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Use of Disaggregated Rainfall Data for Distributed Hydrological Modeling in Yodo River Basin

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Synopsis

This study tested the disaggregated rainfall field as the input field for hydrological simulation of various sub-catchments of the Yodo River. The multiplicative random cascade (RC) method (based on the beta lognormal model), the multiplicative random cascade HSA (RCHSA) method, and the space-time rainfall modeling (STRaM) method are employed to disaggregate the rainfall field from coarse (48-km, 100-min) to fine (3-km, 10-min) resolution. The Yodo River model, an OHyMoS assisted distributed hydrological model with saturated-unsaturated surface-subsurface flow mechanism, is used for simulating the runoff at Ootori, Ieno, Kamo and Inooka having catchments areas of 156 km^2, 476 km^2, 1469 km^2 and 1589 km^2 respectively. The simulated discharge using the disaggregated rainfall with STRaM is quite similar to the one obtained from using the radar observed rainfall.

Keywords: downscaling, rainfall field, yodo river model, RCHSA, STRaM method

1. Introduction

A fully distributed hydrological modeling, which includes distributed process descriptions, takes spatially and temporally distributed input fields, and employs fully distributed parameterization, often finds difficulty in producing entirely satisfactory outcome. Most of the distributed hydrological models are reported being unable to make accurate hydrological simulation and/or prediction (Reed *et al.* 2004). There are multiple reasonings that cause an advanced distributed hydrological model perform inferior than a simple lumped parameter model.

Existence of scale gap between meteorological studies and hydrological studies is often cited as the dominant cause failing the distributed hydrological modeling. Most meteorological models perform well at the scale of several hundred kilometers in space and monthly scale in time. But the hydrological analyses require daily scale in time and few kilometers in space or even a finer scale. Numerical weather simulators of much finer scales in space and time are feasible but they are suffered heavily by a larger degree of uncertainty caused by problems in parameterization and lack of knowledge of meteorological processes at much finer scales (Bates *et al*., 1998; Chen *et al.*, 1996; Giorgi and Mearns, 1991; Houze, 1997). This weakness comes to the core of the problem area because the hydrometeorological data are the one of key-role player in the hydrological studies involving a distributed hydrological model (Shrestha et al., 2004a). Recent advances in distributed hydrological modeling are continuously at odds with the use of inappropriate scale at various levels of the modeling (Shrestha, 2005). There is continuous interest in the study of scale dependent features and scale effects in hydrological modeling to understand the current limitations.

A poor outcome is associated with the uncertainty coming not only from the heterogeneity of the parameters, processes and input field but also from their scale of representation (Shrestha *et al.*, 2005). An intuitive solution to overcome the scale mismatch between the input field and the process description is to employing an appropriate disaggregation of the input field. Predictably, the basic tenet of this solution is the accuracy of the hydrological simulation involving disaggregated rainfall field, whose original source is of a much coarser scale equivalent to the one we usually obtain from a regional scale meteorological model. While such a claim at first glance seems unexpected, it is examined in this study involving multiple sets of disaggregated rainfall in multiple catchments of different sizes. The rainfall is disaggregated into finer resolution using three different disaggregation methods from a coarse scale rainfall field that was initially aggregated from radar observed rainfall field of fine resolution.

In order to disaggregate the rainfall field, the multiplicative random cascade methods based on beta lognormal model are used. First two methods are the random cascade method (the RC method) and the random cascade hierarchical and statistical adjustment method (the RCHSA method). The third method is the space-time rainfall modeling method (STRaM method). Shrestha *et al.*, (2004) and Shrestha (2005) have described the methods in detail. These methods yield the disaggregated rainfall fields that are fed into the hydrological model. The hydrological model used in this study is the Yodo River model (Sayama *et al.*, 2004).

