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申請者氏名	陸　眞姫		

指導教員氏名	~~井上隆信~~ ~~松本一博~~ ~~木曽祥秋~~ 青木伸一、加藤茂

論　文　要　旨（博士）

論文題目	Water exchange and material transport in a semi-enclosed estuary – The characteristics and long-term changes in Hamana Lake – (半閉鎖性内湾における海水交換と物質輸送 –浜名湖におけるその特性と長期的変化–)

水域の富栄養化により，赤潮，貧酸素水塊等が頻繁に発生する閉鎖性内湾において，その原因を正しく把握し，解決策を講じるためには，海水交換とそれに伴う物質輸送を，解明することが重要である．本研究では，浜名湖の枝湖のひとつである閉鎖性の高い猪鼻湖において2005~2007年に行った夏期の観測データ及び浜名湖における最近約50年間の長期間観測データ，夏期再現の数値シミュレーション結果を用いて，猪鼻湖及び浜名湖における海水交換・物質輸送特性及びそれらの長期的な変化を明らかにした．また，長期的な水質変化をもたらす原因に対しても論じた．

猪鼻湖と浜名湖との湖水交換については，風の影響が大きく，表層で浜名湖への流出，中・底層で猪鼻湖への流入という2層構造の流れが明らかになった．すなわち，淡水は表層のみを通して流出することから，表層流量と淡水流量の差の補償流として中・底層を通して猪鼻湖へ流入する．このとき交換流量は淡水流入量の2.2~4.2倍程度であった．また湖内の鉛直混合についても，潮汐や淡水流入よりも，風の影響が支配的であることがわかった．猪鼻湖と浜名湖をつなぐ水路での流れ及びリンの分布の2層構造，すなわち，表層では懸濁態リンの浜名湖への流出，中底層では溶存態リン（その大部分がリン酸態リン）の猪鼻湖への流入が推察された．ボックスモデルによりリンの収支を検討したところ，夏期には底泥へのリンの蓄積が示唆され，底泥はリンの貯蔵庫であり，同時に湖水へのリンの供給源になっていると推察された．また酸素とリンの収支モデルを構築し現地データで検討した．

浜名湖は，湖口部の導流堤建設以後潮汐や塩分は増加したが，1967年頃に安定状態になった．これにより1980年以前は溶存酸素が比較的高かった．アンモニア態窒素（NH_4-N）濃度は1965年頃最も低く，1980年以降増加傾向であり，リン酸態リン（PO_4-P）は1965年頃減少したが，1980年以降増加した．この原因については，外部導流堤の建設による海水流入，水温上昇，リンの溶出フラックスの増加等が推察された．すなわち，外部導流堤は海水交換率を増加させ底層水質環境を改善したが，1980年以降地球温暖化による水温上昇及びリンの溶出フラックスの増加が水質悪化をひきおこしたと考えられる．

浜名湖システムの長期的（1965-2002年）変化のシミュレーションによれば，潮汐残差流は1965-1969年より1984-1988年で強くなったが，1984-1988年と1998-2002年間はほとんど差異がなかった．また塩分分布は潮汐残差流の分布と似ていた．海水交換率は1960年代と1980年代間に大きくなり，1980年代後半以降にも維持していることが推察された．

浜名湖における導流堤の影響を評価したシミュレーションでは，外部導流堤によって海水交換が向上し水質が改善されたことがわかった．しかし，外部の東導流堤延長及び内部導流堤建設は海水交換向上にその役割を果たしていなかったことがわかった．

浜名湖の長期的変化に及ぼす導流堤以外の要因については，長期的変化計算と導流堤影響計算の比較を試みた．河川流入量と気象的変化は流動場・密度場及びエスチュアリー循環に影響を与えた．シミュレーションにより，湖水温の上昇が水質変化の大きな要因であると推察できた．

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Hamana Lake is situated in the middle part of Japan and connected to the Pacific Ocean through a narrow inlet, thus this lake has very high closeness. Hamana Lake has suffered environmental issues such as eutrophication, red tide and hypoxic water. To reveal the characteristics of the water exchange and the material transport and to investigate the long-term variations in water exchange and material transport, and an accompanying water quality change for about recent 50 years, and to clarify what caused water quality changes, long-term measurements in Hamana Lake and short-term/intensive measurements in Inohana Lake were analyzed and the physical and ecological systems of the lake were simulated by the coupled hydrodynamic and ecological models.

