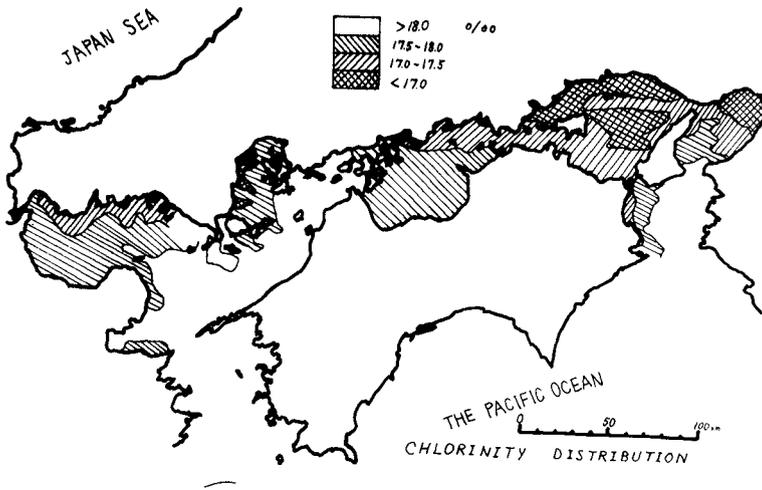


Fig. 2. Chlorinity Distribution of the Surface Water.

chlorinity measurement (1) of the sea which indicates that the sea contains water only slightly less brine than oceanic sea water. One measure of the water pollution is given in Fig. 3 as transparency measurement. Another indication is shown in Fig. 4 as one of COD measurement of the surface water. These two figures indicate that substantial portion of the sea is judged as polluted and that the most polluted area is where it is innermost, enclosed and coastal area.

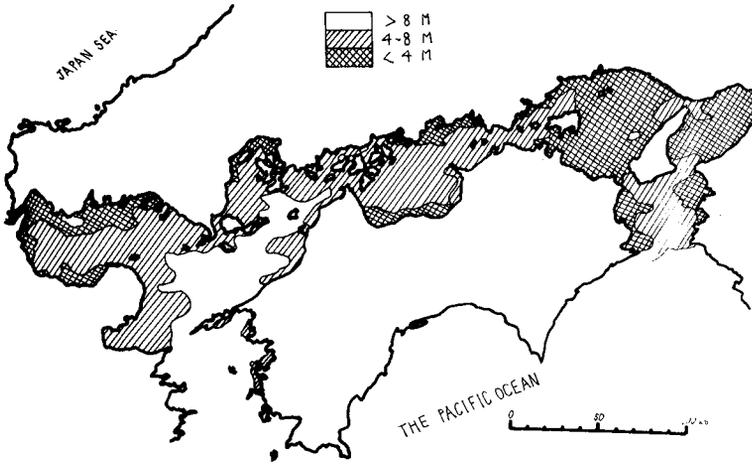
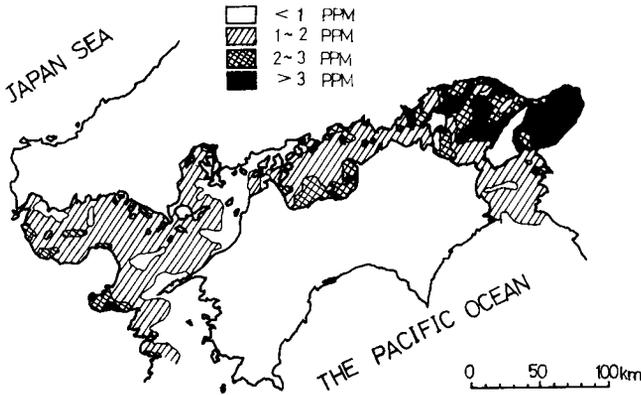


Fig. 3. Measured Transparency



**May. 22, 1972**  
**COD (Surface Layer)**

Fig. 4 COD distribution

It is to this problem that the senior author undertook a hydraulic model study of this sea (2). The plan view of this model is shown in Fig. 5. Its horizontal and vertical length scale ratios are 1 to 10,000 and 1 to 1,000 respectively. The model tide generated at one end of the Fig. 5 propagated into the model through branched channels whose lengths were adjusted in such a way that the phase difference at the openings is obtained. The study carried out with this model includes existence of the tidal residual flow and effluent diffusion-dispersion pattern which is followed up to a period of several years. The smallness of the model and uncertainty on modelling turbulent diffusion, however, were limiting factors of this study. The latter problem is discussed in the following section.

