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WATER AND HEAT BALANCES IN THE MIDDLE-REACH CATCHMENT OF TAMA RIVER AND SENSITIVITY ANALYSIS

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A distributed model of water and heat transfers is described at first. The subgrid heterogeneity of land use is considered by using a nesting method. Evapotranspiration and latent heat flux are computed by the Penman-Monteith equation, infiltration excess during heavy rains is simulated by a generalized Green-Ampt model whereas saturation excess during the remaining periods is obtained by balance analysis in unsaturated soil layers. Surface temperatures are solved by the Force-Restore method. Two dimensional groundwater flow is simulated to consider the interactions between grid cells. The river flow routing is conducted by using the kinematic wave method. The model is applied to the middle-reach catchment of Tama river and it is verified by the observed discharges at the catchment outlet in the three years from 1992 to 1994. Finally, sensitivity analysis shows the effects of input data and model parameters on annual water and heat balances.

Key Words : *Water balance, heat balance, distributed model, urbanization, Bowen ratio, calibration by daily discharge*

1. INTRODUCTION

Distributed physically based hydrological models give a detailed and potentially more correct description of the hydrological processes in a catchment than other models. However, because of heavy computational burden and capacity limitation, efficient simulation methodologies of hydrological processes are still required to be developed. On the other hand, the atmospheric models require more reasonable description of land surface parameterization of the hydrological processes and heat processes. For this purpose, several soil-vegetation-atmosphere transfer schemes (SVATS) have been developed in the last decade. However, it seems that the considerations of hydrological processes are still too simple in these models. In addition, the subgrid heterogeneity problem has drawn attentions of both hydrologists and meteorologists in recent years.

Based on these backgrounds, a distributed model for water and heat transfers is developed by using more efficient modeling methods of dynamic processes of water and heat cycles. It is applied to the middle-reach catchment of the Tama river in Tokyo and verified by the observed discharges at the catchment outlet, the Ishihara station. A sensitivity study is conducted to show the effects of input data and model parameters on water and heat balances.

2. MODEL STRUCTURE

(1) The vertical structure inside a grid cell

In this study, the partly urbanized catchment with an area of 579 km^2 is simulated using a grid cell size of 1km by 1km and a time step of 1 hour. It may give rise a big error if the land use inside a grid cell was assumed to be uniform. Therefore, a nesting method[1)] which reflects composition of different land uses inside a grid cell is used to consider the subgrid heterogeneity of land use. The area average of water and heat fluxes in all land uses is conducted to calculate the averaged fluxes in a grid cell.

The diagram of the model structure inside a grid cell utilized in this study is shown in **Fig.1**. Land use is at first summarized into 3 groups, namely a water body group, a soil-vegetation group and an impervious area group. The soil-vegetation group consists of bare soil, tall vegetation (forest or urban trees) and short vegetation (grass or crops). The impervious area group consists of impervious urban cover and urban canopy. For the soil-vegetation group, 8 vertical layers, namely an interception layer, a depression layer, 3 upper soil layers, a transition layer, an unconfined aquifer and a confined aquifer, are included in the model structure.

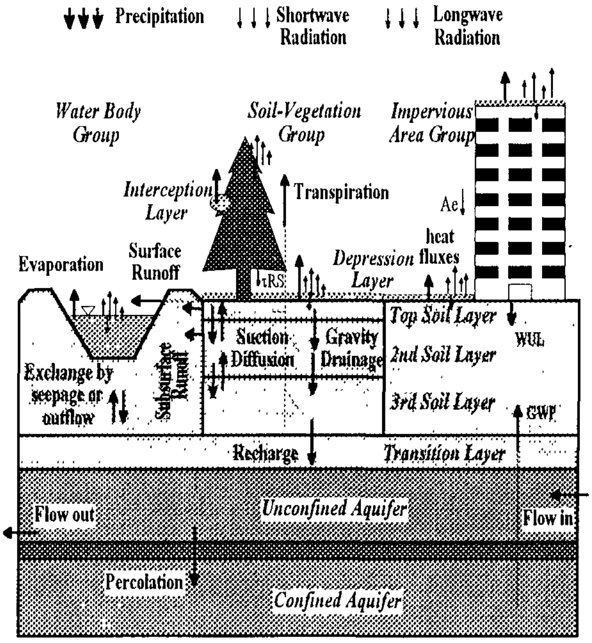

Fig.1 Diagram of model structure inside a grid cell

a) Water balance

Water balances in different land uses are connected together by assuming there is a same groundwater storage. The water balance equation for a whole grid is as follows

