

Title:

Simulation of the effects of the alteration of the river basin land use on river water temperature using the multi-layer mesh-typed runoff model.

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Abstract

A model displaying river water temperatures was established, and applied to a small river basin. Based on the results, the effects of the alteration of the river basin on the budget and river water temperature were discussed. The model was a multi-layer mesh-typed runoff model, and the behavior of water and heat transference was depicted. Also, in order to verify the model, the daily changes of streamflow and river water temperature were measured and compared with the model results. From the calculation, the flow rate and river water temperature profile agreed well with the measured ones along the streamline. Using the model, the effects of deforestation and air temperature rise on river water temperature were discussed. With deforestation, the temperature in summer was calculated to rise and fall in winter. This was explained by the change of flow pass of surface and subsurface. The air temperature was thereafter changed in the model. From the simulation under the air temperature rises, the daily air temperature was evenly changed through a year, and the ratio of the change of the river water temperature to the air was less than unity (i. e., $>1 \text{ } ^\circ\text{C}_{\text{river water}} / ^\circ\text{C}_{\text{air}}$). By close investigation of the model calculation, the most influential factor was determined to be subsurface temperature. The rise of surface temperature was also less than unity, due to the enhancement of heat loss with the augmentation of evaporation at the surface, and because the subsurface temperature is calculated on the surface temperature as boundary condition, rise of subsurface temperature was also less than unity. Overall, the mechanism of the alteration of river water temperature was described as follows: with the change of river basin land use or meteorological conditions, the pass of subsurface flow is changed, and the streamflow and river water temperature are also changed.

Author keywords: River water temperature; Multi-layer mesh-typed runoff model; Heat transfer; River basin

1. Introduction

Global temperature is predicted to rise due to human activities, and the influences of global warming are believed to be a great threat to the natural environment and human activities (Harasawa et al., 2001; Smith et al., 1989). Recently, a considerable number of studies have been focused on various natural and socioeconomic effects of global warming on aquatic ecosystems. These changes are considered to cause disruptions such as the deterioration of river water quality, eutrophication of lakes and coastal zones and so on (Avila et al., 1996; Cruise et al., 1999; Fukushima et al., 2000; Magnuson et al., 1997; Ozaki et al., 1999, 2000; Pilgrim et al., 1998; Schindler et al., 1997; Sumi et al., 1996). Also, due to global warming, the water temperature rises are thought to affect various living organisms directly or indirectly, and thus cause changes in ecological situations (Gitay et al., 2002). Water temperature changes arisen from increased temperatures will alter thermal cycles of lakes and the solubility of oxygen and other materials, and thus affect ecosystem structure and function. Climate change will affect freshwater ecosystems through alteration in hydrological processes. For example, river water temperature rises have been proven to influence fish thermal habitats in streams (Jensen, 1987; Eaton and Scheller, 1996).

So, for the modeling of riverine ecosystems, it is important to discuss how the stream water temperature changes, as well as the streamflow, due to the alterations of the river basin with the urbanization, or the meteorological changes. A large number of researchers investigated these effects experimentally or by field researches (Moore et al., 2005a). For streamflow, the many elaborated models have been developed and applied for river water discharge management (Tang et al., 2005; Bellot et al., 2001). For stream water temperature, however, the calculation in the models mainly begins with certain upstream points, and the integrated models on the water discharge models have not been well developed yet. Moore et al., (2005a) summarized the present research situation of this field, and discussed the

effects of riparian microclimatic changes on the stream temperatures. For further investigation, they pointed out the influences of surface/subsurface water exchange on stream water temperature.

In this paper, the mesh and multi-layer runoff model was applied for a small stream, and the behavior of heat transfer was modelled on the water runoff model. In order to verify the model, the daily changes of streamflow and river water temperature were measured, and the calculation with the model was conducted using on meteorological data and compared with the measured data. The reason why this stream was selected for this study is that intensive measurements of air and stream temperature could be conducted along the streamline, and, also, different land use could be seen for this small area. The mechanism of the river temperature formation itself is common from a microscopic view. Hence, the knowledge obtained from the simulation of physical processes would be common to other rivers independent of the study river's spatial scale.

2. Field measurements

The Yamanakatanigara river has a catchment of 1.7 km² and is located in southwest Japan (Fig. 1), of which the topographic height is between 200 and 300 m above sea level. The total catchment area is located on the campus of Hiroshima University. The climate condition of this area is moderate, with a yearly averaged temperature of 13 °C (2003), and a mean annual precipitation of 1,500 mm (2003). Precipitation is mainly rainfall, and snow falls just several times in a year. About half of the area is forest, and the rest is pavement. The stream length is around 1.0 km, and there are two ponds in the area; the one is in an upstream zone (pond A), and the other is in a midstream (pond B).

In the study area, five stream temperature measuring points were located (St. 1~5; Fig. 1), and the temperature was measured with a small, portable and autonomous data logger (StowAway TidbiT; Onset Computer corporation, USA). Also, the streamflow was predicted from the H-Q curve obtained from

the consecutive measurement of the depth of water from 2000/11/01 to 2001/01/31 and the occasional stream velocity measurements at the time of rain occurrence at St. 2.

The meteorological data were collected from the meteorological data acquisition system (<http://home.hiroshima-u.ac.jp/hirodas>) in Hiroshima University (At. 1; Fig. 1). This point was supposed to represent the catchment area and data for air temperature, precipitation, humidity, and wind velocity were acquired.

To know the depth profile of the subsurface temperature and to determine the heat transfer coefficient experimentally, the subsurface temperature was measured at different depths at a point in the forest area near St. 2 at the interval of one hour. Measured depths were 3, 20, 40, and 60 cm, and the duration was 2003/02/08~11/29 (the data were not obtained from 06/05 to 08/13 due to the operational trouble).