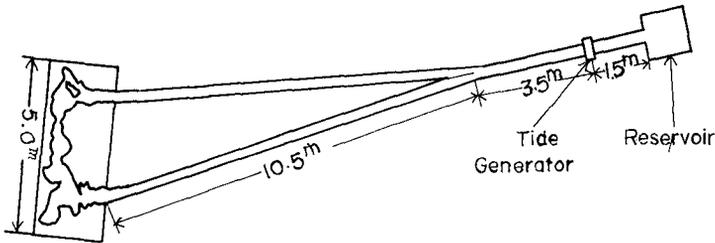


Fig. 5. Plan View of the Small Scale Model.

The Similarity Law

To simulate the dynamical behavior of the tidal flow phenomenon in the model, the well-known Froude's law is invoked to give the following:

$$t_r = x_r h_r^{-\frac{1}{2}} \tag{1}$$

where  $t_r$ ,  $x_r$  and  $h_r$  are time, horizontal length and vertical length scale ratios of model to prototype respectively. Further, the friction coefficient of the sea bed surface has to be scaled as follows:

$$C_r = x_r^{-1} h_r \tag{2}$$

where  $C$  is the friction coefficient. Inpractice length scale ratios  $x_r$  and  $h_r$  have to be given in advance of construction of the model

and the model bed surface is modified with roughness elements to satisfy Eq. (2). It is herewith proposed to model turbulent diffusion by invoking the Richardson's power law on turbulent diffusivity, K, given as

$$K = \frac{1}{3} \epsilon_r^{4/3} l_r^{4/3} \quad (3)$$

where  $\epsilon_r$  is the energy dissipation and  $l_r$  is the horizontal length scale. Equating the scale ratio for K derived from this power law and the one from the dimensional viewpoint, and observing that remains constant for wide range of length scale leads to the following:

$$K_r = x_r^{4/3} = x_r^2 t_r^{-1} \quad (4)$$

where  $K_r$  is the scale ratio for the turbulent diffusion coefficient. Eq. (4) is further reduced to the following:

$$t_r = x_r^{2/3} \quad (5)$$

Substitution of Eq. (5) into Eq. (1) gives

$$h_r = x_r^{2/3} \quad (6)$$

These last two equations imply that once the horizontal length scale ratio is chosen, then the vertical length and the time scale ratios follow.

Validity of this law is observed in Fig. 6 which gives a plot of diffusivity measurements in various tidal flow models and corresponding prototype data.

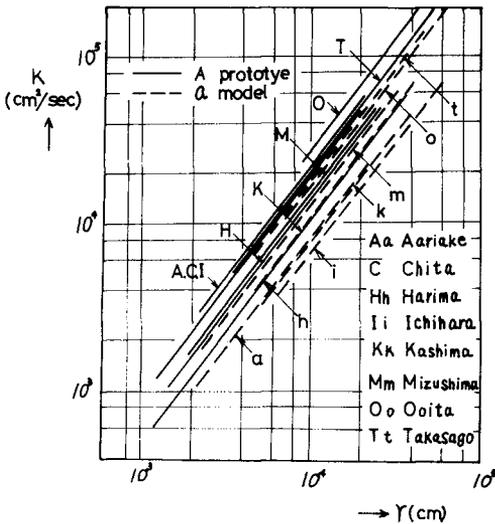


Fig. 6. Comparison of Measured Diffusivity, K, versus Length Scale r .

