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One-Dimensional Water Quality Model for Water Management in Tidal Rivers

感潮河川の水質管理を目的とした１次元水質モデル

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ABSTRACT: Water systems in lowlands consist of tidal rivers, open channel networks and several water structures. The water management of such systems requires problem analysis on water quantity and water quality. In this paper the water problems of tidal rivers in Indonesia are analyzed and the problems to be solved for the future and present time are proposed. As major subjects, it is pointed out that the integrated water management for the water systems from the aspect of water quantity and water quality is necessary. Additionally, the concept for the development of tools (computer models) is proposed. The major water quality parameters for the water management of tidal rivers in Indonesia are chloride and suspended solids. Through the water quality problem analysis, one-dimensional water quality model, so called branch-node model, is developed and the applicability of the model is examined in the Rokkaku River in Japan. The water movement is simulated using existing computer model for water management systems. It shows that those calculated results of water movements, water level and discharge, agree with the observed data. The calibration of chloride concentration is carried out to estimate dispersion coefficient and the calculated results agree with the observed data. The calculations for the suspended solid concentration match with observed data.

KEYWORDS: lowland, tidal river, water management, water quality model

1. Introduction

Issues on water management for tidal rivers have been spread in many parts of the world. There are problems such as sedimentation, eutrophication and seawater intrusion. They are significantly important since the tidal rivers are diverted to be source of water. In Asian countries such as Thailand and Indonesia, tidal rivers are utilized for various activities, e.g. irrigation and drinking water (TDRI, 1987; PDSS, 1996). In this situation, the tidal rivers need appropriate management for the aspect of water quantity and water quality. This effort is aided through the development of a computer model. In this paper the concept of the computer model is developed through the analysis on water problems using case situation of tidal rivers in Indonesia. As a matter of fact that water systems in lowland include channel networks, the model should be applicable for channel networks and rivers under unsteady flow (Koga et. al., 1988). The calibration for the model is done using observed data on the water level, chloride and suspended solid concentration in the Rokkaku River in Japan. Assuming that the Rokkaku River could represent tidal rivers in Indonesia, furthermore, an idea of the implementation of the results is presented.

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2. Water Problems in Tidal Rivers of Indonesia

The water quantity problem is related to the human activities and the amount of rainfall. In Java, high population density, intensified agriculture and industrial activities raise some water problems because of not only less amount of available water but also limited amount of water in acceptable quality. Another cause is that the rainfall is unevenly distributed throughout the year. In wet season, the estimated amount of water is about 175 billion m^3 (70% of annual precipitation). This causes flooding on 6 % of the Java areas. In dry season, it is only about 78 billion m^3 (30% of annual precipitation) that is not enough for high-populated cities such as Jakarta and Surabaya. In other islands, the water problems have not yet seriously arisen because low population density and enough amounts of water resources slack the conflicts between beneficiaries (World bank, 1988). However, the other water problems arise very specifically related to the natural properties, for example, less rainfall in some parts of Sumatra, highly organic contents of water in Kalimantan and rapid river flows in Sulawesi.

The quality of water in tidal zones could severely under the influence of urbanization, industrialization, natural erosion, etc. River water and coastal ecosystems in northern part of Java are under the pressure from urban and industrial expansions. For example, in the west Java the averaged chemical oxygen demand (COD) loading to the river waters is 371 t/day, and 41 % of them comes from industrial wastes (IHE, 1985a). Additionally, suspended solid is another indicator of erosion for most rivers in Java. The northern coasts of Java with average depth 15 m, sedimentation takes place producing flat areas. It has also been reported (IHE, 1989) that the annual sedimentation in West Java could reach 100 t/ha. Moreover, the residue of artificial fertilizer potentially pollutes the river water in the northern coasts of Java (DGWR, 1989). Different from those in Java, in South of Kalimantan the water quality at the tidal zones is naturally rich in pyrite and silt. Iron-containing mineral is present in the sediment, and brackish water is rich in organic matters and sulfates (Roelse et.al., 1986). Furthermore, they reported that the existence of sulfate reducing bacteria and aerobic environment lead to the formation of pyrites from ferric dioxide.

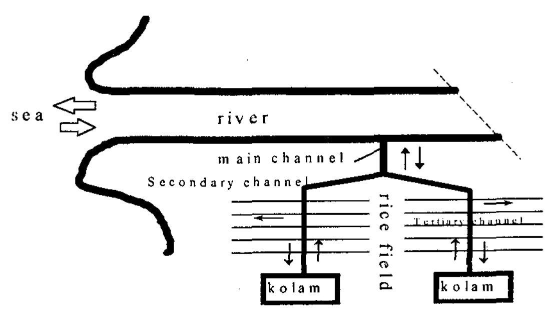

Figure 1. An example of tidal river utilization for rice fields in Barambai, South of Kalimantan (Roalse et.al., 1986).

