Spatial Variation in Water Column Structure, Nutrients, Chlorophyll and Zooplankton in an Estuarine Transect of Southampton Water

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Abstract. Estuary systems are complicated and closely related to humans. The understanding of estuary systems is important to scientific study and human develop. An investigation was conducted on 3rd November 2009 by RV Callista along the Itchen estuary of Southampton Water with the aim of determining spatial variability in physical water column structure, nutrients, chlorophyll and zooplankton of Southampton Water, and recognizing the links between them. The salinity and temperature values are relatively lower at surface upper estuary than that of deep lower estuary. Water stratification is observed around upper and mid estuary. The nutrient Si exhibits conservative behaviour with a linear relationship with salinity gradient, while P shows non-linear with salinity, which may indicate an addition behaviour. Chlorophyll distributes high concentration at surface upper estuary and relatively uniform and low concentration at downriver area which is mainly due to light and nutrients factors. Water turbidity affects chlorophyll distribution by reducing light availability in the water column, while chlorophyll can in turn influence water turbidity. The abundance dominant species of the estuary are Copepoda and Appendicularia. The mid estuary has the highest zooplankton abundance, while the lower estuary has the most zooplankton groups. Zooplankton distribution is relative to food distribution, temperature, light and salinity profiles.

1. Introduction

Estuary is an area with complicated interaction between fresh river water and salty seawater. Its complexity is due to the spatial and temporal variation of physical, chemical and biological properties and the interaction between them. Estuary systems are closely related to human activities, as they provide natural resources, energy and suitable living conditions to humans. Therefor the researching and understanding of estuary system are important to scientific study and human develop.

Southampton Water is a shallow, partially mixed coastal plain estuary located on the south coast of England [1]. It is essentially consistent with marine character, with low level of salinity and temperature variation at lower estuary and some surface stratification at upper estuary [2][3]. The water temperature varies with season, with the minimum values in winter and maximum values from mid summer until early autumn. The tide of Southampton Water is complex in character called double high tide, within a period of 2 to 3 hours [4]. The chlorophyll concentrations are lower in winter and higher in summer, especially in the upper water layers [5]. Zooplankton abundance varies seasonally, with low values in winter, increasing levels from early spring, and with high values during summer [3].
The aim of this investigation is to determine spatial variability in physical water column structure, nutrients, chlorophyll and zooplankton of Southampton Water, and to recognize the links between the features and dynamics.

2. Materials and methods
An investigation was conducted on 3rd November 2009 by RV Callista at 13 stations along the estuary in Southampton Water, starting from Northam Bridge (station 1), passing through Dock Head (station 6), then ending at Calshot (station 13). The parameters including temperature, salinity, fluorescence and transmissometer data were collected by the CTD (Conductance, Temperature, Depth) instrument. Water samples were taken at both the surface and the bottom on the transect. Zooplankton samples were collected at upper, mid and lower estuary. Samples and data analyses determined the concentrations of chlorophyll and nutrients, identified and enumerated the major zooplankton groups existed and constructed contour plots of the important parameters along the transect.

The first 5 stations were set by salinity change (at intervals of 2 salinity units). As the estuary salinity was approaching that of seawater, from station 6 the stations were set every one nautical mile along the estuary. Station setup information shows in Figure 1 and Table 1.

![Figure 1. Station setup.](image)

| Station | Distance from start (Nm) | GMT | Coordinates |
|---------|-------------------------|-----|-------------|
| 1       | 0                       | 1006| 50°54.851N  |
| 2       | 0.18                    | 1020| 50°54.822N  |
| 3       | 0.58                    | 1054| 50°54.59N   |
| 4       | 0.82                    | 1106| 50°54.486N  |
| 5       | 1.42                    | 1128| 50°53.984N  |
| 6       | 2.78                    | 1215| 50°52.662N  |
| 7       | 3.52                    | 1231| 50°52.074N  |
| 8       | 4.44                    | 1236| 50°51.560N  |
| 9       | 5.48                    | 1251| 50°50.888N  |
| 10      | 6.52                    | 1331| 50°50.105N  |
High tide of 4.7 m occurred at 10:35 GMT, and low tide of 0.8 m was at 16:36 GMT. The majority of the sampling period was with the tide at a high level above 4 m. Wind speed was much variable, from 5 knts at the first station, and rapidly enhanced to a maximum of 25 knts at station 6, followed by a little deceleration. The cloud cover was 6-8, and it rained at intervals. The parameters including temperature, salinity, density, fluorescence and transmissometer data were collected by CTD, measured about every 1 meter in depth at each station. The CTD used on Callista was a Falmouth Scientific Instruments (FSI) integrated CTD profiler with fluorometer and transmissometer, mounted on a rosette frame with Niskin bottles for water sampling. Data were logged by FSI propriety software. Water samples for nutrient analysis and chlorophyll measurement were taken at both the surface and the bottom from the first 12 stations. Zooplankton samples were collected at upper (station 2), mid (station 7) and lower (station 12) estuary by using zooplankton net with 200 μm mesh and 0.3 m radius. Other important parameters, such as water depth, wind speed and direction, Secchi disk depth and cloud cover were monitored and recorded at each station.

