A distributed runoff model for flood prediction in ungauged basins

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Abstract Lumped parameter models are quite difficult to apply to ungauged or information-poor basins, because such models need model parameters calibrated using historical hydrological data. On the other hand, distributed parameter runoff models are suitable for ungauged basins, because they have the ability to define model parameter values based on spatially distributed data such as topographic data, land-use data, radar rainfall and remote sensing imagery. This paper introduces the development of the grid-cell based distributed Kinematic Wave Runoff (KWR) model proposed by the authors in 1997, and describes its applications to two basins: the Yada River (Yada-gawa) and the Shonai River (Shonai-gawa) basins in Japan. Since simulation without model parameter optimization showed good results, the distributed runoff model could be very useful for ungauged basins. The authors also expanded this model into a physically-based distributed rainfall–sediment–runoff model for flood and sediment movement at a catchment scale. They confirmed its usefulness for prediction of sedimentation in the upper Brantas River basin, East Java, Indonesia.

Key words DEM; grid-cell based kinematic wave runoff model; rainfall–sediment–runoff model

INTRODUCTION

Lumped parameter models are often used for flood runoff prediction and flood plain management, because of their simple concept and relatively short computation time. However, lumped models need model parameters calibrated using historical hydrological data. Therefore lumped models are quite difficult to apply to ungauged or information-poor basins. Distributed parameter runoff models are suitable for ungauged basins because they have the ability to define model parameter values with spatially distributed data such as topographic data, land-use data, radar rainfall and remote sensing imagery. The authors developed the grid-cell based distributed Kinematic Wave Runoff (KWR) model in 1997 (Kojima, 1997; Kojima *et al.*, 1998). This distributed runoff model needs geographical data such as flow direction, slope and land cover on each grid-cell for developing the hydrological modelling. And the model parameters, and equivalent roughness coefficients are defined using land cover/use based on either the National Land Information developed by Geological Survey Institute (GSI) or remote sensing imagery.

This paper introduces the development of the grid-cell based distributed KWR model and describes its applications to two basins: the Yada River (Yada-gawa) and the Shonai River (Shonai-gawa) basins, Japan. The authors also expanded this runoff model into a physically-based distributed rainfall–sediment–runoff model for flood and sediment movement at the catchment scale in the upper Brantas River basin, East Java, Indonesia.

GRID-CELL BASED KINEMATIC WAVE RUNOFF (KWR) MODEL

The KWR model has the following features:

– A *d*-m square area on a node point of a *d*-m DEM is considered as a sub-basin, which is called a grid-cell (cell). The whole river basin consists of many square cells.
– A DEM produces drainage paths. A drainage path connects each upper cell with lower cells. Discharge from an upper cell to the lower cells flows to only one direction of eight neighbourhood cells.
– In each cell, the total amount of outflow from the upper cells is the inflow to the cell, and the outflow from the cell is calculated using the kinematic wave model with the inflow and the rainfall over the cell.

Figure 1 shows the concept of the grid-cell based distributed KWR model. The topographic properties such as slope angle and slope length are produced with a DEM and drainage paths are based on the DEM. The model needs the equivalent roughness of each cell. The authors investigated the optimum values of the equivalent roughness of each land use category.

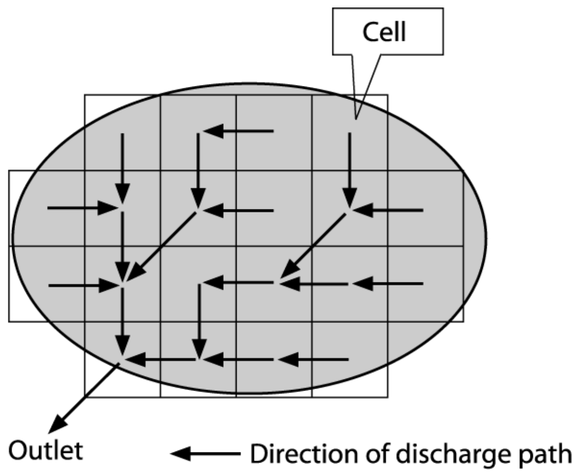

Fig. 1 Illustration of a grid-cell based distributed runoff model.