To utilize river water in Kalimantan, Kolam systems have been implemented since 1971 (Figure 1). The systems consist of main and secondary channels that convey river water to a Kolam as a storage pond. The tertiary channels distribute the water to paddy fields and also drain the water to the main channel that has an open connection with the river. Acidification and toxification take place in used water that remains in the tail of the tertiary channels and returns to the paddy fields at high tide. It has been reported (Roelse et.al., 1986) that the used water harms paddy production.

3. Improvement of the Tidal River Systems

In Kalimantan, water quality of the tidal rivers for agriculture needs to be improved based on appropriate technology. It means that the applied technology should meet the available skilled personnel, low costs of construction and simple operations. There are some possible alternatives to improve the water quality for rice production. However, the most interesting solution concerning hydrodynamic point of view is an effort to flush the acid water out from the systems as suggested by Roelse et. al. (1986). This could be done by separating canals for discharging water from the agriculture areas and for incoming water from the river. Therefore, the structures for water intake should be located at the upper side than the outlet of the used water. Addition to that, groundwater table should be maintained at a certain level to avoid oxidation. These methods need drainage canals and man-operated gates.

In Java, water quality of the rivers can be improved since sedimentation and wastewater discharges are controlled. Terracing and reforestation technique applied in steep-sloped watersheds is one of the ways to control erosion (World Bank, 1988). Besides, an emergency solution is usually practiced through construction of weirs or small dams along steep-sloped rivers to reduce the flow velocity, although the costs of construction are not always cheaper than the costs of dredging sediment from irrigation channels (Dwiwarsito and Graff, 1987). At the downstream side of the rivers, the sea water intrusion is usually handled by gates installed near the river mouth. Moreover, other water pollution problems by domestic and industrial loading should be solved by providing wastewater collection and treatment systems (Terangna, 1992). There seem no other alternatives to improve water quality of the rivers in Java even though the proposed methods need large costs.

The improvement of the water systems requires information on the hydrological properties; e.g. the flow velocity and the river water levels, and on the characteristics of the water quality; e.g. chloride, suspended solids, etc. A reliable way to get the information can be conducted through computer simulations. Based on the results of the simulations, some decisions on the water management are easily made. For example, the operation of water gates requires data on the water levels and chloride concentrations at a certain intervals. Seawater intrusion should be monitored and controlled to avoid dehydration of plants. So an applicable computer model is the core of river water management.

Tidal river is one of elements of the water systems in lowland area as well as open channel networks for drainage and/or irrigation. Water management for the water systems including tidal river should be integrated from the aspect of water quantity and water quality. In order to control water movement, hardware of the water structures, such as Kolam systems, channel networks, weirs are indispensable. At the same time the software is necessary for the water management systems. Main and final purpose of developing the software is generally to analyze the water policy and also to apply the input/output information to the water management systems. The definite utilities of the software are 1) planning and designing the water distribution systems and water pollution control systems, 2) making rules to control the water structures, 3) evaluation of the impacts of water policy concerning water quality and quantity. Functions required for the computer model are 1) bridging the input/output information between the water sub-systems e.g. tidal river and channel networks, tidal river and water structures, 2) applicability for unsteady state of water movement and water quality, 3) acceptability for a lot of experts of various fields, such as hydrology, biology, chemistry, etc. From the above viewpoints, one-dimensional water movement and water quality model, so called branch-node model, is developed using the graph theory and the Galerkin method (Finite Element Method). The proposed model is useful for computing water movement and water quality in channel networks including tidal rivers (Booij, 1980; Sudjono and Koga, 1996).

4. Mathematical Formulation of the Water Quality Model

Flows in open channel networks and tidal rivers are supposed to be well-mixed in vertical and lateral directions. The one-dimensional flow model and water quality parameters can be developed by averaging over the whole cross-section of the flow. According to the graph theory, governing equations for tidal rivers can be expressed in the same way as those for open channel networks.

4.1. The formulation of water movement

A set of two equations is used for the flow computation in network systems.

The momentum equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial (Qv)}{\partial x}+gA\frac{\partial h}{\partial x}+J(Q,h)=0 \qquad (1)$$

Q: discharge; v: average flow velocity; A: flow cross section, h: water level; t: time; g: gravity; x: the distance along the axis of the channel, and J: the slope due to friction.