3. Model description

3.1. Spatial and temporal scheme

The area of each mesh was 200*200m, and 43 meshes cover the river basin (Fig. 1). The subsurface depth for calculation was 14.8m, and was segmented into 4 (the depth of each layer was 0.3, 1.0, 3.5, 10.0 m from the surface). This depth profile is based on the configuration of the ground and geologic formation in Japan. The depth of basement rock, which is not contribute to the river flow, is generally ten to several tens of meters in mountainous areas of Japan. The time step of the calculation of discharge was 10 minutes. Input meteorological data were air temperature, precipitation, solar radiation, wind velocity, and humidity. The time resolution of the data was day, except for precipitation and wind velocity (10 minutes). While the time resolution was 10 minutes in the calculation of water discharge, the predicted discharges could consequently be compared on a daily basis with the measured ones. For an approach run for obtaining the stable values at the start of the simulation, calculation was begun nine days before the start of

the simulation period. Thus, to obtain the model results for one year (365 days), the calculation was made for 374 days.

Land use was classified into five groups: forest, paddy field, plowed field, urban area, and water (Table 1).

In the calculation for pond A and B, the averaged pond depth and width were fit to the actual ones. The outflow from pond A was very small in both actual situation and model calculation. This is because the area of the outflow was much smaller than other direct inflow areas to the river.

The temporal and spatial resolution was determined in this way; the observed most rapid change of stream conditions, such as flow rate, occurred in the order of ten minutes. For this reason, the time step was set to be 10 minutes. Mesh size should be longer than the water movement in one time step. Flow velocity of the stream was in the order of 0.1 m s^{-1} . So water moved 60 m in 10 minutes. Spatial mesh size was desired to be smaller as long as it exceeded the order of 60 meters. For this reason, mesh size was set at 200 m.

3.2 Calculation of heat transfer

Water and heat transfer are calculated based on surface and subsurface layers according to the theory of the water temperature dynamics (Arai, 1974; Jacquet, 1983; Thomann and Mueller, 1987). The basic calculation methods and hypotheses were shown to be as follows;

- Evapotranspiration was calculated for each mesh.
- Albedo and coverage were averaged in each mesh.
- Air temperature, precipitation, and wind velocity were assumed to be the same in all meshes.

The overall heat budget was calculated as follows:

$$(1-a)I=(R_1-R_2)+H+LE \quad (1)$$

where a: albedo, I: solar radiation, R_1 : long-wave radiation from surface, R_2 : long-wave radiation from atmosphere, H: sensible heat transfer, and LE: latent heat transfer.

Each coefficient is described as follows:

$$R_1 = e \cdot s \cdot (T_s + 273)^4 \quad (2)$$

$$(e = 1.0, s = 8.14 \cdot 10^{-11} (\text{cal K}^{-4} \text{ cm}^{-2} \text{ min}^{-1}) = 1.17 \cdot 10^{-7} (\text{cal K}^{-4} \text{ cm}^{-2} \text{ day}^{-1}))$$

$$R_2 = s \cdot (T_{\text{air}} + 273)^4 (a + b \cdot e_{\text{air}}^{1/2}) \quad (3)$$

$$(a = 0.51, b = 0.062 (\text{mb}^{-1/2}))$$

$$H = h(T_s - T_{\text{air}}) \quad (4)$$

$$(h = 2.0 \times 10^{-4} (\text{ly sec}^{-1} \text{ K}^{-1}) = 1.7 \times 10^1 (\text{ly day}^{-1} \text{ K}^{-1}))$$

$$LE = k(e_s - e_{\text{air}}) \quad (5)$$

$$(k = 1.5 \cdot h)$$

where T_s : surface or water temperature, T_{air} : air temperature, e_{air} : vapor pressure in atmosphere, e_s : vapor pressure at ground or water surface.

Using equations (1)~(5), T_s and evapotranspiration were determined.

In the forest, leaf coverage was supposed to influence the irradiation and evaporation. They were assumed to decrease in proportion to the coverage ratio. The coverage ratio was derived based on the fisheye photographs taken in the forest. Based on the black and white color pictures, a year was divided into two seasons (**Table 1**), and the coverage ratios were averaged for each season.

Figure 3 shows the procedure and scheme of the model calculation. Two parameters were calibrated for fitting to the actual values; one was the heat transfer coefficient calibrated by fitting to the subsurface temperature profile, and the other was hydraulic conductivity calibrated by fitting to the river discharge. For other parameters, the values in the textbook (Arai, 1974) were applied for this model. Snowfall was also modelled, but because of a very small snowfall, this process could not be verified in this study.

3.3 Calculation of water transfer

Precipitation in an urban area was discharged into the storm sewer. The flow of storm sewer through surface run-off, irrigation channels of paddy fields, and a river was described using the kinematic wave method. Even in other land uses, surface runoff is described using the kinematic wave method. Subsurface flow was described using the linear storage method. The thickness and hydraulic conductivity of subsurface layers are shown in

table 2. The fitted values of hydraulic conductivity (horizontal) was in the range of $10^0 \sim 10^{-4}$ m hr⁻¹ and decreased with the layer depth. The obtained hydraulic conductivity was within the range of sand to silt.

3.4 Calculation of subsurface temperature

The subsurface temperature was described by the following heat transfer equation:

$$\frac{\partial T_s}{\partial t} = \chi \frac{\partial^2 T_s}{\partial z^2} \quad (6)$$

where χ is the heat transfer coefficient.

To solve this equation, the vertical profile of subsurface temperature at the starting time is set as the initial condition, and temperatures at the surface and infinite depth are set as the boundary condition (the temperature at infinite depth was set to be constant).

3.5 Calculation of river water temperature

Integrating the water and heat transfer calculation, the river water temperature was calculated in the following equation:

$$C\rho D \frac{\partial T_w}{\partial t} = H_0 + \frac{C_r}{A} \sum_i q_i (T_{in} - T_w) \quad (7)$$

where C: specific heat, ρ : density, D: water depth, T_w : water temperature, H_0 : heat flux from the water surface, A: water surface area, q_i : inflow water volume, and T_{in} : inflow water temperature.

The value of H_0 was determined by the equations (1)~(4), and the second term in the left side of the equation (7) were obtained from the water budget in the surface and subsurface layer. For water temperature in each subsurface layer (layer A~D), the averaged value for each layer was used.