We concentrate our efforts on testing the use of disaggregated rainfall field irrespective of their inter-relation with the variability of model parameters in various subcatchments of the Yodo River in Japan (Figure 1). The standard set of the model parameters are calibrated using the radar observed rainfall field. Similarly, we validate that the disaggregated rainfall field can produce promisingly accurate discharge simulation if the disaggregation scheme is sufficiently good. Thereby the meteorological models and hydrological models can agree to accomplish the goal of making better simulation irrespective of the scale mismatch.

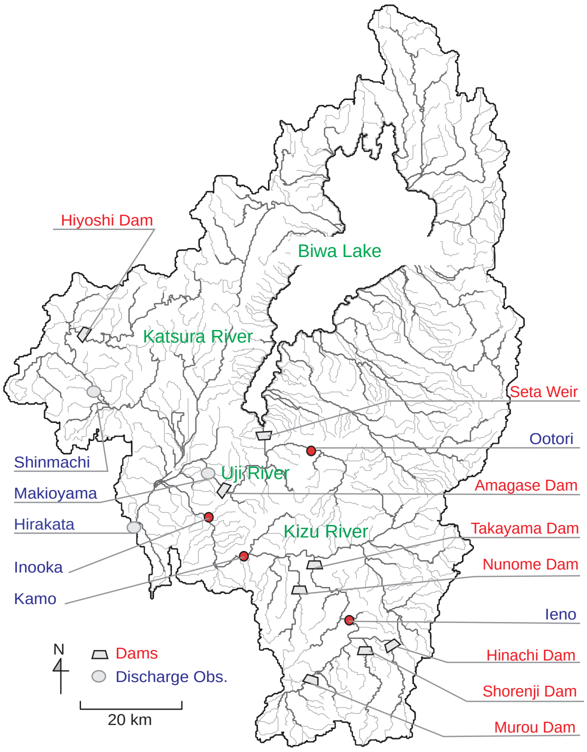

Fig. 1. Location of the study region.

The rest of this paper is organized as follows. We motivate the need for bridging the scale gap in section 1 and 2. To surmount this quandary, we demonstrate that while the distributed hydrological model includes all major components of catchment complexities (section 3), the simulation results are hardly perfect (section 4). Furthermore, to show the importance of proper space-time structure of rainfall field, we present the simulation results using the disaggregated rainfall, which we use to show that an improper disaggregation scheme yields very uncertain runoff but a good runoff simulation is possible to obtain from the disaggregated rainfall if the disaggregation method is accurate and robust (Section 5). And we conclude in section 6.

2. Disaggregation of rainfall field

There is a large scale difference between global scale (climate or atmospheric) models and regional or local hydrological models. Still these models are necessary to be coupled in order to understand and predict a clear scenario of local and regional impacts on hydrological cycle due to global changes. Coarse scale products of GCMs are an inadequate basis for assessing local / regional scale impacts as it is hardly able to resolve many important sub-grid scale processes (Hostetler, 1994; Wilby *et al.*, 1999). The need of disaggregation is pretty high to use the outputs obtained from current GCM scale. It is necessary to identify the sub-grid scale features for local or regional hydrological analysis, which is not seen in a coarser scale frame.

The analysis based on hydrological simulation are highly dependent on rainfall structure as it has significant effect in simulation results of small to large-scale catchments (Shrestha *et al.*, 2002). Many methods have been developed to fulfill the ambition of modeling the rainfall structure properly, for example, Schertzer and Lovejoy (1987), Marsan *et al*, (1996), Gupta and Waymire (1993), Over and Gupta (1994), Tustison *et al.* (2002), etc. We took the method proposed by Over and Gupta, (1994). This is a discrete form of multiplicative random cascade method, which has ability to separate rainy and non-rainy area. This method is called the Random Cascade method (RC method) in this paper. In addition to the RC method, two new disaggregation methods we developed, the RCHSA method and the STRaM method (described in next paragraph), are also used for disaggregating the coarse scale rainfall field.