APPLICATION OF THE KWR MODEL TO THREE BASINS

The Yada River basin

The Yada River basin is about 110 km^2, and located at Aichi, Japan. The basin is in the Seko upper area of the Shonai River basin (see Fig. 5). The basin is almost wholly urbanized, but has a forest area in the upper basin. The Yada River basin is classified into seven land-use classes such as forest, urban, grass, paddy field, bare soil, river and

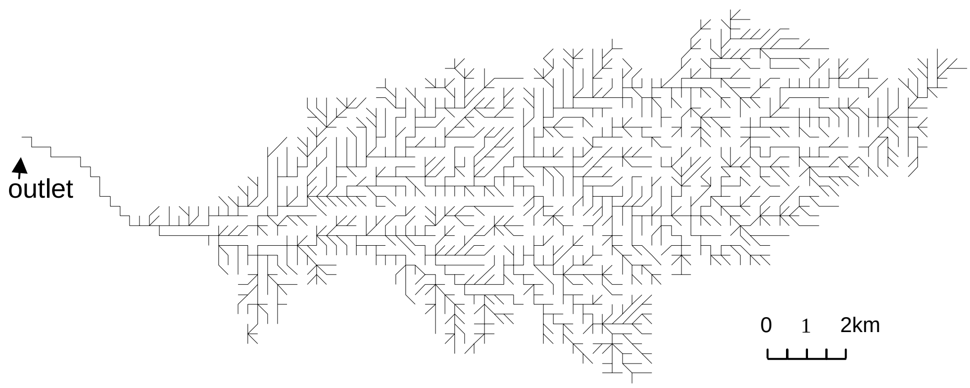

Fig. 2 Drainage paths with 250-m resolution at the Yada River basin.