Precipitation temperature was supposed to be equal to that of the ground surface. Theoretically, precipitation temperature should be derived from the wet-bulb temperature. In this study, precipitation temperature just after contacting the ground surface was observed to be equal to that of the ground surface in the field survey. Hence, the precipitation temperature was

substantially set to be identical to the surface and subsurface temperature.

4. Results

4.1 Observed temperature variations

The observed variations of air and river water temperature, and precipitation are shown in **Fig. 4**. All of these are the daily averaged values. The seasonal variation of the river water temperature was lower than that of the air temperature. The river water temperatures at St. 1 to 3 were similar to each other and that at St. 4 was different from them, suggesting the influence of pond B on St. 4 (for St. 5, while the data were not obtained after June 2002 due to mechanical troubles, the tendencies agreed well with the values of St. 4 for the measured period). Water temperature at St. 4 is supposed to be similar to that of pond B because the location is quite near to the discharge of the pond, and the temperature profile is similar to the water temperature in thermal equilibrium with air (EWT) due to the longer retention time. From the field observation in pond A, no direct outflow was observed except for the rainfall period. The effect of pond A on river water temperature could be limited.

4.2 River water discharge

Figure 5 shows the observed and calculated river water discharges after a 24-hour moving average. The calculated values agreed basically with the observed ones. The ratio of total river discharge to the precipitation during the period was 52% for observation, and 37% for calculation. In the autumn, the observed value of baseflow was higher, and in the winter, on the contrary, it was lower than the calculated one. This would be due to the seasonal changes of water viscosity in the soil. Hydraulic conductivity decreases with an increase in viscosity, and this model does not consider this effect.

4.3 Estimation of subsurface temperature profile

The subsurface temperature was observed every one hour at depths of 3, 20,

40, 60cm (**Fig. 6**), and then the heat transfer coefficient and the temperature at the deepest depth were fit to the measured profile using the equation (6). The value for best fitting was $0.065 \text{ m}^2 \text{ d}^{-1}$ for the heat transfer coefficient, and 15°C for the temperature at the deepest depth (**Fig. 7**; observed and calculated values at 60cm). The predicted temperature at the deepest depth was significantly higher than the one-year averaged surface temperature (13°C). The subsurface temperature is generally influenced by the long-term climatic changes (Sakura, Y. 2000) and can differ from the short-term average (one or several years average).

Using the equation (6) with the obtained parameters, the subsurface temperature profile was determined using the calculated surface soil temperature. For calculation, the vertical profile of subsurface temperature on the starting date was needed as the initial condition. Firstly, the calculated surface soil temperature was approximated to a sine curve, and then, the subsurface temperature profile was determined under periodic boundary conditions. Using the result, the profile at the starting time is used as the initial condition for the actual calculation.

4.4 Prediction of river water temperature

Using the obtained parameters, temporal changes in the river water temperature was calculated (**Fig. 8**). At all the sampling stations, the calculated values agreed well with the obtained values. Our model was proved to simulate the river water temperature properly. The range of annual variation of the calculated water temperature was smaller than that of the observed one at St. 1. The reason for the attenuation in the calculation could be the mixture of subsurface water, which had smaller annual variation. In the calculation, even in the case that the deep subsurface water directly came out to the river, the subsurface water temperature was supposed to keep the deepest subsurface temperature just before the mixture to river water, and the effect of heat exchange during the rise of deep water into the surface layer was neglected. At other stations, this discrepancy was not clearly observed. This may be due to the fact that the heat exchange in

the river flow overwhelmed this discrepancy in the downstream. Further, this means that the model properly describes the heat exchange process in the river.

The patterns at St. 4 and 5 were different from those at upstream stations. This would be owing to the effect of approximation of equilibrium water temperature at pond B because similar temperature patterns were also observed in the model, and this change at pond B was apparently due to the approximation of equilibrium in the calculation.

5. Discussion

5.1 Effect of heat transfer on water surface

The river water temperature is determined by the water budget and heat transfer on water surface. The reliability of water budget can be basically checked by the observation of river discharge. In this section, heat transfer on water surface was tentatively omitted in the calculation (H_0 was set to zero in equation (7)) in order to consider the effect of surface heat transfer. **Figure 9** shows the results at St. 1, 3, and 5. During rainfall periods, the spike changes in water temperature are similar to those including heat exchange. During dry periods, on the other hand, the tendency is fairly different (indicated by arrows at St. 5 as example). The baseflow temperature during dry periods approaches to the annual averaged temperature. Baseflow water was calculated to come from the subsurface water, and was influenced more by the subsurface temperature. This model can be considered as the combination of water budget and surface heat transfer, and it was proved that the description of heat transfer on water surface (H_0 in equation (7)) plays an important role in describing water temperature. During a rainfall period, heat transfer on water surface is less effective because the discharge amount is a lot and because the contact time is shorter.

5.2 Effect of forest area

The study field area is dominated by forest. In order to estimate the effect of forest on water temperature, the forest area is reduced in the simulation. For this purpose, 50% of the forest in each mesh was changed to pavement area. Overall, temperature rose in summer and fell in winter, and the rate of the rise in summer was higher than the rate of fall in winter. (Fig. 10; at St. 5, this change rate is relatively small because the equilibrium state is once attained in the upstream part at the pond B.) This means that the forest area has the effect to moderate the range of annual water temperature variation. This effect was widely observed in the field studies (Moore, et al., 2005a, b, Johnson and Jones, 2000) and it was demonstrated that this model mechanically describes the effect of moderation. In order to understand the mechanism of the forest effect, the simplified, one-mesh calculation was made. In this calculation, almost all the area in the mesh (99%) is hypothesized to be covered with the forest or urban area. **Figure 11** shows the results of these two extreme situations. As to river water flow, baseflow is minimized in the urbanized case (Forest=1%). As to water temperature, temperature becomes higher in winter, and lower in summer for a forested area (**Fig. 11(c)**). The model proved that forest moderates the seasonal water temperature change. To examine the mechanism in more detail, the vertical profile of subsurface temperatures was changed to be constant with the depth (**Fig. 12**). The water temperature was drastically changed, and became closer to the air temperature. This means that via the discharge from the deep subsurface layers, constant water temperature affects the river water temperature of a forest area directly.