$$P+WUL-GWP=E+R1+R2+RG+\Delta S \quad (1)$$

where P is the precipitation, WUL the leakage of water use which is set as 10% of water use based on the Annual Report 1992 by the Department of Water Supply of Tokyo Metropolitan., GWP the pumped groundwater, E is the evapotranspiration, $R1$ the surface runoff, $R2$ the subsurface runoff, RG the groundwater outflow, ΔS is the storage change of unsaturated soil and aquifers.

Evapotranspiration is constituted by interception of vegetation canopies; evaporation from surfaces of waters, soil, urban cover and urban canopy, and from top soil layer; transpiration from the dry fraction of leaves with the source from the 3 soil layers. The Rutter model[2] is used to compute interception. The Penman equation is adopted to compute potential evaporation from which actual evaporation from soil is computed using a wetting function. The Penman-Monteith equation[3] is used to calculate transpiration.

Surface runoff of water group is assumed to be the rainfall subtracted by evaporation. For urban group, surface runoff will occur after the depression storage reaches maximum. For soil-vegetation group, it consists of two parts: one is rainfall excess (during heavy rain periods) which is computed according to a generalized Green-Ampt model for multi-layered soil with unsteady rainfall[4]; the other is saturation excess (in other periods) calculated according to water balances in soil layers and unconfined groundwater layers.

Subsurface runoff is computed according to land slope and soil hydraulic conductivity.

Groundwater outflow is estimated by storage function. Outflow coefficient is based on topography and geology[5].

b) Heat balance

Heat balance of each land use is also analyzed respectively. Interaction between soil and vegetation is considered by use of a parameter, the fraction of transmitted short-wave radiation of vegetation, whereas that between urban cover and urban canopy is considered by using another parameter, the view factor of urban cover. The heat balance equation is as follows:

$$RSN + RLN + Ae = lE + H + G \quad (2)$$

where RSN is the net short-wave radiation, RLN the net long-wave radiation, Ae the artificial energy consumption, lE the latent heat flux, H the sensible heat flux and G the heat conduction into soil.

Net short-wave radiation equals to incoming short-wave radiation subtracted by short-wave reflection. Short-wave reflection coefficient is considered to be variable and is related to solar zenith angle, soil moisture content or canopy heights.

Net long-wave radiation equals to downward long-wave radiation subtracted by upward long-wave radiation, and is related to air temperature and surface temperature.

Energy Consumption: statistics of energy consumption indices on 7 types of urban land use are used to consider impacts of human lives on energy balance in urban area. A half of energy consumption is assumed to be emitted to land surfaces and the other half to air.

Latent Heat Flux equals to evapotranspiration timed by the latent heat of water.

Sensible Heat Flux is computed by the aerodynamic method, namely, it depends on the aerodynamic resistance and the difference between land surface temperature and air temperature.

Heat Flux into Soil is calculated by the heat balance Eq.2.

Surface Temperature Ts: the Force-Restore method (FRM) is used to solve surface temperature with the calculation of coefficient α referred to Hu and Islam [6] which not only ensures minimum distortion of FRM to sinusoidal diurnal forcing but also makes distortion to higher harmonics negligible.

(2) The horizontal structure

The interaction among grid cells is considered through two dimensional groundwater flow in the unconfined aquifer. It is described by the following nonlinear Boussinesq equation:

$$C_u \frac{\partial h_u}{\partial t} = \frac{\partial}{\partial x}\left(kh_u \frac{\partial h_u}{\partial x}\right) + \frac{\partial}{\partial y}\left(kh_u \frac{\partial h_u}{\partial y}\right) + Q3 + WUL - RG - Per \quad (3)$$

where *Cu* is the specific yield, *hu* the groundwater head in the unconfined aquifer, *k* the hydraulic conductivity of the unconfined aquifer, *Q3* the recharge from unsaturated soil layers, *WUL* the leakage of water use, *RG* the ground-water outflow to rivers and *Per* the percolation from the unconfined aquifer to the confined aquifer.