The RC method generates spatially uncorrelated rainfall field. This is the major drawback of the RC method for many practical applications as the spatial structures of rainfall are observed to have spatial correlation (Bell, 1987). The RC method is modified by Shrestha *et al.* (2004b) and is named the Random Cascade Heirarchical and Statistical Adjustment method (the RCHSA method). The RCHSA method generates a spatially correlated rainfall field by controlling the spatial location of the cascade generator weights while it undergoes into multiplicative cascade process. Both the RC method and the RCHSA method employes the spatial disaggregation only.

The Space Time Rainfall Modeling method (the STRaM method) includes an improved version of the RCHSA for the spatial disaggregation and the temporal disaggregation based on the rainfall translation mechanism (Shiiba *et al.*, 1984). In this method, the magnitudes of random cascade generator weights are restricted to remain within an envelope that defines the relation of the cascade generators for a successive level of disaggregation. The temporal disaggregation is firstly guided by a spline interpolation to generate a dummy rainfall field. The dummy rainfall field is updated based on the discrepancy between the translated rainfall field and the dummy rainfall field. The combination of the improved RCHSA method and updated dummy field provides the Space-Time disaggregation of the coarse rainfall field.

The rainfall data is obtained from a radar located at Miyama Radar station in Central Japan. The data was recorded in a typhoon event of 1991 September. The data set is having 3-km spatial resolution and 5-minute temporal resolution. This resolution setting is used to calibrate the hydrological model paramters. Further, the data is upscaled to 48-km spatial resolution and 100-minute temporal resolution. This resolution setting is the coarsest resolution, which is later disaggregated to 3-km spatial resolution and 10-minute temporal resolution. For the RC method and RCHSA method, because they do not have the temporal disaggregation component, the rainfall field is linearly interpolated in time to match the hydrological model's requirement.

3. Description of the Yodo River model

The Yodo River hydrological model was developed aiming to attain high accuracy in hydrological simulation via distributed hydrological modeling in the Yodo River basin in Japan. This model is developed to analyze the complex hydrological variability in the Yodo River basin, which has a large natural water storage depression, called as the Biwa Lake, and installation of several numbers of dams and control structures for operating multipurpose reservoirs. This model is also developed using OHyMOS libraries and hence simulates water movement following automated procedures and linking sub-basin models together to produce total run-off. Main features of the Yodo River model include following features in addition to that of the MaScOD model are:

a. This model defines a greater catchment as a combination of multiple smaller sub catchments each having approximately 150-km^2 coverage.
b. Each sub catchment further includes distributed hydrological modeling which is developed based on 250-m resolution DEM
c. This model contains current anthropogenic controls over the river flow such as the Dam release policies, and multi-reservoir operation rules.
d. This model uses measured data of channel geomorphology e.g. Channel width and depth.

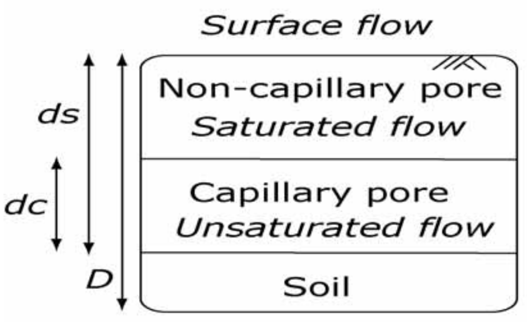

Fig. 2. Schematic of the soil layer in an element of the Yodo River model

3.1 Element model description

The element model, which is responsible to yield runoff from the interaction of soil water storage in multiple layers of soil and soil water storage capacity, is based on the saturated-unsaturated flow mechanism (Tachikawa *et al.*, 2004). This model takes into account three types of flows: unsaturated flow in capillary pore, saturated flow in non-capillary pore, and surface flow on soil surface. Figure 2 shows the schematic diagram of the soil layer of the model. In which, D [m], d_s [m], and d_c [m] denote the soil depth, depth of water in saturated condition, and the maximum water content in the capillary pore respectively. Figure 3 shows the stage-discharge relationship of the model. This relation is defined by a non-linear runoff yield relation that is given by

