Quantification of the vertical transporting process of substance in marine bay

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Abstract. In order to quantify the vertical transporting process of substance in marine bay waters, this paper established vertical content difference model, substance sedimentation amount model and substance accumulation amount model, and demonstrated the model performance based on the quantification of the vertical transporting process of Cu in Jiaozhou Bay, Shandong Province, China. Results showed that during 1982-1985 the absolute sedimentation amount and relative sedimentation amount of Cu were 0.29-18.23 μg L⁻¹ and 74.3%-96.2%, respectively, and for absolute accumulation amount and relative accumulation amount were 0.32-3.71 μg L⁻¹ and 76.1%-95.6%, respectively. By means of these models, the horizontal and vertical changes in surface and bottom waters and the change processes could be defined. This approach was straightforward yet was reliable enough to quantify the vertical transporting process of substance in marine bay.

1. Introduction
Along with the rapid development of industry, a large amount of wastes were discharged to the environment, and many marine bays have been polluted since ocean is the sink of pollutants [1-8]. Hence, understanding the transporting process of pollutants in marine bay is essential to both scientific research and pollution control practice [9-12]. However, quantification of the transporting process of substance in marine bay waters remains challenge due to the complexity of the transporting process[13-16].

Cu is one of the heavy metal elements widely existing in the natural environment, and has been widely exploited and utilized for thousands of years. This paper established vertical content difference model, substance settlement amount model and substance accumulation amount model, and demonstrated the model performance based on the quantification of the vertical transporting process of Cu in Jiaozhou Bay, Shandong Province, China. The major aim of this paper was to quantify the vertical transporting process of substance in marine bay waters.

2. Models for vertical content difference, sedimentation amount and accumulation amount.
In order to quantify the vertical transporting process of substance in marine bay waters, we established vertical content difference model, substance sedimentation amount model and substance accumulation amount model.
amount model. Supposed that substance contents in surface waters ranged from \(a\) to \(b\) \((a < b)\), while in bottom waters ranged from \(c\) to \(d\) \((c < d)\).

The substance content difference model is described as:
\[
L = a - c, \quad H = b - d
\]
(1)
where, \(L\) represents the vertical change of low value, and \(H\) represents the vertical change of high value.

The substance sedimentation amount model is described as:
\[
D_a = b - a, \quad D_r = 100 \times \frac{(b - a)}{b}\%
\]
(2)
where, \(D_a\) represents the absolute horizontal change of substance content in surface waters, indicates the subtracted substance content was transported to bottom water. \(D_r\) represents the relative horizontal change of substance content in surface waters, indicates the percentage of subtracted substance content which was transported to bottom water.

The substance accumulation amount model is described as:
\[
F_a = d - c, \quad F_r = 100 \times \frac{(d - c)}{b}\%
\]
(3)
where, \(F_a\) represents the absolute horizontal change of substance content in bottom waters, indicates the subtracted substance content was transported to and fixed in sediment in sea bottom. \(F_r\) represents the relative horizontal change of substance content in bottom waters, indicates the percentage of subtracted substance content which was transported to and fixed in sediment in sea bottom.

By means of these models, the horizontal and vertical changes in surface and bottom waters and the change processes could be quantified, and the performance was demonstrated in next section.

3. Model performance

3.1 Study area and data collection.
Jiaozhou Bay is located in the south of Shandong Province, eastern China \((35°55′-36°18′\ N, 120°04′-120°23′\ E)\). The total area, average water depth and bay mouth width are 446 km\(^2\), 7 m and 3 km, respectively. This bay is a typical of semi-closed bay which is connected to the Yellow Sea in the south. There are a dozen of rivers, and the majors are Dagu River, Haibo River, Licun River, and Loushan River etc., all of which are seasonal rivers \([17-18]\). The investigation on Cu in Jiaozhou Bay was carried on in July and October 1982, May, September and October 1983, July and October 1984, and April, July and October 1985 \([3-16]\) (Fig. 1). Cu in waters was sampled and monitored follow by National Specification for Marine Monitoring \([19]\).