The continuity equation:

$$\frac{\partial B}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (2)$$

B: total wetted cross section as a function of the water level *h*; $dB/dh = b$, *b*: width of storage. The schematization of the branch-node network is shown in Figure 2. A branch (m) connects two nodes, $I_{(m)}$ and $J_{(m)}$. The physical definition of the node is non-capacity point. The discharge and water level in the branch (m) are defined by their values at both ends of the branch as also shown in Figure 2, $Q_{1,m}$, $Q_{2,m}$, for discharge, and $h_{1,m}$, $h_{2,m}$, for water level. These water levels, $H_{I(m)}$ and $H_{J(m)}$, are identical to the ones at the nodes located adjacent to the ends of the branch.

Through elimination approach, water levels can be calculated and then the discharges at the ends of the branch can be obtained. Computational detail of the water flow is described in the report in ICES subsystem FLOWS (Booij, 1980) and Duflow manual (1992).

4.2. The formulation of concentration

The flow in the hydraulic networks is supposed to be well mixed. The concentrations can be uniform in a cross section.

The mass conservation equation:

$$\frac{\partial BC}{\partial t}+\frac{\partial S}{\partial x}\pm P=0 \qquad (3)$$

S: mass transport rate; C: average concentration; P: reaction rate.

The mass transport rate is written as follow:

$$S = QC - AD\frac{\partial C}{\partial x} \tag{4}$$

D: dispersion coefficient.

There are four possibilities of the flow direction in a branch, i.e. inward to the branch from the nodes and outward from the branch as shown in Figure 2.

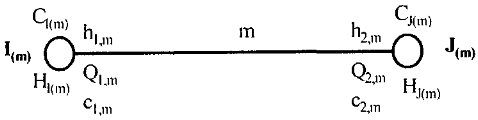

Figure 2. One branch and the nodes.

If the flow is inward direction:

$$c_1 = C_i \quad \text{if } Q_1^+ \geq 0; \tag{5a}$$

$$c_2^+ = C_j^+ \quad \text{if } Q_1^+ < 0; \tag{5b}$$

If the flow is outward direction:

$$S_1 = Q_1 \cdot c_1 \quad \text{if } Q_1^+ \leq 0 \tag{6a}$$

$$S_2 = Q_2 \cdot c_2 \quad \text{if } Q_1^+ > 0 \tag{6b}$$

c_1^+ and c_2^+: the concentration at the ends of the branch.

C_I^+ and C_J^+: the concentration at the nodes.

4.3. The formulation of settlement and erosion

Settlement process and re-suspension process in tidal rivers are influenced by flow properties (i.e. friction velocity), cohesive properties of suspended solids and deposited mud. Herein, the formulae proposed by Futawatari and Kusuda (1993) are applied into the developed model.

Vertical fluxes for erosion, (F_e, kg/m^2-s):

$$F_e = \beta\left[\frac{u^{*2}}{u_e^{*2}} - 1\right]^m \quad \text{for } u^* \geq u_e^* \tag{7a}$$

$$F_e = 0 \quad \text{for } u^* < u_e^* \tag{7b}$$

β: coefficient of erosion rate [kg/m^2-s], and m: exponent$\approx$ 1.7

$$\beta = (-0.375\ C_{cl}+2.609)\ 10^{-4} \quad \text{for } C_{cl} \leq 4.37 \tag{8a}$$

$$\beta = (-0.00438\ C_{cl}+0.99)\ 10^{-4} \quad \text{for } C_{cl} > 4.37 \tag{8b}$$

C_{cl}: the concentration of chloride [kg/m^3].

u^*_e: critical bottom friction velocity of erosion [m/s].

$u^*_e = 0.025$ for fluid mud

$u^*_e = 0.030$ for mud bed

Vertical fluxes for deposition (F_d, kg/m^2-s):

$$F_d = -w\,C \qquad \text{for } u^* \le u_d^* \tag{9a}$$

$$F_d = 0 \qquad \text{for } u^* > u_d^* \tag{9b}$$

w: settling velocity [m/s].
u^*_d: critical bottom friction velocity of deposition [m/s].
The settling velocity of suspended solid is expressed as a function of non-dimensional concentration of suspended solids, C_{ss}/C_0.

$$w = 0.0000357 \qquad \text{for } C_{ss}/C_o \le 1 \tag{10a}$$

$$w = \{7.407 \log (C_{ss}/C_o)+0.411\}\ 10^{-4} \qquad \text{for } C_{ss}/C_o > 1 \tag{10b}$$

C_{ss}: average cross sectional concentration of suspended solids [kg/m^3].
C_0: reference concentration of suspended solids$\approx$ 0.125 [kg/m^3] and the u^*_d is set to be 0.005 m/s.