5.3 Effect of air temperature change

In order to consider the influence of air temperature change on water temperature, a calculation was made under the condition where the air temperature was 1°C higher above the present condition (2002) (**Fig. 13**). In this calculation, it was assumed that the temperature at the deepest depth would increase 0.85°C. This change should be in agreement with that of calculated surface soil temperature change. (0.8~0.9°C; the reason why

surface soil temperature change is less than unity is that the enhancement of evaporation suppresses the temperature rise). The water temperature rise was calculated to be about 0.8~0.9°C. Further, the recalculation was made under the condition that the temperature at the deepest depth=1°C, and the river water temperature increase was not about 0.8~0.9°C but about 1.0°C, indicating a direct effect of subsurface temperature on the river water temperature.

The actual data analysis using the data obtained in various different rivers in Japan showed the suppression of increase of river water (Ozaki et al., 1999, 2001, 2003). The enhanced evaporation could be the reason for this tendency. This result indicates the indirect evaporation effect; i.e., when air temperature increases, surface soil temperature also increases, but the rate is less than that of air temperature, due to the enhanced evaporation, and subsurface soil temperature follows surface soil temperature changes, and then, subsurface soil and water temperature primarily affects river water temperature. The analysis of the previous section (section 5.2) also showed the importance of temperature on subsurface waters inflows to a river. For understanding river water temperature, these results indicate the importance of subsurface conditions.

6. Conclusion

In order to predict river water changes caused by changes in meteorological condition and land use, a mesh and multi-layer river water prediction model was built and applied to a stream with a small basin. The model outputs agreed well with the measured ones. Using the model, the mechanism of river water changes was discussed. It was clearly indicated that the subsurface dynamics play a very important role in the forming of the river water temperature. In addition, it was proved that water temperature could be a good indicator for evaluating the performance of the river water hydrological model.

Future studies should concentrate on checking the model description for

other land covers. Performance should be proved particularly for paddy or other fields, and in addition, the effect of sewage water and/or snow should be considered by applying it to other rivers with different types of basins.

Lastly, in the mechanisms discussed in this paper, the following points should be considered in future studies:

- The spatial scaling-up of the model

This model is proved only for extremely small streams. So its applicability to larger rivers should be verified.

- Effect of rainwater

This model neglects the heat capacity of rainwater itself. That is, the river water on the ground is set to be equal to the surface soil temperature. However, surface soil temperature is influenced by the heat capacity of rainwater and this effect should be included in the future.

- The seepage subsurface water to river

The water temperature of seepage is set as equal to the subsurface soil temperature just before the mixing to the river even when the deep layer water directly flows into the river. This follows the description of water movement of an ordinary hydrological water flow model. But, when the deepest water flows through the shallow layers, the water might be influenced by these temperatures. In our model, in fact, daily changes of modeled river water temperature fluctuated more than the observed one, and this discrepancy may be due to this model of the description, as modeled river water temperature can be rapidly changed correspondent to a change in proportion of the subsurface layers flowing into the river.

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Table 1 Hydrological conditions of the river

Table 2 Subsurface depth profile

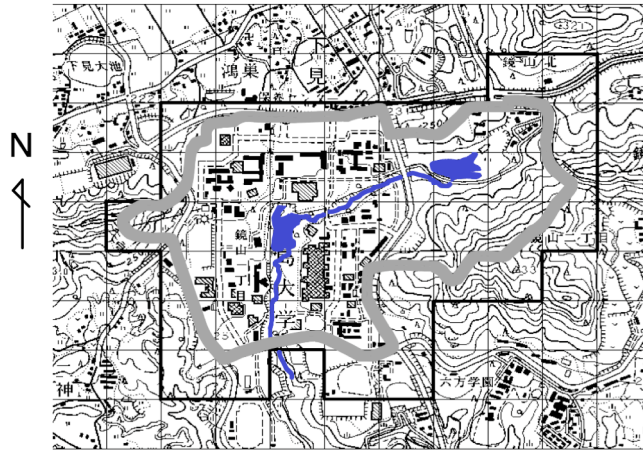


Fig. 1 Map of study area; stream (blue area), basin (bold gray line), and meshes of the runoff model
(Mesh size: 200m × 200m)