Water and zooplankton samples and CTD data collected by Callista were analysed on the following days. The analyses determined the concentrations of chlorophyll, dissolved Si and P in the water samples, identified and enumerated the major zooplankton groups existed and constructed contour plots of the important parameters along the transect. The concentrations of chlorophyll dissolved Si and P in the water samples were determined by using the method of Parsons et al. [6]. The water samples were allowed to react with a molybdate solution under conditions that lead to the formation of silicomolybdate or phosphomolybdate complexes. Then a reducing solution was used to reduce the complexes and simultaneously give a blue colour to indicate the Si or P concentration in the solution. The absorbance of the Si solution was measured by using a Hitachi U-1500 UV/Vis Spectrophotometer at 810 nm with a 1 cm cell of sipper system, and for P determination by a Hitachi U-2800 UV/Vis Spectrophotometer at 882 nm with a 4 cm cell of sipper system. Organisms in 5 mL subsample of a 1000 mL zooplankton sample were identified and counted using zooplankton counting chamber under anatomical lens by each member of the group. And the replicate counting results were averaged and converted into the form of organisms per m$^3$ respectively for upper, mid and lower estuary.

The data of nutrients concentration, chlorophyll concentration and zooplankton abundance were analysed and illustrated by Microsoft Office Excel 2003. The plotting software Surfer v8.05 was used to analyse salinity, temperature, fluorescence and transmissometer data collected by CTD and construct contour plots of these parameters.

3. Results

3.1. Salinity and temperature along the transect
The salinity diagram of the estuary (Figure 2) shows that water salinity increases from upriver areas to downriver areas along the estuary and from shallow water to deep water. The lowest salinity occurs at the surface of upper estuary with the value around 26, while the high value of more than 34 is observed at lower estuary after 5 Nm. The contour lines before 2 Nm see high denseness that means intensive changes of the water salinity; while the following areas have gradually increased distance between contours which indicates slight variation downriver, especially at the area behind 5 Nm. Salinity stratification is observed in the area before 5 Nm on the transect. Similar with salinity, on the temperature diagram (Figure 3), the high denseness of the contours at start area means intensive change of the water temperature, while the low denseness of the contours at downriver areas shows relatively less changes. The distribution of temperature along the estuary shows high variation at the surface and relatively low variation at downriver areas. Generally surface river water at upper estuary
is colder than bottom seawater at lower estuary. Before 5 Nm, the water column shows temperature stratification in this estuarial area.

3.2. Estuarine distribution of nutrients Si and P

The distribution of dissolved Si in the Itchen estuary represents approximately linear relationship with salinity (see Figure 4). The riverine end member concentration of dissolved Si is 165.88 μmol/L, while that of seawater is 7.56 μmol/L. The points of the two end members are joined by Theoretical Dilution Line (TDL). Other points that represent Si concentrations at certain salinity, distribute approximately on TDL. The distribution of $\text{PO}_4^{3-}$ in the Itchen estuary shows non-linear relationship with salinity change (see Figure 5). The riverine end member concentration of $\text{PO}_4^{3-}$ is 2.63 μmol/L, while that of seawater is 0.62 μmol/L. Except the points of the two end members, almost all points in the $\text{PO}_4^{3-}$ diagram are distributing above TDL.

3.3. Fluorescence, chlorophyll concentration and water turbidity

The distribution of fluorescence data along the transect, which is relative to chlorophyll concentration, shows slightly higher values in surface water than that of bottom at most area. And the fluorescence values at the first several stations are relatively lower than those of the last ones (see Figure 6a).
The turbidity of the water column along the transect is expressed by the transmissometer profile (see Figure 6b). High transmissometer values with light grey areas in the diagram stand for low turbidity levels and low transmissometer values with dark grey areas in the diagram indicate high turbidity levels of the water column. The turbidity around 1 Nm, 5 Nm shows relatively high level, while around the start, 3 Nm and 7 Nm, the turbidity values see relatively low levels. The distribution of turbidity shows variation with water depth and with distance along the transect.

Comparing with the fluorescence data, the chlorophyll concentrations, measured from discrete acetone extracted samples, see higher level at the surface than bottom at most stations, except at 6Nm with low concentration at surface water and high concentration at bottom water (Figure 6c). Although fluorescence and chlorophyll concentration should be positive correlation, these data fail to reveal that relationship (Figure 6d).

Figure 6. Graphs for chlorophyll and turbidity. (a) Contour plot for fluorescence; (b) Contour plot for turbidity; (c) Chlorophyll against distance; (d) Fluorescence against chlorophyll.

3.4. The distribution of main zooplankton groups
Figure 7 presents the distribution of main zooplankton groups along the Itchen estuary.