5. The Simulation Result and Discussion

The necessity of integrated water management for tidal rivers in Indonesia is described in the above as well as the concept for computer tools. In order to evaluate the applicability of computer tools, calibration with observed data is necessary. However, implementation for collecting observed data is rather difficult in Indonesia. The data collection of suspended solids and other water qualities in the Rokkaku River has been done. Moreover, some important phenomena, which can formulate the reaction rate of the water quality, have been cleared. Therefore, the observed data are used for calibrating the proposed models. The points of observations along the river are located at Rokkaku bridge and Umada bridge. The distance of those points from the river mouth is 10.7 km and 16.6 km, respectively.

The thirty minute-interval measurements of chloride concentrations have been done for three events during spring and neap tide. At spring tide (date: 1984-03-17 and 1984-07-28) when the tidal difference is about 5 m, the maximum concentration of chloride at the Rokkaku bridge are 5000 and 7000 g/m^3. At neap tide (date: 1984-05-26), the maximum concentration of chloride at the Rokkaku bridge is 10000 g/m^3 with the tidal difference of about 3.5 m. Ten years monitoring in the shallow area of Ariake Bay indicates that the salinity is affected remarkably by the river discharge regardless of the seasons (Fujimoto, 1988). Furthermore, he stated that during rainy season between May and October the salinity variation is irregular and sometimes decreases because of the rainfall. In contrast, the salinity variation is small or nearly constant during wintertime. In this study, the observed data of chloride concentration at the river mouth are used as boundary conditions. The calculated results of the chloride concentrations by the proposed model, shown in Figure 3, 4 and 5, agree with the observed data as appropriate dispersion coefficients are used. The accuracy of the calculated concentrations of chloride is important for the calculation of suspended solids.

The suspended solid concentrations were measured concurrently with the chloride concentrations. Other measurements on turbidity in Ariake Bay by Itoh et. al. (1988)

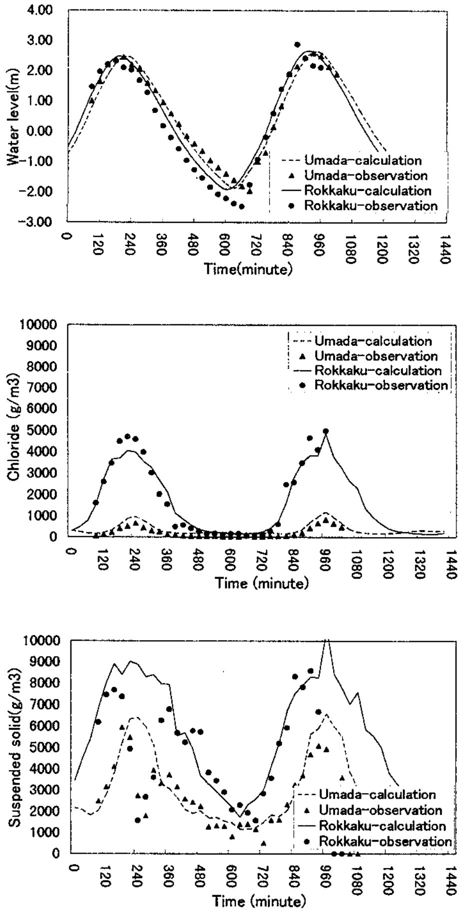

Figure 3. Spring tide at the Rokkaku River.
Date: 1984-03-17.

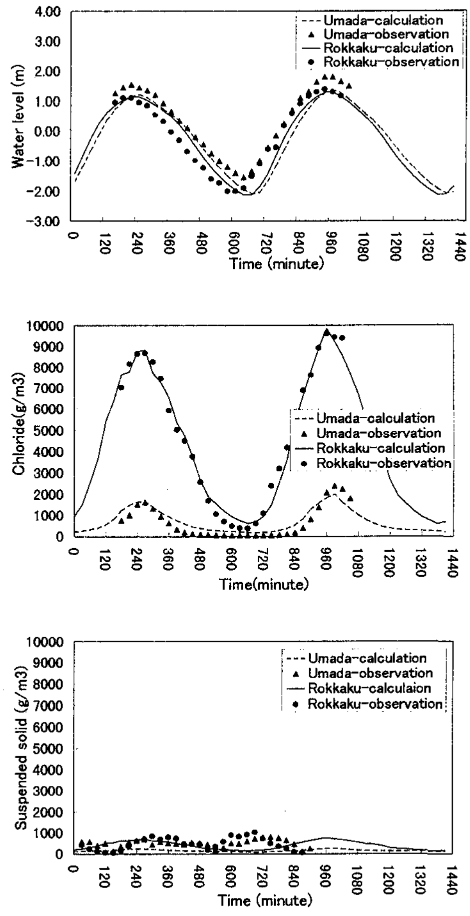

Figure 4. Neap tide at the Rokkaku River.
Date: 1984-05-26.