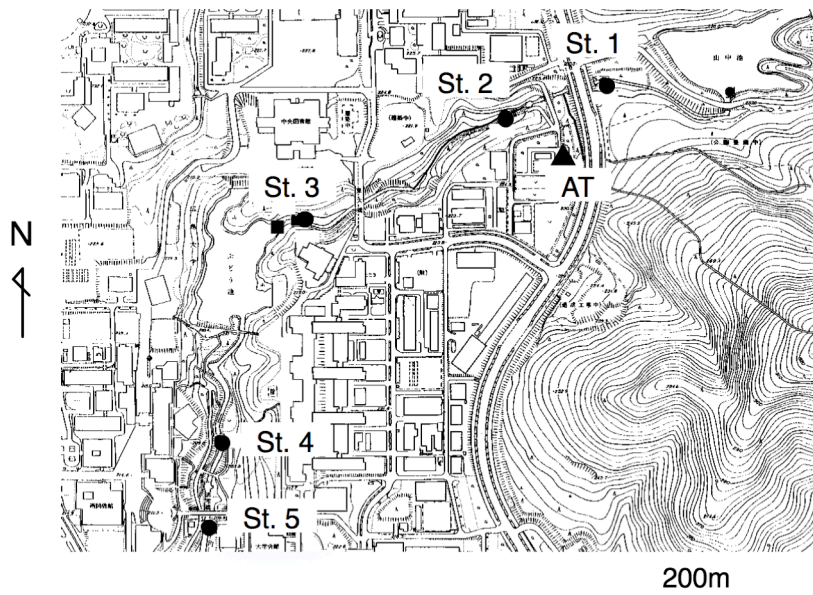
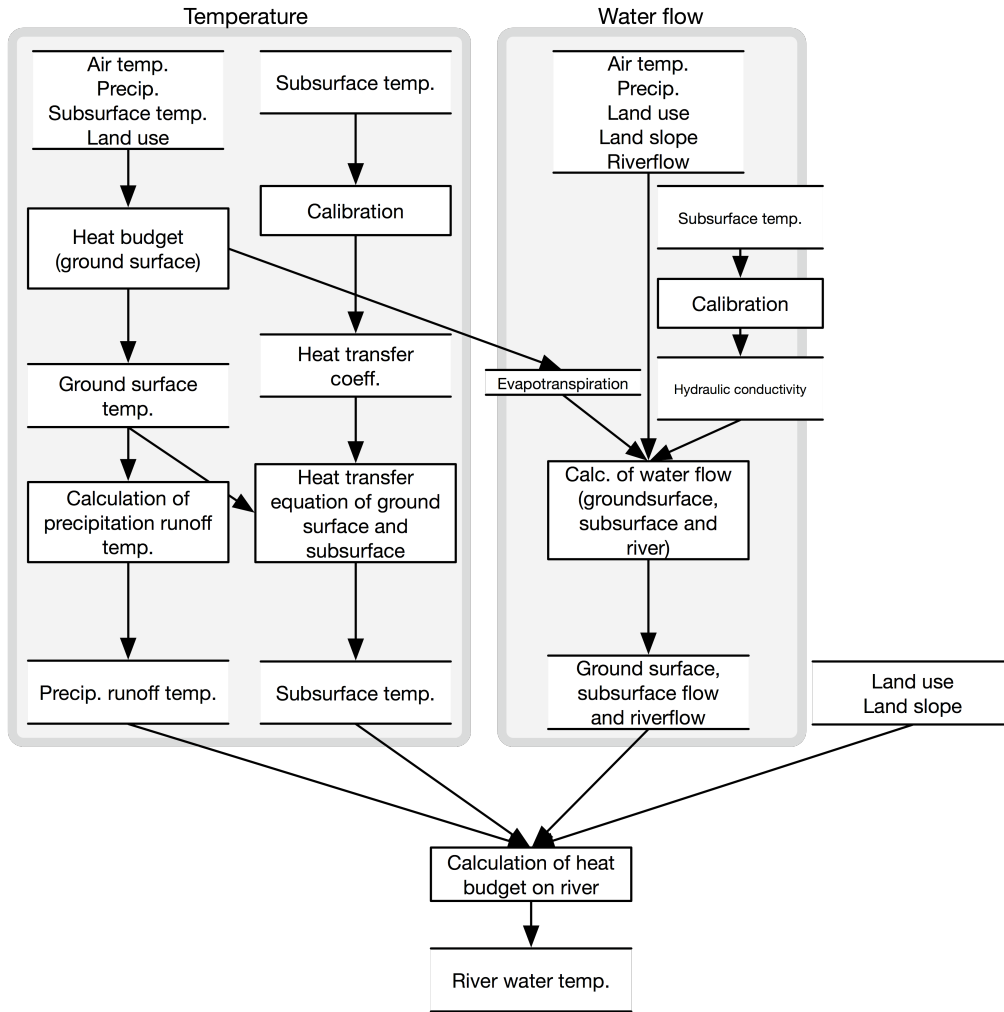


Fig. 2 Sampling stations of air and water temperature, streamflow, and other atmospheric conditions
(●: station for water temperature, ■: station for streamflow, ▲: station for air temperature)