River flow routing is conducted for every sub-catchment and main river channel by using the kinematic wave method. Overland flow is simplified as lateral inflow to rivers because the concentration time is estimated to be shorter than the simulation time interval in this study.

3. APPLICATION

(1) Study area and input data

The middle-reach catchment of Tama river is shown in **Fig. 2**. It is located at the western part of Tokyo Metropolis with an area of 579km^2. There are 2 discharge stations of the Ministry of Construction, one of which is the Chobubashi station, the catchment inlet from upstream Tama river and another is the Ishihara station, the catchment outlet to downstream Tama river. Roughly speaking, the region south-west to the Tama river is dominated by natural streams whereas the region north-east to the Tama river is dominated by combined sewer system.

Land use data and topography data are based on the Fine Digital Information System (FDIS) of Japan Geography Institute which is renewed once five years. The land use distribution in 1989 is shown in **Fig.3**, using a grid resolution of 100m × 100m. It is considered to be able to represent the land use in 1992, 1993 and 1994 because urbanization speed is quite low in recent years in the region.

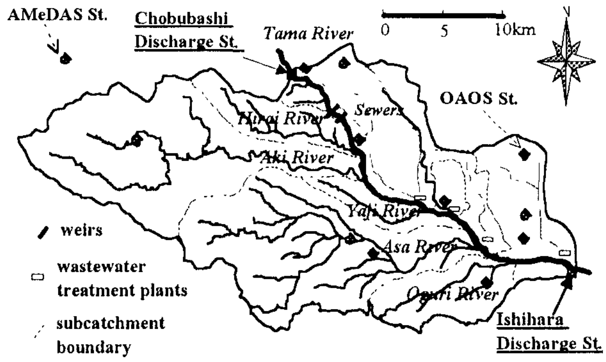

Fig.2 Middle-reach catchment of Tama river

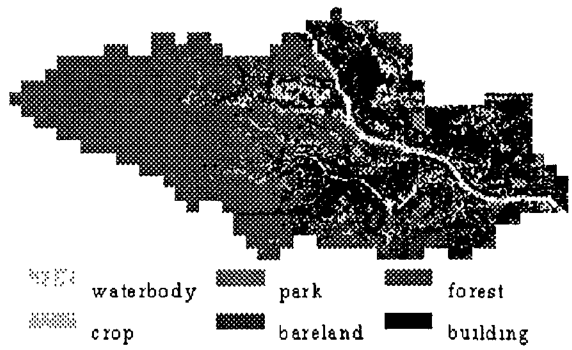

Fig.3 Land use distribution (1989)

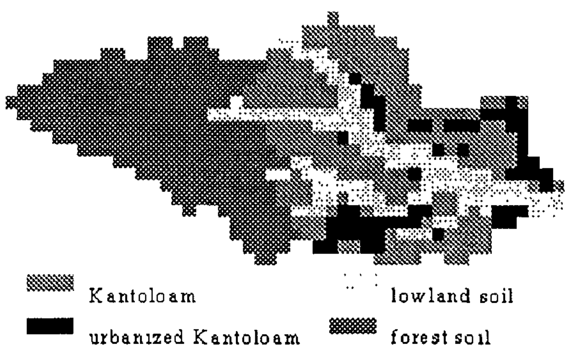

Fig.4 Soil distribution

Soil distribution of top soil layer is shown in **Fig.4** which is based on the soil map and the surface geology map made by National Land Bureau of Tokyo Metropolis. Four kinds of soils are considered. Lowland soil distributes in alluvial area along rivers. Brown Forest soil corresponds to western forest area in the catchment which belongs Palaeozoic or Mesozoic geological zone. Kantoloam exists in eastern diluvial tableland zone which is assumed as urbanized Kantoloam if urban area fraction is over 0.8. Soils below the top layer are considered as Kantoloam in the whole catchment. Soil parameters are referred to Herath[7] and Tanimoto[8].

Aquifer parameters are set according to the geology information in every sub-catchment. Roughly speaking, they correspond to two categories, one is Palaeozoic or Mesozoic geological zone with thin aquifers and the other is alluvial or diluvial zone with thick aquifers, though there is a transition zone between them.

The time step is set as 1 hour and the size of every grid cell is set as 1km by 1km in this paper.