$$q = \begin{cases} v_c d_c \left(\dfrac{h}{d_c} \right)^{\beta} & 0 \le h \le d_c \\ v_c d_c + v_a (h - d_c) & d_c < h \le d_s \\ v_c d_c + v_a (h - d_c) + \alpha (h - d_s)^m & d_s < h \end{cases} \tag{1}$$

where, q is the discharge per unit width [m^2/s]; h is the stage [m]; v_c and v_a are flow rates from the capillary pore and non-capillary pore respectively. When k_c and k_a be the saturated hydraulic conductivities in capillary pore and non-capillary pore, respectively, then $v_c = k_c\ i$ and $v_a = k_a\ i$ for i representing intensity. The β is a non-dimensional parameter that describes the reduction of hydraulic conductivity in capillary pore as the water content reduced. The β equals to be k_a / k_c so as to keep the continuity of the stage-discharge relationship between the capillary pore and non-capillary pore.

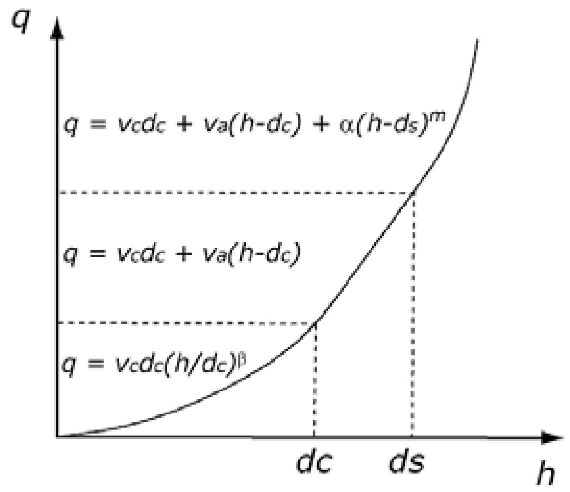

Fig. 3. Stage-discharge relationship for saturated-unsaturated layer

3.2 Flow Route Model (FRM) and Total simulation system

The flow route model of the Yodo river model is based on kinematic wave routing model. Runoff yield obtained from the element model are routed downstream through a kinematic wave approximation, which relates the unit discharge q [m^2/s] and the runoff depth h [m]. This is given by

$$q = \alpha h^m \tag{2}$$

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r(t) \tag{3}$$

where α is a parameter ($\alpha = \sqrt{i}/n$, i = slope [rad], n = roughness coefficient [$m^{-1/3}s$]), m is a constant (m = 5/3), and $r(t)$ is the rainfall treated as the lateral inflow per unit length [m/s].

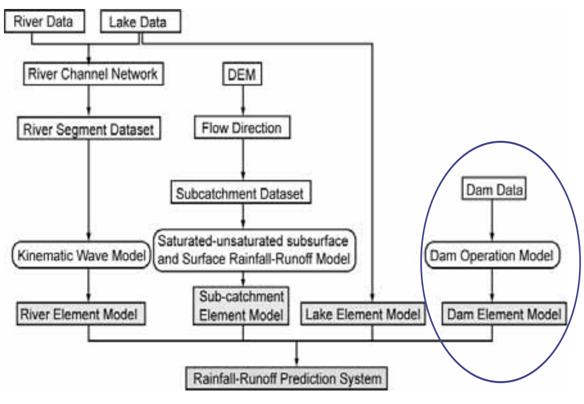

Fig. 4. Schematic of the Yodo River Model components

There is also a Dam Operation Element Model (DOEM) included in the Yodo river model, which can include the operational dam control mechanism in the simulation system (see Figure 4). The DOEM is developed and included in this model to investigate the effect of anthropogenic activity in hydrologic system of the Yodo river basin. Since, these issues are irrelevant to this study, the DOEM is made defunct while building the total simulation system. Also more details of the DOEM are excluded here.