(a) Programming flowchart



(b) Mesh and layer modelling scheme

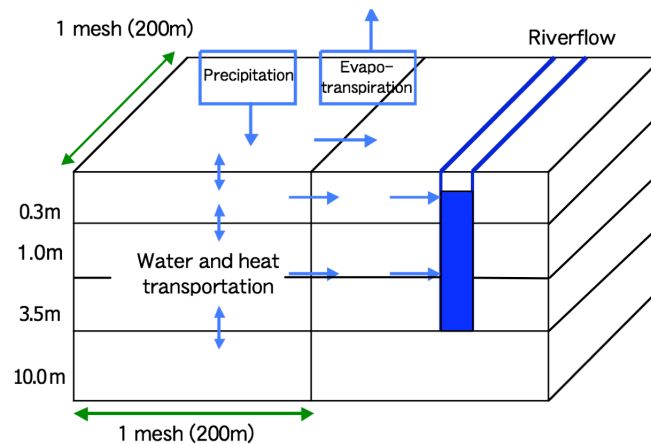


Fig. 3 Schematic diagram of model calculation

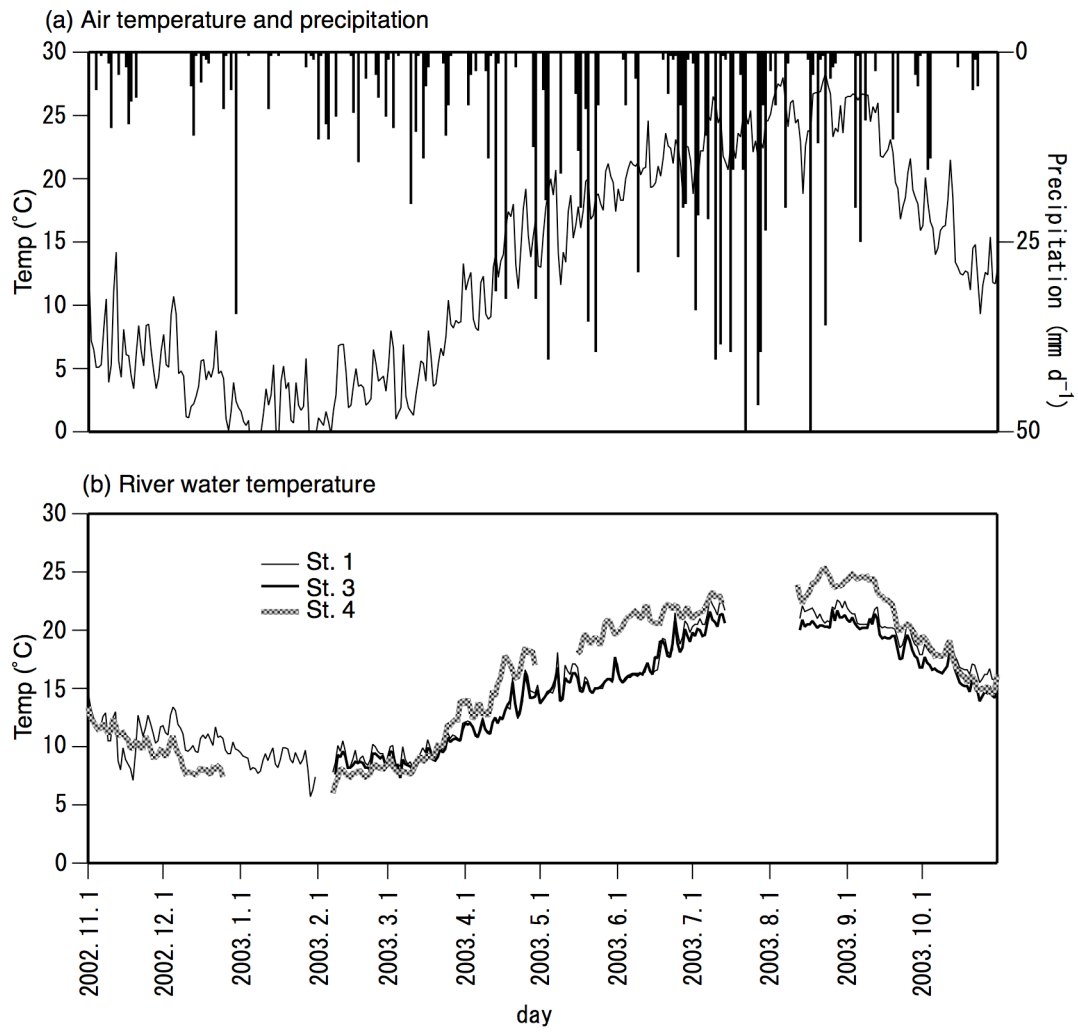


Fig. 4. Precipitation, air and river water temperatures

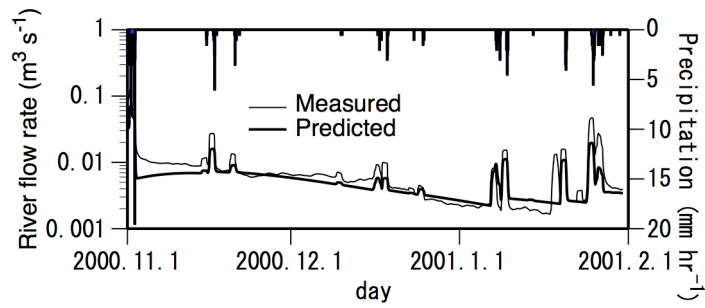


Fig. 5. Measured and predicted streamflow

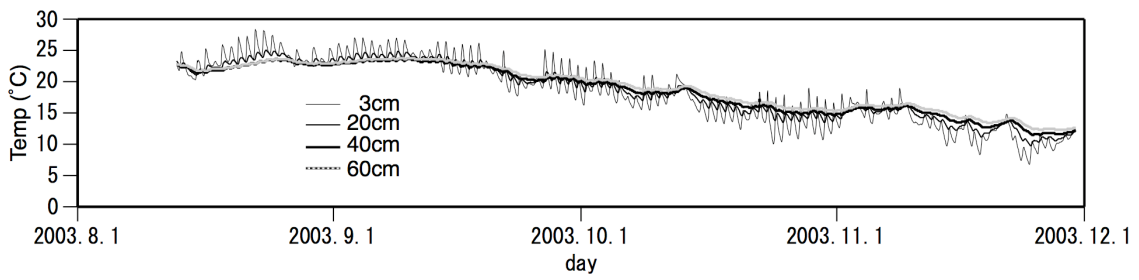


Fig. 6. Subsurface temperature profile

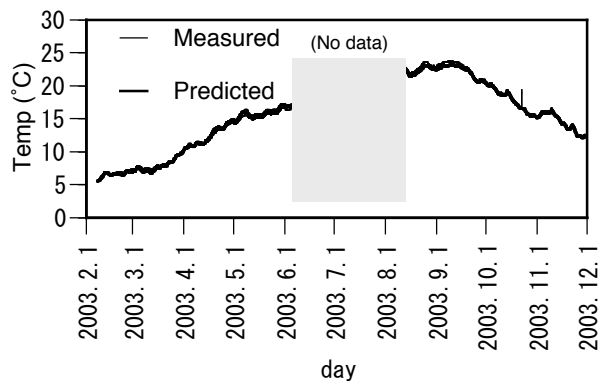


Fig. 7. Measured and predicted subsurface temperature (depth: 60cm)