![Fig. 1 Geographic location of Jiaozhou Bay](image-url)
3.2 Vertical changes of Cu contents.
In order to quantify the vertical changes of Cu contents, for each sampling site in a same voyage investigation, Cu contents in surface waters was subtracted by which in bottom waters, and the difference represented the ‘vertical content difference’. In 1982, the vertical content difference of Cu contents in July and October were -0.96 to 1.30 μg L⁻¹ and -0.11 to 0.11 μg L⁻¹, respectively. In 1983, the vertical content difference of Cu contents in May, September and October were -0.53 to 16.65 μg L⁻¹, -1.50 to 2.53 μg L⁻¹ and -1.23 to 1.74 μg L⁻¹, respectively. In 1984, the vertical content difference of Cu contents in surface waters in July and October were -2.69 to 1.47 μg L⁻¹ and 0.50 to 1.39 μg L⁻¹, respectively. In 1985, the vertical content difference of Cu contents in April, July and October were 0.00 to 0.27 μg L⁻¹, -0.20 to 0.00 μg L⁻¹ and -0.03 to 0.09 μg L⁻¹, respectively.

It could be found that the vertical content difference of Cu contents were showing seasonal variations. The reason was that Cu in Jiaozhou Bay could be sourced from marine current, river flow, atmosphere deposition, overland runoff, etc., and the source strengths were changing with time. By means of water’s effect [20-22], the vertical content difference of Cu in marine bay were changing, and quantification of the the vertical transporting process was essential to environmental protection.

3.3 Sedimentation and accumulation amounts of Cu in Jiaozhou Bay.
By means of the models described in above, the sedimentation amount and accumulation amount of Cu in Jiaozhou Bay during 1982-1985 were quantified as listed in Table 1. During 1982-1985, the absolute sedimentation amount and relative sedimentation amount of Cu were 0.29-18.23 μg L⁻¹ and 74.3%-96.2%, respectively. This indicated that the sedimentation of Cu was relative high and stable, and the sedimentation was increased/decreased with the increased/decreased of Cu contents in surface waters. Obviously, the sedimentation of Cu contents in Jiaozhou Bay waters was remarkable and complete.

During 1982-1985, the absolute accumulation amount and relative accumulation amount were 0.32-3.71 μg L⁻¹ and 76.1%-95.6%, respectively. This indicated that the accumulation of Cu was relative high and stable, and the accumulation of had no connection with with the increased/decreased of Cu contents in surface waters. Obviously, the accumulation of Cu contents in Jiaozhou Bay waters was also remarkable and complete. In general, the calculations show that the sedimentation and accumulation of Cu in Jiaozhou Bay was significant.

| Table 1 Sedimentation amount and accumulation amount of Cu in Jiaozhou Bay |
|-----------------------------|------------------|------------------|------------------|------------------|
| Year | Variation range in surface waters/μg L⁻¹ | Variation range in bottom waters/μg L⁻¹ | Vertical content difference/μg L⁻¹ | Absolute sedimentation amount/μg L⁻¹ | Relative sedimentation amount/% | Absolute accumulation amount/μg L⁻¹ | Relative accumulation amount/% |
|     | 0.50 to 3.56 | 0.77 to 20.6 | 0.28 to 2.00 | 0.10 to 0.39 | 0.23 to 3.22 | 0.24 to 3.95 | 0.13 to 2.97 | 0.10 to 0.42 | 0.27 to 0.34 | 0.46 to 16.65 | 0.15 to −0.97 | 0.00 to −0.03 | 3.06 | 19.83 | 1.72 | 0.29 |
|     | 85.9 | 96.2 | 86.0 | 74.3 | 2.99 | 3.71 | 2.84 | 0.32 | 92.8 | 93.9 | 95.6 | 76.1 |

4. Conclusions
Models of vertical content difference model, substance settlement amount model and substance accumulation amount model were established to quantify the vertical transporting process of substance
in marine bay waters. These models were straightforward yet were reliable enough to quantify the vertical transporting process of substance in marine bay.

During 1982-1985, the absolute sedimentation amount and relative sedimentation amount of Cu were 0.29-18.23 μg L⁻¹ and 74.3%-96.2%, respectively, the absolute accumulation amount and relative accumulation amount were 0.32-3.71 μg L⁻¹ and 76.1%-95.6%, respectively. The sedimentation and accumulation of Cu in Jiaozhou Bay was significant.

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