(2) Calibration and verification

The model's calibration is conducted by adjusting various parameters and initial values such as soil's and aquifer's etc. to make the simulated discharge match the observed one at the Ishihara station in 1992. For example, the saturated hydraulic conductivity of Kantoloam is set as 6.17×10^{-6} m/s, and the outflow coefficient and the initial effective storage are set as 0.012 and 60mm respectively for unconfined groundwater in Aki river subcatchment. The calibrated model is then verified by the observed discharges at the Ishihara station in 1993 and 1994 with all of parameters kept unchanged.

Comparison of daily discharges is shown in **Fig. 5**. We can see that the simulated discharges are favorably matched with the observed ones. The relative errors of annual average discharges are 1.4 %, 6.6% and 11% in 1992,1993 and 1994 respectively.

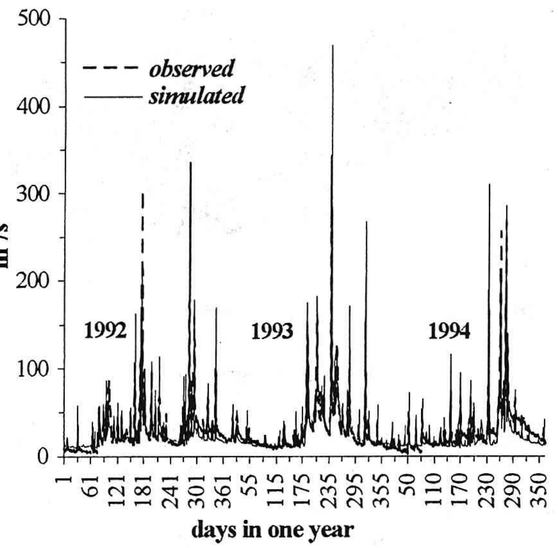

Fig. 5 Daily discharges at the Ishihara station

In addition, the deduced inflow into wastewater treatment plants in 1992 by the model is 283×10^6 m^3 which also match well with the statistic value 291×10^6 m^3.

(3) Annual water and heat balances

Annual water balance and heat balance are shown in **Table 1** and **2** respectively. The notations are same with those in Eq.1 and 2. Distributions of main water and heat budgets in 1992 are shown in **Fig.6**

Table 1 Annual Water Balance (mm)

YEAR	P	WUL	GWP	E	R1	R2	RG	ΔS
1992	1555	47	187	630	442	44	306	-7
1993	1494	47	184	638	392	44	315	-32
1994	1423	47	187	710	380	33	213	-54

Table 2 Annual Heat Balance (MJ/m^2)

YEAR	RSN	RLN	AE	lE	H	G
1992	3549	-1601	149	1548	544	4
1993	3316	-1566	148	1570	326	3
1994	3708	-1606	148	1743	511	-3

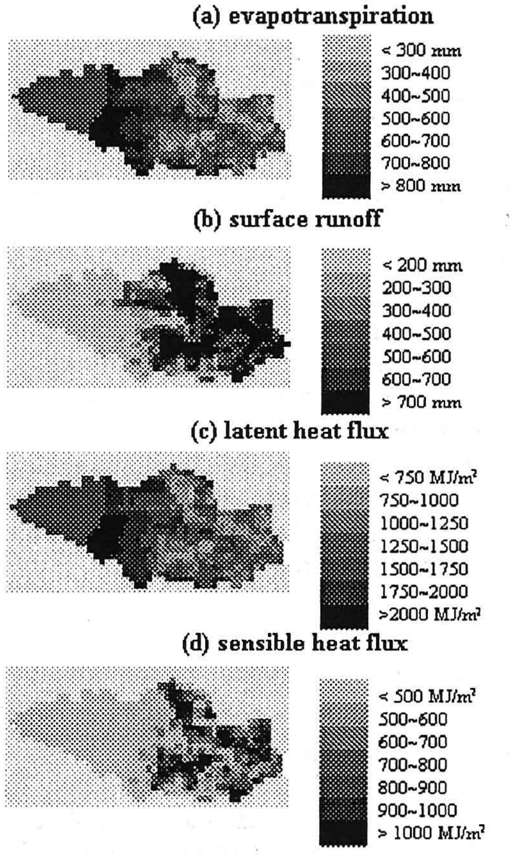

Fig. 6 Distribution of main water and heat budgets

From these tables and figures, we can see that: (i)The annual direct runoff (R1+R2) coefficient in this catchment is around 0.3, the annual ratio of evapotranspiration to precipitation around 0.4~0.5 and the annual Bowen ratio is around 0.2~0.35. (ii) The annual water and heat budgets vary with years to different extent. For example, in 1994, which was a hot year with a lower annual precipitation compared with 1992, direct runoff and groundwater outflow decreased, whereas evapotranspiration increased because of more solar energy from 1992 levels.