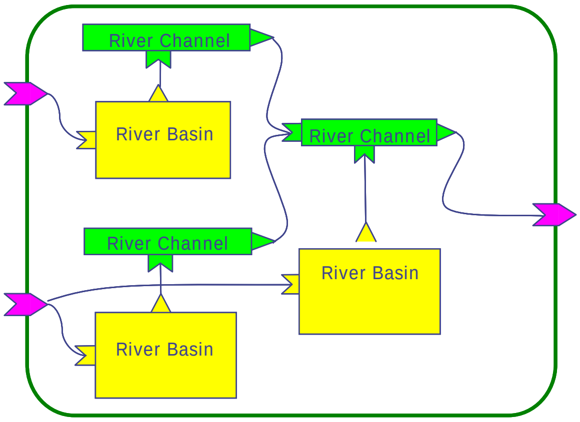

Fig. 5. Schematic simulation system of the Yodo River Model

The elements of the Yodo river model (Figure 5) are combined through the DSP and DRP of the OHyMoS system to build a total simulation system. For this operation, the model uses the OHyMoS library. The details are available on http://hywr.kuciv.kyoto-u.ac.jp/~shiiba/documents /unix/ohymos/.

4. Calibration of model parameters

The Yodo River hydrological model was calibrated using the radar observed rainfall as the input data. Because the model is configured to accept the 3-km spatial resolution and 10-minute temporal resolution data format, it average the 5-minute temporal resolution of the radar rainfall into 10-minute resolution. The calibration process did not employ any automated algorithm but the initial guesses of parametric values are referred from previous studies, e.g. Tachikawa *et al.*, (2004). The parameters for the routing models are kept same for all study basins. Only the saturated hydraulic conductivities (k_c and k_a), the permissible depth of water in soil layers (d_s and d_c) and the initial discharge. These values are slightly modified (trial method) until the simulated hydrograph comes enough closer to the observed one.

Figure 6 shows the simulation result at Inooka (1,589 km^2), which is definitely not a best-matched result. Not only to the parametric values, the simulation results also depends on model components we involved in the simulation. Presence of multiple numbers of dams upstream to Inooka, which massively modify the downstream flow, easily disconfirm that our model is solidly grounded in reality. Inclusion of the dam elements, as mentioned above, may improve the modeling task.

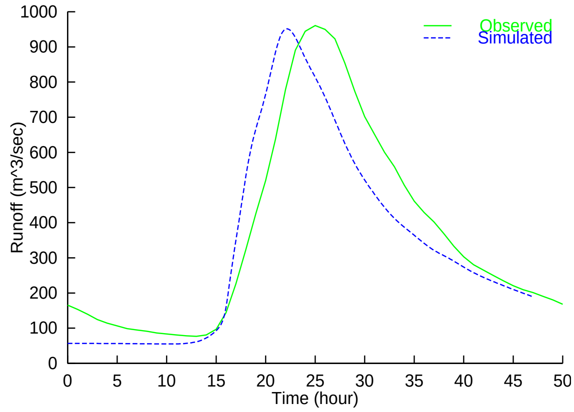

Fig. 6. Hydrograph at Inooka (1,589 km^2)

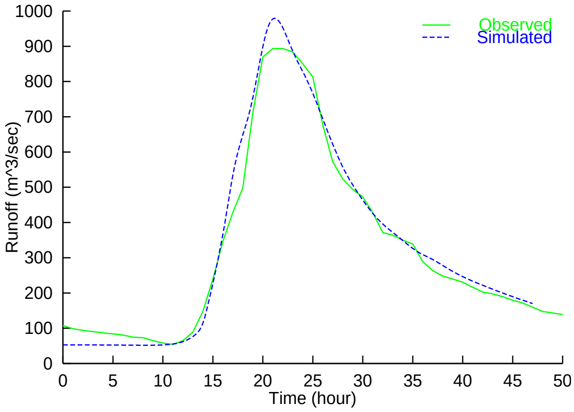

Fig. 7. Hydrograph at Kamo (1,469 km^2)