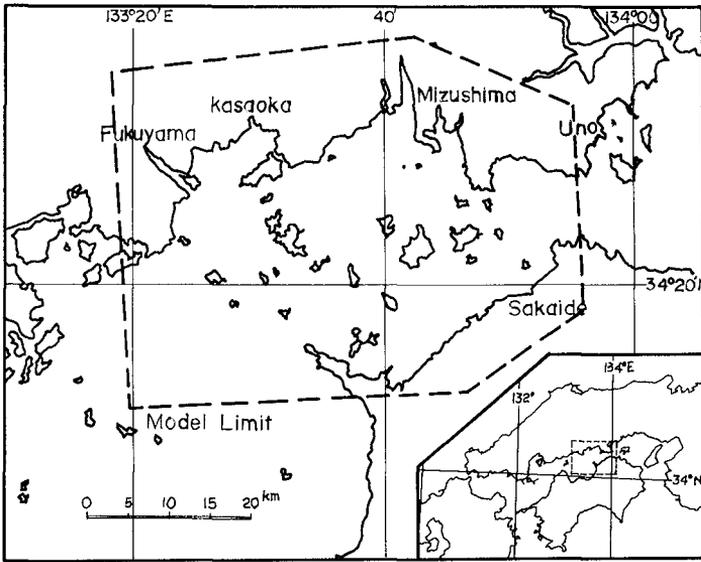


Fig. 7. Plan View of the Mizushima Bay Area.

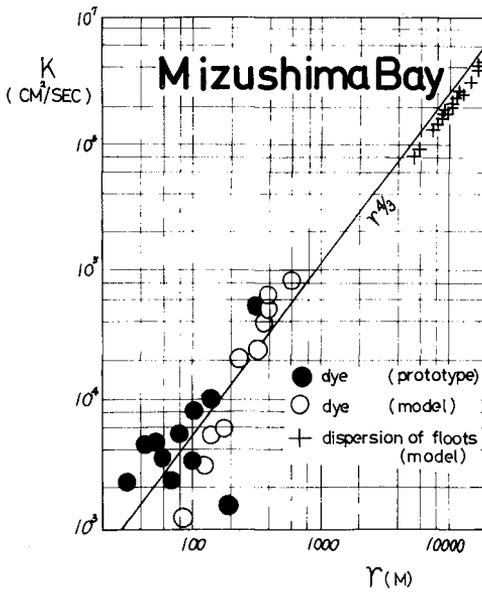


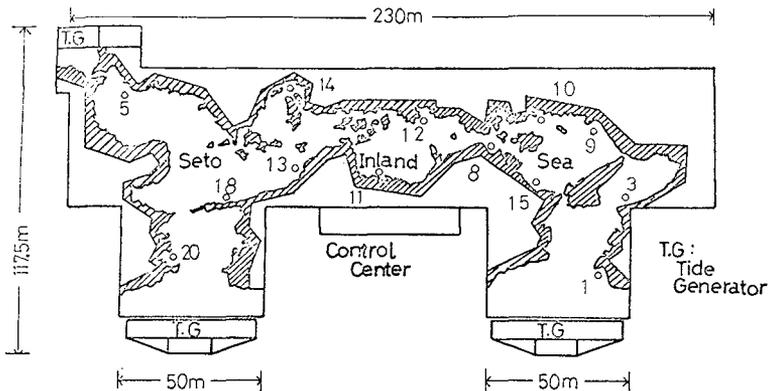
Fig. 8. Measured Diffusivity of the Mizushima Bay Study.

Fig. 6 indicates that  $\nu_r$  can be regarded as constant for wide range of length scale.

More detailed study based on this similarity law was the Mizushima Bay model study (3). The model area is shown in Fig. 7. This bay is a small part of the whole Seto Inland Sea. The horizontal length scale ratio was chosen as 1 to 2,000. According to Eqs. (5) and (6)  $\nu_r = \nu_p = 1/160$ . Fig. 8 gives comparison of measured diffusivity  $\nu_r$  in the model and prototype.

#### The Seto Inland Sea Hydraulic Model

On the basis of the preliminary studies described in the preceding sections, the Seto Inland Sea Hydraulic Model which covers the entire region was constructed in 1973. The model scale ratios are 1/2,000 in the horizontal direction and 1/160 in the vertical direction according to the similarity law Eqs (5) and (6). It is housed in a building of 230 m x 100 m (Fig. 9). The model is equipped with three separate tide-generating facilities of weir type which are operated centrally at the control room. The tide generating system is equipped with an electric computer which can generate complex functions to simulate tidal motion and handle data processing devices. The model includes more than seventy rivers on which regulated flow mixed with dye solution to simulate the diffusion of pollutant is discharged. Major facilities of the model include two sets of cranes: observation stations and water sampling stations. The former consist of four traveling cranes carrying eight camera-mounted, gondola-shaped stations 15 meters above the model surface. The latter is made up of two steel grills of 10 m by 10 m hung by two traveling cranes. These grills can travel



Plan view of the tidal flow model. Numbered circles indicate locations of wave gauges.