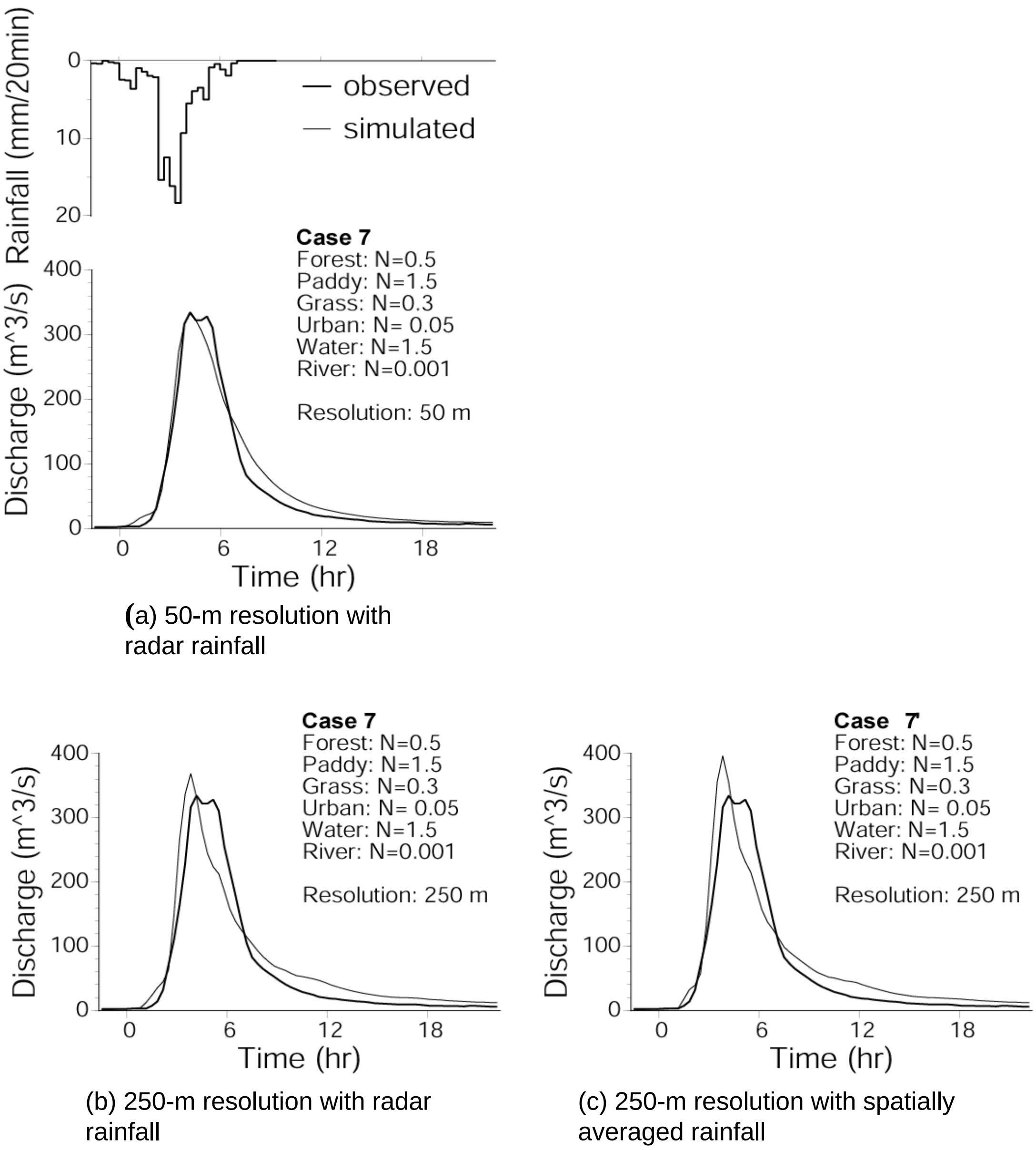

Fig. 3 Comparison of simulated and observed hydrographs.

water. In this basin, two drainage paths were produced with a 50- and 250-m DEM. Figure 2 shows the drainage paths defined by the 250-m DEM resolution. Two grid-cell based distributed KWR models were developed with 50- and 250-m resolution drainage paths. Figure 3 shows the comparison of the observed and simulated hydrographs. Figure 3(a) and (b) show the simulated hydrographs with the 50-m resolution model and the 250-m one, respectively. Comparison of Figs 3(a) and (b) shows that the 250-m model has a tendency to give earlier peak time and larger peak discharge than the 50-m model.

Radar rainfall observation is one of the solutions to prediction in ungauged basin, because it does not need many raingauges. Radar rainfall data was used with the grid-cell based distributed KWR model in the Yada River basin. The radar rainfall data are about 2-km grid spatially distributed data (see Fig. 4). The grid-cell based distributed KWR model can take into account these spatially distributed rainfall data. Hydrographs were simulated using the radar data and its spatially averaged rainfall data, and the effects of the spatial distribution of rainfall on the simulated hydrograph were investigated. Figures 3 (b) and (c) show the comparison of the hydrographs using two kinds of rainfall data. The simulated hydrograph with the spatially averaged rainfall estimates a larger peak discharge than the hydrograph with radar rainfall. Figure 4 shows how the greatest rainfall intensity zone moved from the lower site to the upper site. The movement of the rainfall area affects the peak discharge volume.

The optimum equivalent roughness coefficient of forest class in this basin is 0.5. This is within the range of values conventionally used in Japan, which is 0.4 to 0.8 (River Bureau, 1998).