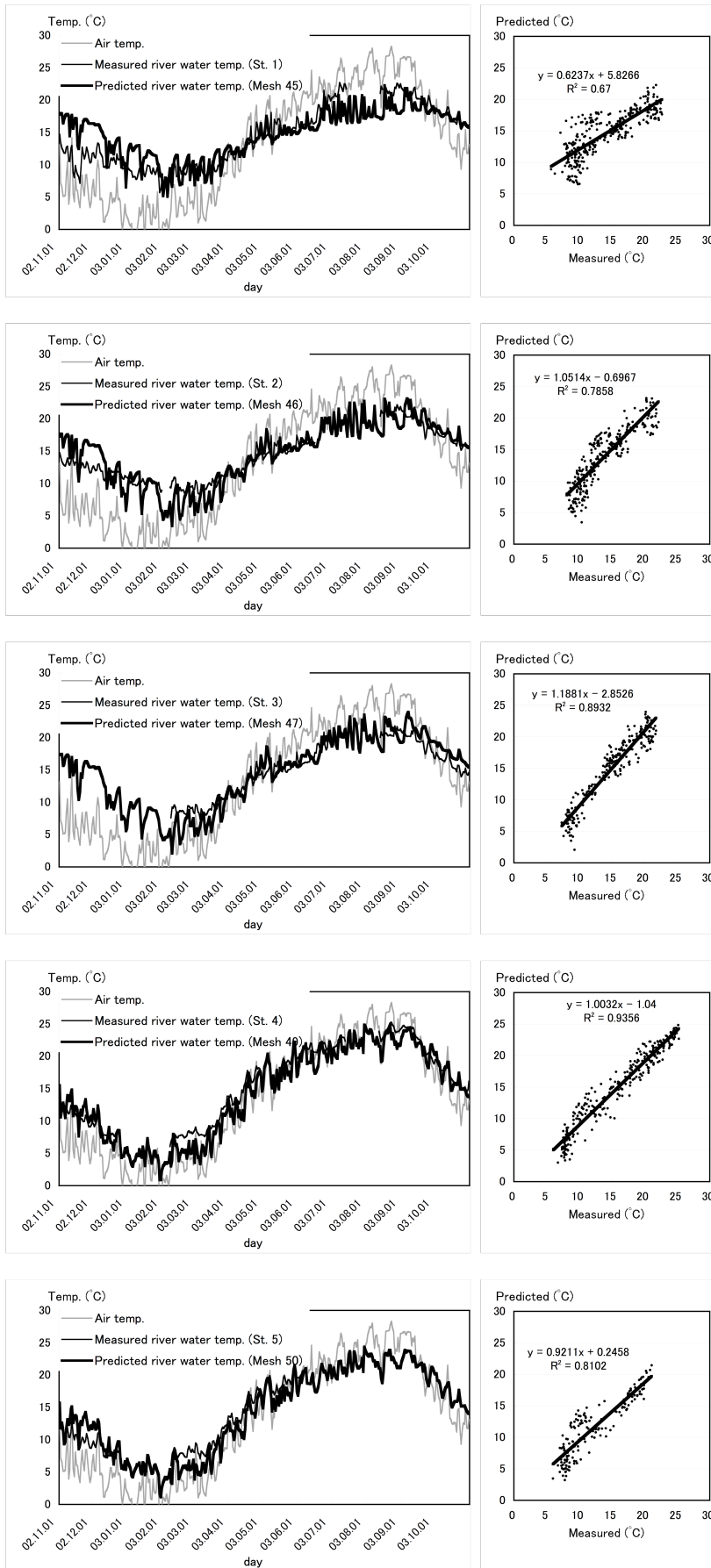


Fig. 8. Measured and predicted river water temperatures

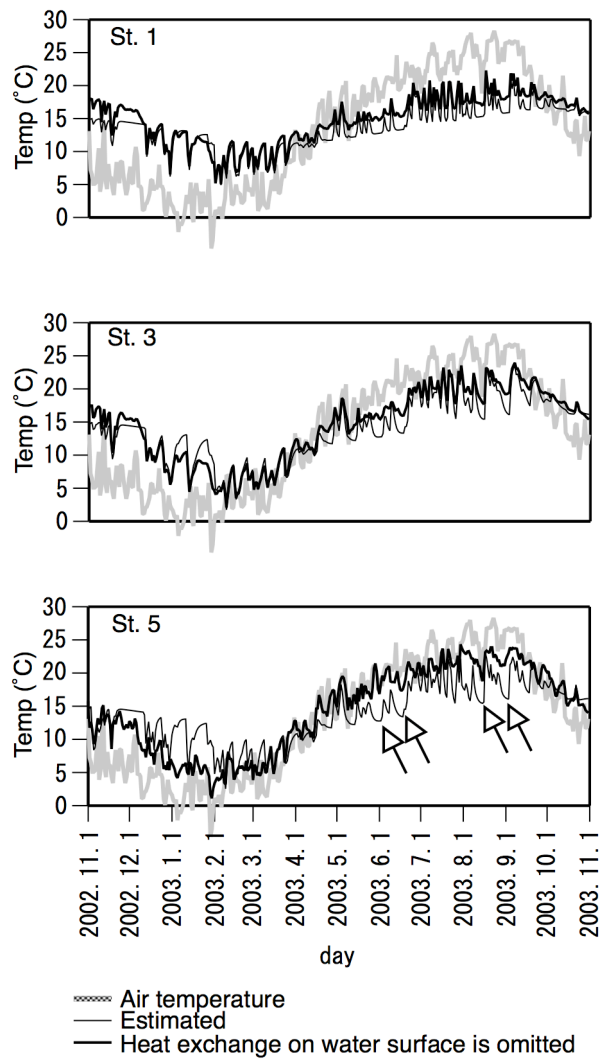


Fig. 9. Effect of heat exchange on water surface of the model
(arrows at St. 5 indicate the part of discrepancy)

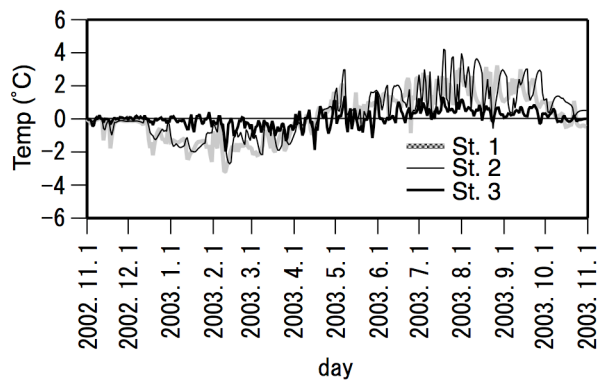


Fig. 10 Difference of the simulation between the existing and forest area 50% decreased conditions