Fig. 9

in all three directions as well as rotate around its vertical axis and can be brought at any desired position above the model surface in order to extract water sample without disturbing the flow.

Tidal oscillation of the model water surface is recorded with specially designed wave gauges. In Fig. 10 is shown amplitudes and phase lags of these wave records when the semi-diurnal ( $M_2$ ) tide is given. Their location is indicated as numbered circles in Fig. 9. Field data are also entered in Fig. 10 for comparison. The figure shows that amplitude increases as much as three times and phase lags as much as 6 hours inside of the inland sea. Model-to-prototype correspondence of better than twelve per cent is achieved everywhere without adding any roughness element on the bed surface which has trowel finished with mortar. Further verification study is in progress by adding roughness element on the model surface.

In Fig. 11 is shown preliminary study of dye diffusion. It conforms with earlier studies including Mizushima Bay Model Study.

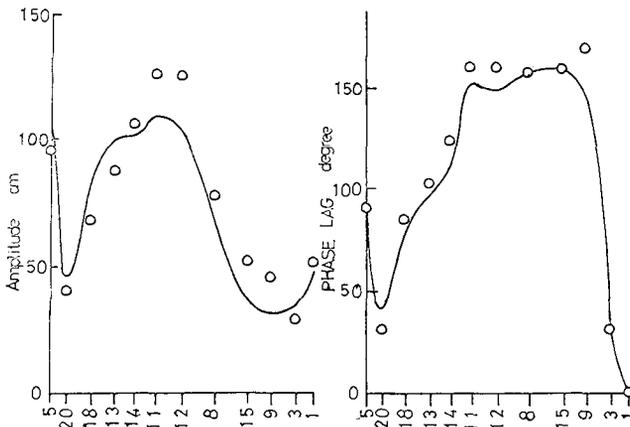
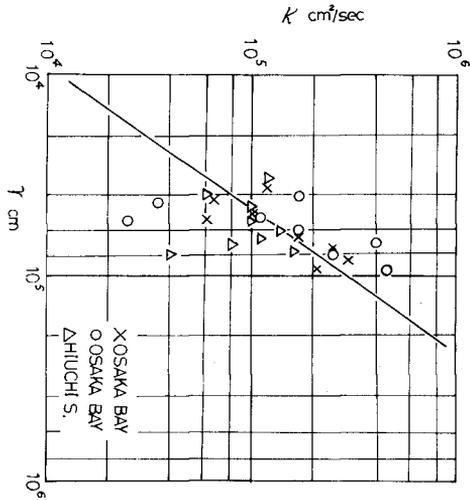


Fig. 10. Amplitude (left) and Phase lag(right) distribution. Circles relate to experimental data of wave gauges whose localities are given as numbers in abscissa. Solid lines relate to field gauge station data.

Fig. 11. Measured Diffusivity of the Seto Inland Sea Model.



#### Conclusion

Polluted state of the Seto Inland Sea is reported herein. As a means to find an effective abatement program of water pollution and to assess future impact on the aquatic environment, use of hydraulic model is asserted. In particular, a new similarity law of turbulent diffusion is proposed and its validity and usefulness has been demonstrated with respect to the results of number of hydraulic model studies.

An outcome of this background, an enormous hydraulic model of the Seto Inland Sea is described and some of the preliminary results are presented.

#### Acknowledgement

The study related to the Seto Inland Sea Hydraulic Model is being financed by Environmental Agency of Japan. Any results of this study are sprung from concerted efforts of the personnel working for the Institute.

#### References

- (1) Figs. 2 through 4 are extracted from large-scale survey of the Seto Inland Sea undertaken by Environmental Agency of Japan in 1972.
- (2) T. Sugimoto and H. Higuchi, "Experimental Studies on the Tidal Mixing in the Seto Inland Sea (I)", Bulletin of Disaster Prevention Institute, Kyoto University, No.14B, 1971, pp.435.
- (3) H. Higuchi and T. Sugimoto, "On the Hydraulic Model Experiment on the Diffusion due to the Tidal Current", Bulletin of Disaster Prevention Institute, Kyoto University, No.12B, 1969, pp.633.