(iii) Both water budgets and heat budgets have big spatial variations in the catchment. For example, the annual evapotranspiration varies from a minimum of 300mm in eastern urban areas to a maximum of 800mm in western forest areas, whereas the annual surface runoff has a converse variation. The annual latent heat flux varies from the minimum 750MJ/m^2 in urban areas to the maximum 2200MJ/m^2 in forest areas, whereas annual sensible heat flux has a converse variation. (iv) Distributions of water budgets and heat budgets have similar patterns. For example, spatial distribution of latent heat flux is similar to that of evapotranspiration and sensible heat flux similar to surface runoff which shows a close relation between water balance and heat balance.

(4) Sensitivity analysis

The sensitivity analysis is conducted to see how the model outputs will behave with the change of inputs and parameters from the sense of annual and catchment average. In the following part, RN is net radiation (RN=RSN+RLN+Ae), I represents infiltration and other notations are the same as those described above.

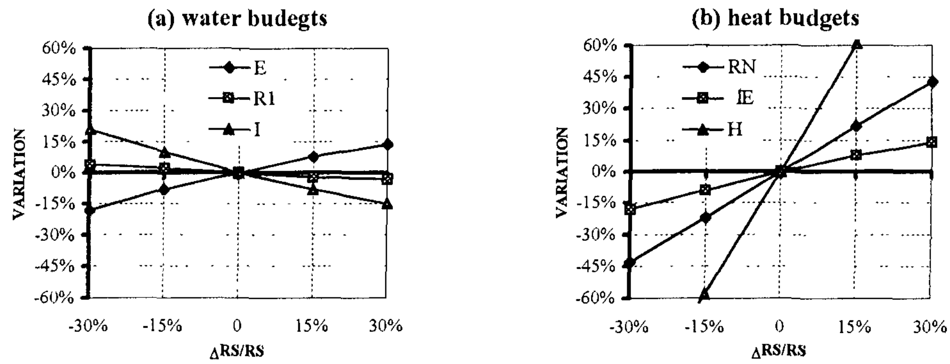

Fig. 7 Effect of incoming solar radiation

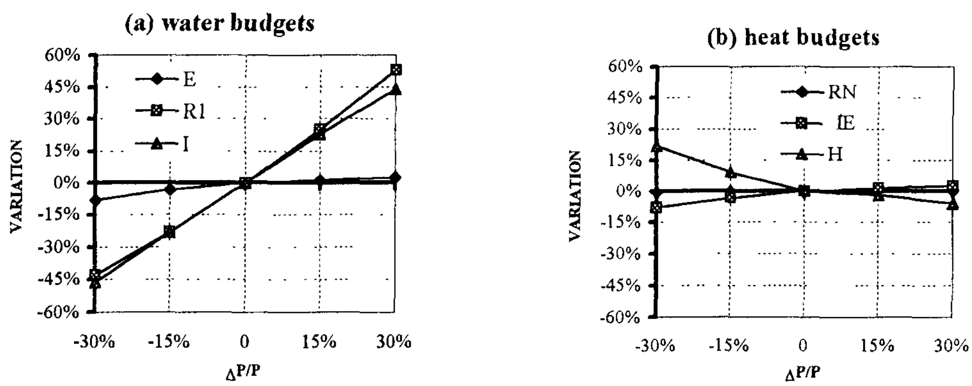

Fig.8 Effect of precipitation

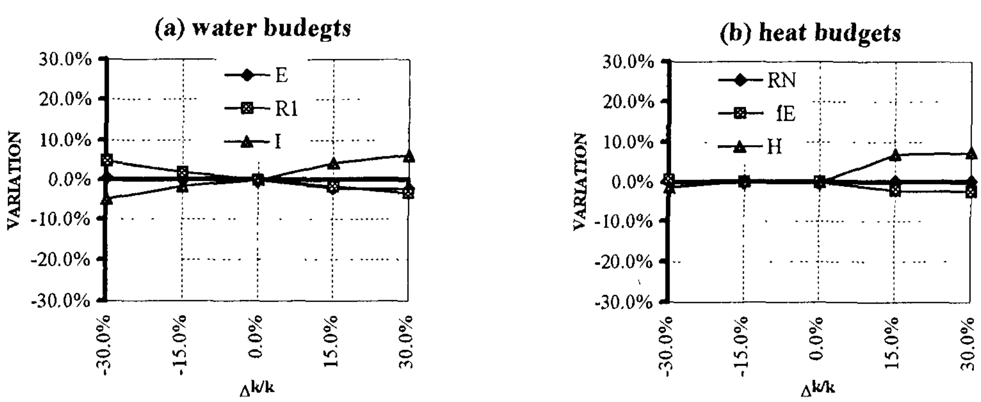

Fig.9 Effect of saturated hydraulic conductivity k

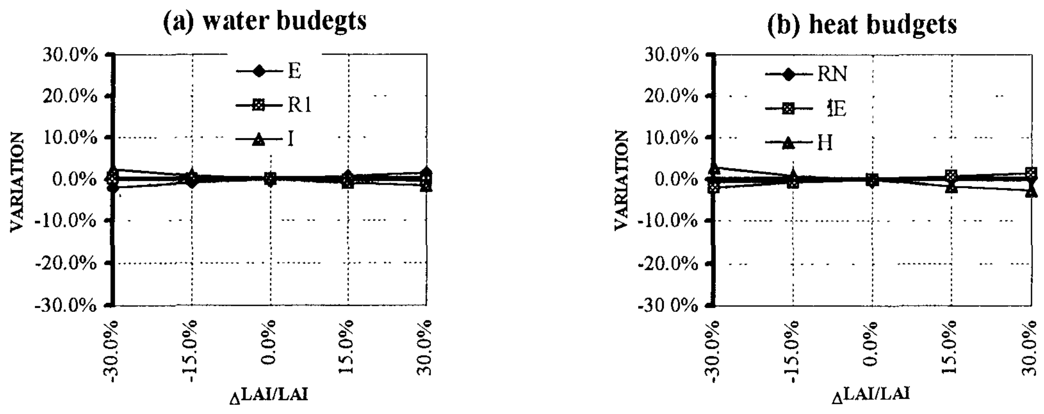

Fig.10 Effect of leaf area index LAI

a) Effect of input data's accuracy

Two main inputs, incoming solar radiation RS and precipitation are selected to study their effects on main annual water and heat budgets in 1992.