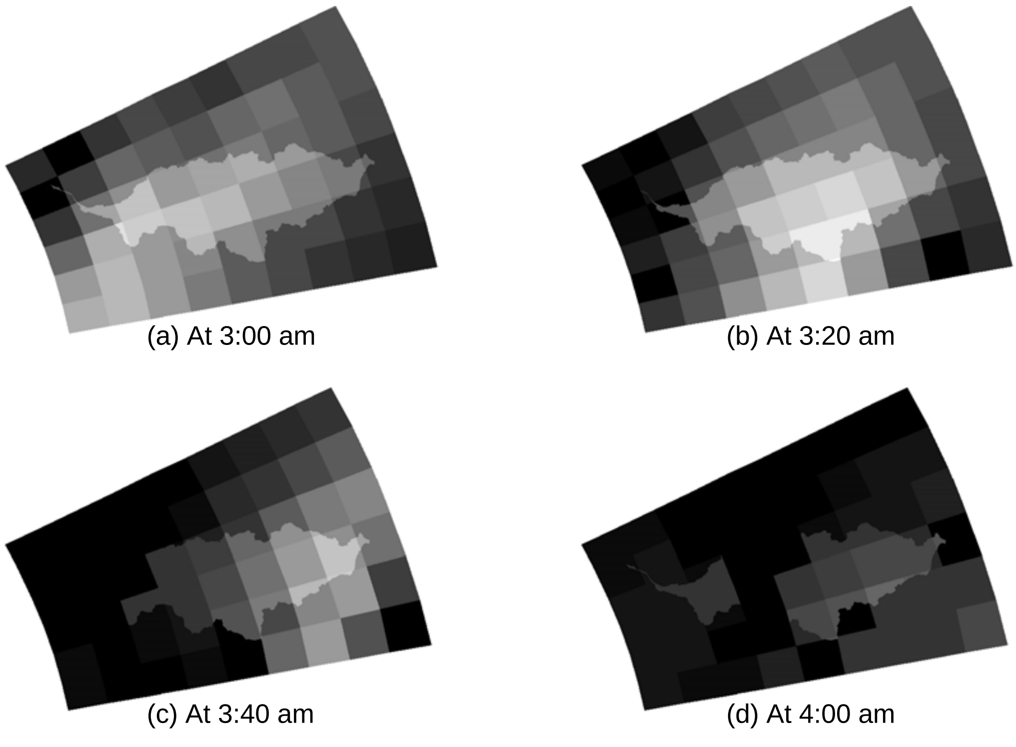

Fig. 4 Distribution of rainfall. The rainfall rate is greater in the lighter areas (the lightest corresponds to about 60 mm/hour), and less in the darker areas.

The Shonai River basin

The Shonai River basin is about 1010 km^2. Its lower basin is almost all urbanized area, while 70% of its upper basin is forest, 15% is urbanized and 15% is other land-use areas. Figure 5 shows the location of the precipitation stations (raingauges) and the discharge sites (gauging stations) in the Shonai River basin. Discharge is observed at Shidami, Tajimi, Toki and Mizunami. The test basin in this study is about 532 km^2 at Shidami upper site in the Shonai River basin. Figure 6 shows the variation of the three evaluation indices, the Correlation Coefficient between observed and simulated hydrographs during the runoff event (COR), Mean Relative Error between observed and simulated hydrographs during the runoff event (MRE), and Relative Root Mean Square Error between observed and simulated hydrographs during the runoff event (R.RMSE), when the value of the equivalent roughness of the forest class is varied. Figure 6 shows that the optimum roughness coefficients for the forest class at Shidami, Tajimi and Mizunami are 1.5, 1.0 and 0.5 respectively.

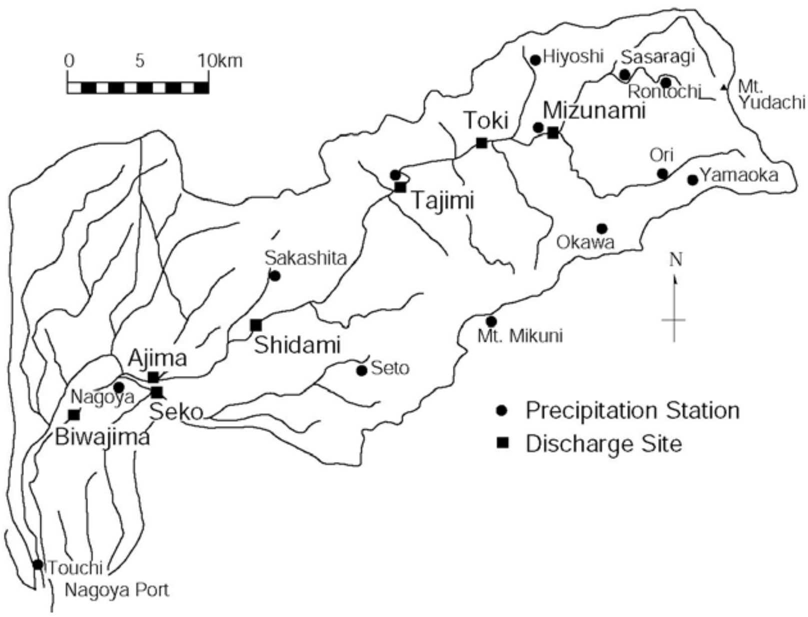

Fig. 5 The Shonai River basin.