At the upper, mid and lower estuary, Copepoda are the most dominant species with the highest abundance of 158 m$^{-3}$, 394 m$^{-3}$ and 206 m$^{-3}$ (total 758 m$^{-3}$) and with the proportion of 65%, 60% and 73%, followed by Appendicularia with the abundance of 56 m$^{-3}$, 159 m$^{-3}$ and 28 m$^{-3}$ (total 243 m$^{-3}$) and with the proportion of 23%, 24% and 10%. Copepoda, Appendicularia and Copepoda nauplii are the only groups appearing at every estuary. The mid estuary has the highest zooplankton abundance of 651 m$^{-3}$, followed by the lower estuary with the abundance of 285 m$^{-3}$ and the upper estuary with the lowest abundance of 244 m$^{-3}$. The lower estuary has the most zooplankton groups. Chaetognath, Cirripedia larvae, Bivalve and Decapoda larvae are only found at lower estuary. The upper estuary has the least groups. The distribution of zooplankton may be due to food distribution, temperature, light and salinity profiles [3].
4. Discussions

4.1. Salinity and temperature
The low salinity level at upper estuary and water surface is due to the dominance of fresh river water with low density at upriver areas, while the high salinity level at lower estuary and deep water results from superiority of salty sea water with high density at downriver areas. The area of salinity stratification indicates an intensive interaction between fresh river water and salty seawater, after that area, river water and seawater are well-mixed and salinity becomes highly uniform and approximately equals to the level of seawater. With respect to temperature, surface river water, which is sensitive to surrounding temperature, has high variation along the transect. The temperature stratification area shows the interaction between river water and seawater. And at lower estuary, the area is well-mixed and dominated by seawater. Salinity and temperature can affect solubility of many nutrient elements and mean water column irradiance, then directly or indirectly affect the distribution of chlorophyll (phytoplankton), hence zooplankton [3][5].

4.2. Nutrient elements behaviour
The linear relationship between Si concentration and salinity indicates the conservative behaviour of Si in the Itchen estuary, which means the only factor that controls the Si behaviour in this estuary is the process of riverine and marine end members mixing. The non-linear distribution of $\text{PO}_4^{3-}$ along salinity gradient may indicate addition characteristics, a non-conservative behaviour, of $\text{PO}_4^{3-}$ in the Itchen estuary. Other processes, however, such as temporal variability or additional sources imputing may also result to such distribution of $\text{PO}_4^{3-}$. To confirm the characteristics of P distribution, further observation and analysis need to be conducted.

4.3. Chlorophyll distribution and its factors
The fluorescence data are reflecting the concentration of chlorophyll. The relationship between these two parameters should be positive linear correlation. The distribution patterns of fluorescence and chlorophyll with depth are similar to each other. Their distribution patterns along distance, however, are not coherent. The calibration of fluorescence - chlorophyll concentration, showed by Figure 6d, fails to reveal the linear relationship between fluorescence and chlorophyll concentration. The mismatch is possibly due to an insufficient sample size, operation and analysis errors.

The distribution of chlorophyll is affected by many factors. Phytoplankton cannot produce chlorophyll without enough light; any factors that influence mean water column irradiance, such as,
surface incident radiation, water turbidity, cloud coverage, will affect the pigment distribution. Besides, other factors, such as tidal mixing processes, wind, rainfall and river flow, can affect the light extinction coefficient, then affect water transparency. In addition, water temperature and nutrient existence can accelerate phytoplankton growth, and then increase chlorophyll concentration [5].

At upper estuary, river water at the surface brings many nutrients such as Si and PO$_4$$_3^-$, and has enough photosynthetic active radiation (PAR) into the water column, providing phytoplankton conditions to grow and produce chlorophyll. The bottom seawater with low nutrients and insufficient PAR has less chlorophyll. At lower estuary, due to water mixing, and the chlorophyll sees relatively uniform vertical distribution. Because we have no data from other days under different weather and tide conditions, we cannot analyse the effects of those factors on chlorophyll distribution from our result. The little difference, however, between surface and bottom chlorophyll concentration may be due to high cloud coverage and strong wind mixing process.

4.4. Water turbidity and chlorophyll
Comparing Figure 6a with b, the distribution pattern of turbidity is relatively coincident with that of chlorophyll concentration. High turbidity values, which mean high light extinction coefficient (k) and low PAR, correspond to low chlorophyll concentration value, while low turbidity areas are coincident with high chlorophyll concentrations. In return, the chlorophyll concentration can affect the water turbidity within the area. Similarly, the high abundance of zooplankton in the mid estuary may be responsible for the high turbidity around 5 Nm. Besides, the variation of turbidity along the estuary is possibly due to the interval rainfall and strong wind-mixing process [5].

5. Conclusion
In conclusion, the physical, chemical and biological features and dynamics are complicated and with strong links between each other. Salinity and temperature stratification is observed around upper and mid estuary, and well-mixed water column at lower estuary. The Si and P concentrations respectively have linear and non-linear relationship with salinity, and exhibit conservative and likely non-conservative behaviours. Chlorophyll concentration is high at surface upper estuary and relatively uniform and low at downriver area which is mainly due to light and nutrients factors. Water turbidity affects chlorophyll distribution by reducing light availability in the water column, while chlorophyll can in turn influence turbidity. The abundance dominant species of the estuary are Copepoda and Appendicularia. The mid estuary has the highest zooplankton abundance, while the lower estuary has the most zooplankton groups. Zooplankton distribution is relative to food distribution, temperature, light and salinity profiles.

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