indicate that rapid increase of turbidity, that is likely generated by re-suspension of bottom sediments, mostly occurs in the early flood and later ebb tides. This seems that the suspended solid concentrations in the river are possibly under the influence of suspended solids in Ariake Sea as well as erosion in the upstream side of the river. To calculate the suspended solid concentration, the calculation on chloride concentration should be proceeded because the coefficient of erosion rate and the settling velocity depend on the chloride concentrations. The calculation on the flux of erosion and deposition requires estimation of the critical bottom friction velocities of erosion and deposition. Futawatari and Kusuda (1993) suggest that the critical bottom friction velocity of erosion is between 0.025 to 0.030 m/sec and the critical bottom friction velocity of deposition is about 0.005 m/sec. There will be interactions between the suspended solids concentrations and the amount of deposited mud. The erosion processes can only happen if there is the deposited mud on the river bottom. The consolidation of mud by gravity and hardening by shear stress is an important state of the mud behavior (Umita et. al., 1987). This implies that the critical bottom friction velocities together with the initial mud distributions along the river are keys to discover the accurate suspended solid concentrations. After some simulation and analysis of the results, the critical bottom friction velocities can be found and finally the results are obtained as shown in Figure 3, 4 and 5. From these figures, it is recognized that the performance of the proposed model is satisfactory.

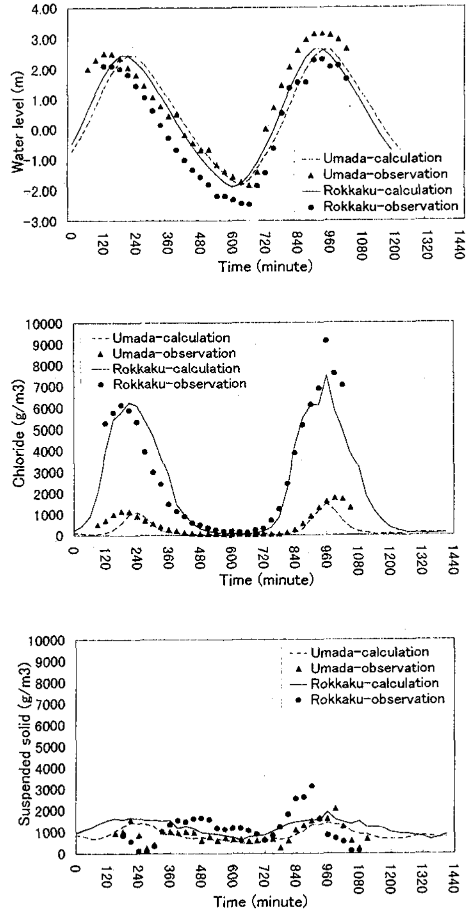

Figure 4. Spring tide at the Rokkaku River. Date: 1984-07-28.

The branch-node model can be widely used for the management of water quantity and water quality in rivers or network systems. The channel networks in lowlands are characterized by small slopes and complicated connections. These situations produce high potential of eutrophication as stagnant water is dominant. A short-term solution for the eutrophication is carried out by flushing the stagnant water out of the systems. A research done in the Saga creeks using the proposed model could indicate the required water to improve the water quality (Koga and Araki, 1993). In this paper, it has been shown that the model is capable to calculate the suspended solid concentrations in tidal rivers. This information is useful to solve serious water problems such as pyrite in the sediment of tidal rivers and the Kolam systems. Additionally, it is pointed out that the development of farmlands and the improvement of irrigation channel networks will encourage the water management systems in a watershed. So, it is necessary to establish integrated management for tidal rivers concerning water quality and water quantity. The developed model is an appropriate tool for this purpose.

Conclusion

The one-dimensional water quality model is capable to calculate chloride and suspended solids concentrations in the Rokkaku River. This means that the model as a tool can be useful to establish water management especially for tidal rivers and the developed systems such as the Kolam systems in Indonesia.

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