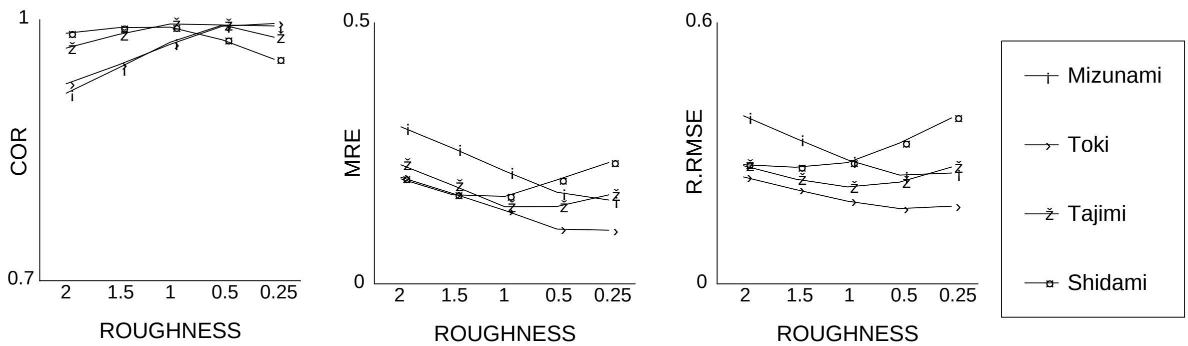

Fig. 6 Variations of the evaluation indices of the grid-cell based KWR model.

DISCUSSION

Assigning the equivalent roughness coefficients to each grid-cell based on the land cover class, one can develop the KWR runoff model without calibration using hydrological data. The conventionally used values of roughness coefficients depend on the land-use category of the basin. However, the optimum values cannot be defined using only land-use category. At the upper site in the Shonai River basin, such as at Toki and Mizunami, the optimum values of the forest class are 0.5. At the lower site such as Shidami, the optimum value of the forest class is 1.5. Other parameters such as topographic and geological properties of the local areas in the basin may affect the optimum values of the roughness coefficients.

RAINFALL–SEDIMENT–RUNOFF MODEL

A physically-based distributed rainfall–sediment–runoff model

A physically-based distributed rainfall–sediment–runoff model for flood and sediment movement at the catchment scale was also developed. Dealing with spatial hydrological and geographical information, this type of model is useful not only for prediction of sedimentation in reservoirs and riverbeds but also for understanding of the severe sedimentation problems caused by land-use change and deforestation. A grid-cell based distributed KWR model considering surface and subsurface flows is constructed here. Rainfall–sediment–runoff is modelled on each grid-cell defined by a DEM with 250-m resolution. The transportation capacity of overland flow on each grid-cell is calculated based on the unit stream power (USP) theory (Yang, 1996) to model sediment yield and sediment deposition processes physically. Sediment generated in slope cells moves in the flow direction derived from the DEM to river grid-cells. Bed load and suspended load in the channel are calculated in river grid-cells.

Application to the Lesti River basin

The model was applied to the Lesti River basin (625 km^2) located in the upper Brantas River basin (12 000 km^2) which is the second largest river in Java Island, Indonesia. The Lesti River basin is covered with volcanic soil due to the Mt Semeru eruption. The Sengguruh dam, located at the junction of the Lesti and Brantas Rivers, was constructed in 1988 for water resources and power generation, but 85% of the gross storage was filled with the sediment eight years after dam construction. Data sets such as flow direction, slope and land cover on each grid-cell are necessary to develop distributed hydrological models. In Indonesia, however, DEM and recent land-use maps are not available, and so this research used GIS for generating a DEM and remote sensing for classifying land cover. Digitizing contour lines on a 1:50 000 topographical map of the area of interest, GIS generated a 250-m DEM. A remote sensing image was used to make a land-cover map with the maximum likelihood classifier. Equivalent roughness coefficient used for the KWR model was assigned to each grid-cell based on the land cover class.

Model validation

A preliminary model study indicated that under the assumption of fixed slope conditions at each grid-cell, regardless of sediment movement, the model predicted huge deposition in some grid-cells. However, by updating elevations with sediment yield and deposition at each time step, the model simulates deposition process at confluences and makes riverbed change more realistic. Consequently, the model has been improved by considering local geomorphological change caused by sediment.