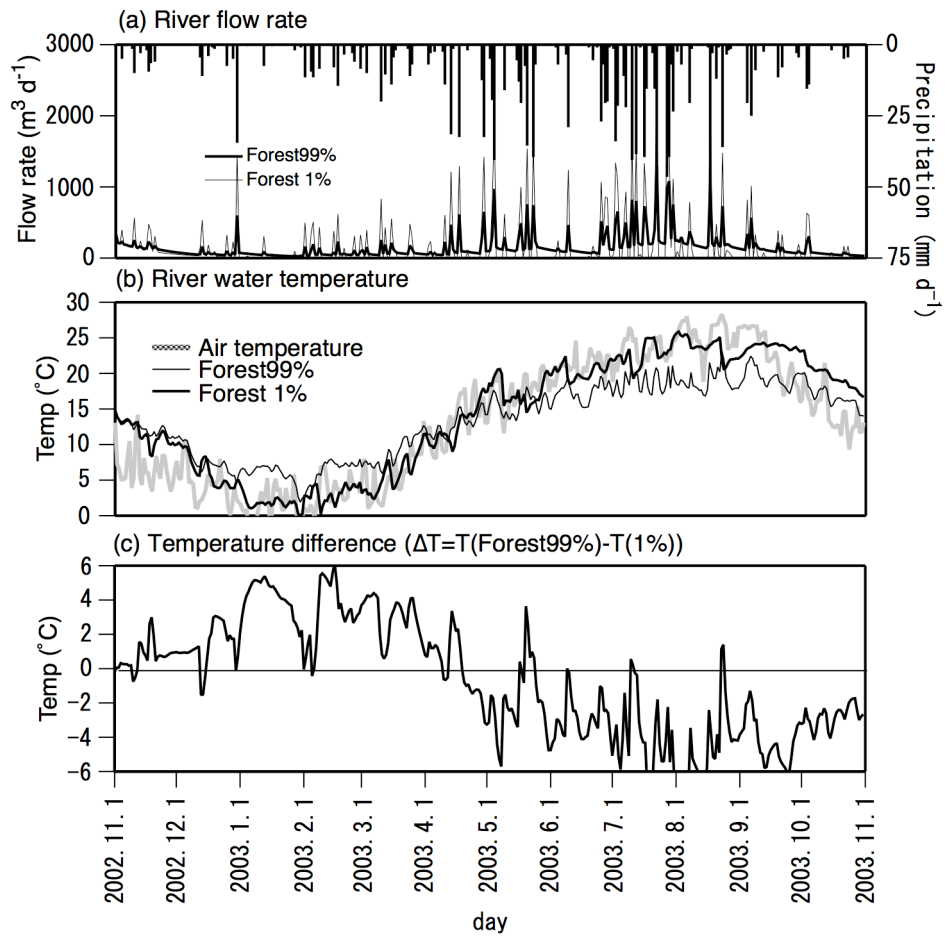


Fig. 11. Results of one-mesh run

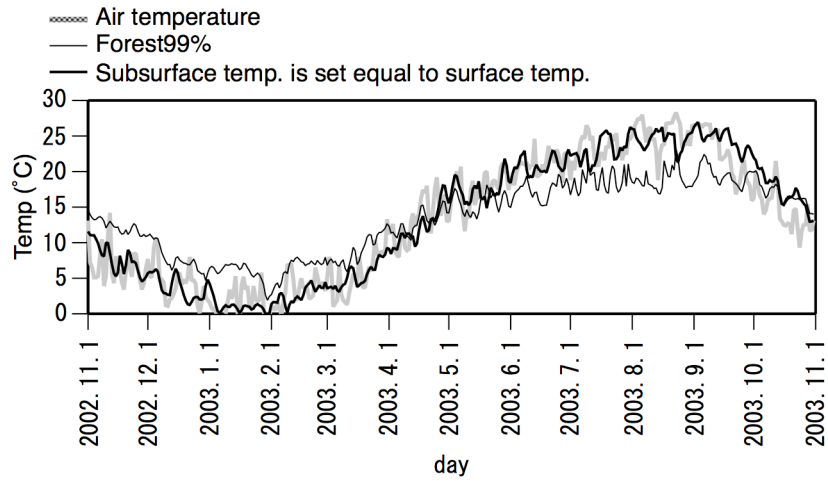


Fig. 12. Results in the condition that the subsurface temperature is set equal to surface temperature (one-mesh run)

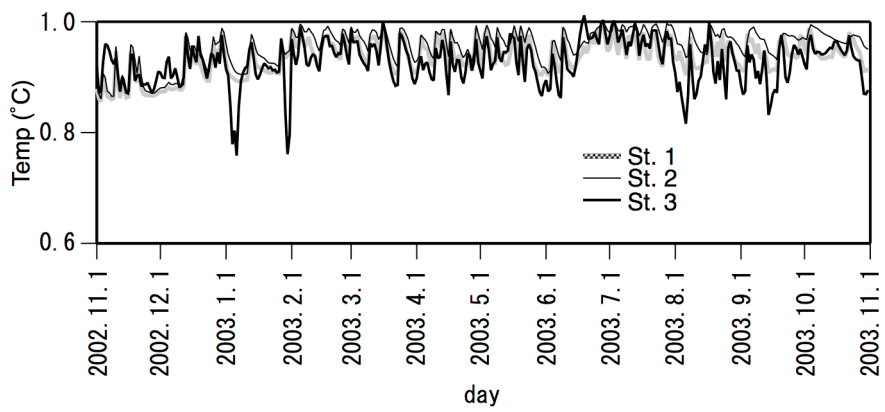


Fig. 13. Difference of the simulation between the existing and the temperature increased (1°C) conditions

Table 1. Hydrological conditions of the river

| Index | | albedo (-) | Coverage (-) |
|-----------------|---------------------|------------|----------------------------------|
| Length | 1.2km | | |
| Area | 1.7km ² | | |
| Forest | 0.86km ² | 0.09 | 0.81(season A), 0.75(season B)** |
| Paddy field | - | 0.06 | 0 |
| Plowed field | - | 0.20 | 0 |
| Urban | 0.81km ² | 0.18 | 0 |
| Water | 0.03km ² | 0.06 | 0 |
| Air temperature | 13.3°C* | | |
| Precipitation | 1,500mm* | | |

*average and sum of 2002.11/01~2003/10.31

**season A: Jul., Aug., Sept., Oct., and Nov.; season B: other months.

Table 2. Subsurface depth profile

| Layer number | Thickness (m) | Horizontal hydraulic conductivity (m hr ⁻¹) | Vertical conductivity (hr ⁻¹) |
|--------------|---------------|--|--|
| A | 0.3 | 1.2 | 0.9 |
| B | 1.0 | 0.025 | 0.033 |
| C | 3.5 | 0.0011 | 0.0003 |
| D | 10.0 | 0.00004 | 0 |