The water exchange in the narrow channel that connects Inohana and Hamana Lakes is dependent upon wind. The flow in the channel had a two-layer structure with the outward (toward Hamana Lake) in the surface layer, but inward (toward Inohana Lake) in the middle and bottom layers. The water exchange between Inohana and Hamana Lakes was 2.2 ~ 4.2 times greater than freshwater discharge. This freshwater went out of the lake through the surface only. This study proposes that the water in the middle and bottom layers went into Inohana Lake as compensating flow with the difference subtracting freshwater input from the surface water-volume flux. The wind effect was also dominant over effects of tide and rainfall as for the vertical mixing within Inohana Lake. Based on a two-layer structure in both the flow-field and the distribution characteristics of phosphorus in the channel: the outward average flow and particulate phosphorus in the surface layer, while the inward average flow and dissolved phosphorus (primarily PO_4-P) in the middle and bottom layers, it is suggested that the water exchange in the channel causes the dissolved phosphorus to flow into Inohana Lake in the middle and bottom layers, and the particulate phosphorus to flow out of the lake in the surface layer. On the basis of measurements and box model results, the phosphorus retention in the bottom sediment has been increasing. The bottom sediment is a repository, and simultaneously a supplier of the phosphorus into the water column during summer. The phosphorus release from the sediment and phosphorus input from Hamana Lake are judged to play an important role to supply the phosphorus into Inohana Lake. Mathematical models for oxygen and phosphorus the ultimate objective of which is to combine two models and predict the changes of bottom dissolved oxygen and phosphorus concentrations associated with changes of the riverine phosphorus load were accomplished to construct separately, although models were so simplified that some model results remained disagreement with observations.

The tide and salinity had increased before being stable around 1967. Generally, in Hamana Lake including Hosoe and Inohana Lakes, prior to 1980, the dissolved oxygen concentration was relatively high. Overall, the NH_4-N concentration was lowest around 1965, and since 1980 has a tendency to increase. The PO_4-P concentration had decreased since around 1965, and again had gradually increased since 1980. As for causes of long-term variations in water exchange and water quality, jetties construction, the water temperature rise and increase of phosphorus release flux are discussed. The construction of outside jetties at the inlet led to the higher water exchange rate, which made the bottom water environment better. Since 1980, the water temperature rise associated with global warming and the increases of phosphorus release flux are responsible for the deterioration of water quality.

In long-term variation simulations from 1965 to 2002, tidal residual currents became stronger in 1984-1988 than 1965-1969. However, the remarkable difference of tidal residual currents was not found between 1984-1988 and 1998-2002. Hence, tidal residual currents had become stronger since the late 1960s, and the strengthened currents have continued until the present. The distribution of salinity was similar to the tidal residual currents in three calculation years. The water exchange became better between the 1960s and the 1980s, and has been sustained without more enhancements since the late 1980s. Such simulation results were consistent with long-term measurements. Simulated long-term variations of phosphorus and dissolved oxygen were somewhat different from observations, because the used model does not include mechanisms of oxygen and nutrients within the sediment and simplifies mechanisms of oxygen and nutrients between the water column and sediment. In assessing for the impact of jetties, owing to outside jetties, the sea water exchange with the ocean had improved and the water quality became better. It is understood that the extension of the east-side jetty did not contribute to increase the tidal prism volume. The inside jetties could not enhance the sea water exchange rate. This research suggests that the river discharge affects the flow- and density-fields, and the estuarine circulation. These are also influenced by meteorological changes. The heat in the lake water seems to have increased with year going, and the water temperature has been increased. Such water temperature change affected biochemical processes. It was difficult to assess the impact of riverine nutrient loads by a simple comparison in this study.