Figs.7 and 8 show that (i) the most sensitive to solar radiation RS is sensible heat flux H, (ii) the most sensitive to precipitation P is surface runoff R1 and (iii)evapotranspiration E is much more sensitive to solar radiation than to precipitation which means solar radiation is a limiting factor to evapotranspiration in Tokyo where the climate is wet.

b) Effect of parameters' variation

Two main parameters are studied here, i.e., the saturated hydraulic conductivity k of soil and aquifers and the leaf area index LAI.

From **Figs.9** and **10** it can be seen that (i) infiltration I, surface runoff R1 and sensible heat flux H are quite sensitive to saturated hydraulic conductivity k and (ii) annual water and heat budgets are not so sensitive to leaf area index LAI as to saturated hydraulic conductivity k.

4. CONCLUSIONS

Integrated and distributed modeling of water and heat transfers are conducted in this study. It adopts several newly suggested methods to describe hydrological and heat processes more efficiently and reasonably. The subgrid heterogeneity of land use is also considered by nesting different land uses in a grid cell. The model is applied to the middle-reach catchment of Tama river and favorably validated by discharge observation at the outlet of the catchment. The close relation of water balance and heat balance is observed. In addition, the effects of input data and parameters on water and heat balances are also studied. It is found that evapotranspiration is much more sensitive to solar radiation than to precipitation which means solar radiation is a limiting factor to evapotranspiration in Tokyo's wet climate. It is also found that most of annual water and heat budgets are less sensitive to leaf area index than hydraulic conductivity.

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