The model performance was verified with historical hydrological data (hourly rainfall and discharge sequences during a rainy season from November 1995 to April 1996) and the sedimentation record in the Senggruh dam. Figure 7 shows the cumulative sediment runoff at the outlet, and the cumulative total sediment yield. Roedjito & Harianto (1995) reported that annual sedimentation at the Sengguruh dam reservoir is around 1×10^6 m^3, while simulated sediment runoff at the outlet in the rainy season is about 0.65×10^6 m^3. The simulation is relatively appropriate, if the following reasons are considered. The simulated sedimentation does not include the sedimentation coming from the Brantas River. The lower panel in Fig. 7 shows the cumulative sediment yield and deposition, indicating that a volume of 4.28×10^6 m^3 of sediment had been generated and that 1.48×10^6 m^3 had been deposited after the rainy season, in the whole basin; therefore, about 3.00×10^6 m^3 of sediment had entered the river channel. The verification indicates that the model reproduces the sedimentation record. Further, the volume of material eroded from the cultivated hillslopes of Mt Semeru is found to be larger than at other places (e.g. forest areas), which is an analogous phenomenon to the natural physical process of sediment erosion.

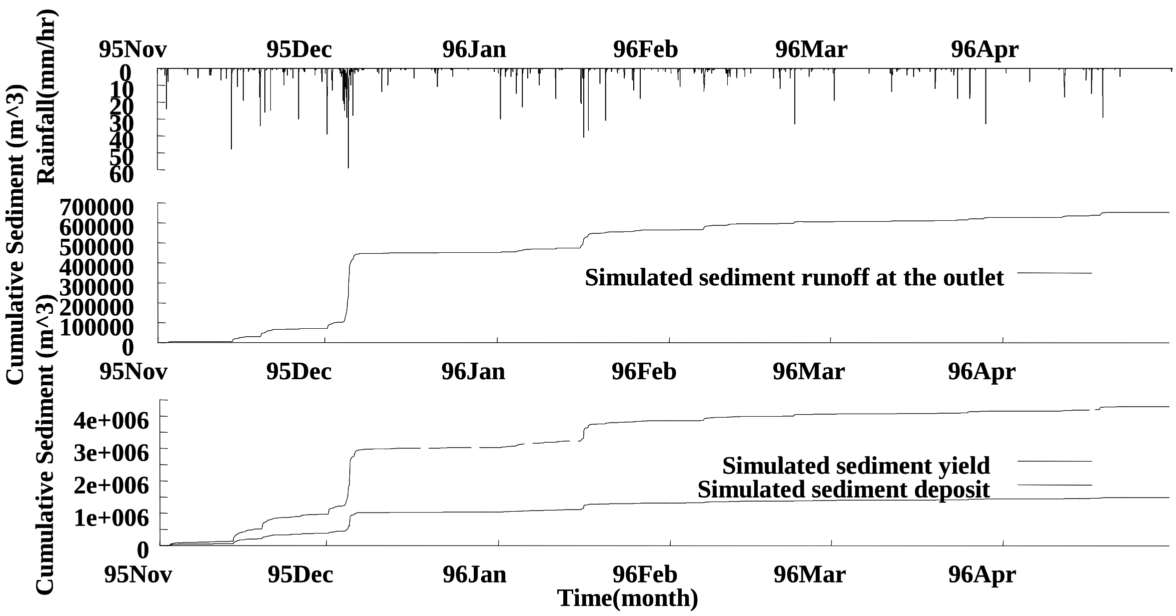

Fig. 7 Rainfall and sediment runoff analysis in the rainy season from 1995 to 1996.

SUMMARY

The distributed runoff model has the ability to define model parameter values with spatial data. The grid-cell based distributed KWR model was applied to two basins. This paper shows that the distributed runoff model, which can take into account spatial data such as remote sensing imagery, land-use data, radar rainfall and topographic data is very useful for ungauged or information-poor basins. The grid-cell based distributed runoff model was expanded into a rainfall–sediment–runoff model, and its usefulness for prediction of sediment yield in a catchment scale was confirmed.

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