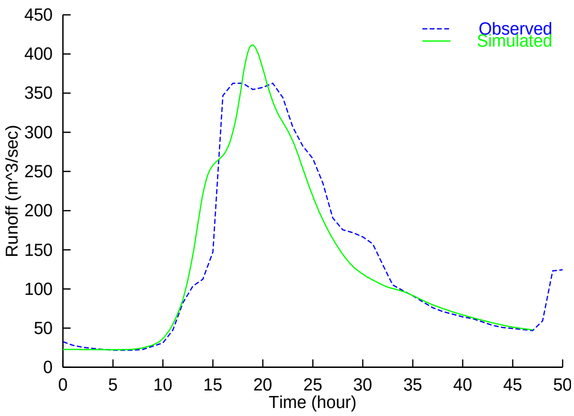

Fig. 8. Hydrograph at Ieno (476 km^2)

Figure 7 shows the simulation result at Kamo (1,469 km^2). This is better than the previous case in catching rising and falling limb of hydrograph. The observed hydrograph presents a clear evidence of peak-cut control set off by the dam-operation, which is abscent in the simulated hydrograph.

Figure 8 shows the simulation result at Ieno (476 km^2). This result can be said as a satisfactory result viewing the presence of three dams upstream. A rapid growth in runoff and very effective peak-cut control are clearly visible in the observed hydrograph. The simulated hydrograph lacks the effect of the anthropogenic control.

Figure 9 shows the simulation result at Ootori (156 km^2). This catchment is very small and also having no dams upstrea. So the observed runoff is less affected by the anthropogenic control. The model with the calibrated parameter set is best-successful to simulate the hydrograph in this catchment.

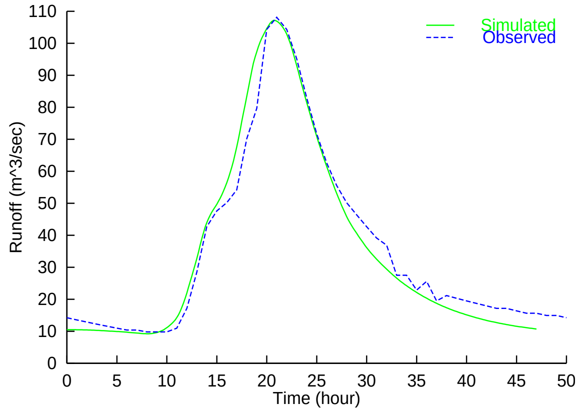

Fig. 9. Hydrograph at Ootori (476 km^2)

5. Simulation results using the disaggregated rainfall

After obtaining the disaggregated rainfall field having 3-km spatial resolution and 10-minute temporal resolution, we ran the hydrological model replacing the radar rainfall by the disaggregated rainfall. Tha parametric values are kept the same, and the deviation from the earlier simulation result is observed. For having chance of strongly stochastic rainfall structure, the simulation is repeated several times and obtained an ensemble of simulation results for each of the different disaggregation methods. Our simulation results seek to prove three hypotheses: (1) that hydrological simulation has significantly high sensitivity to the structure of input field particularly the rainfall (2) that the response to the structure of rainfall field tends to damp as the catchment size grows (3) that the disaggregated rainfall can simulate significantly tiny catchments when improving the space-time structure adequetely.

Figure 10, 11 and 12 shows the hydrographs obtained at Inooka (1,589 km^2) from the use of rainfall disaggregated by the RC method, RCHSA method and STRaM method respectively. The simulation results at Kamo (1,469 km^2) (see Figures 13, 14 and 15), at Ieno (476 km^2) (see Figures 16, 17 and 18) and at Ootori (156 km^2) (see Figures 19, 20 and 21) are similar to the results obtained at Inooka in terms of the bandwidth of ensemble simulation result.

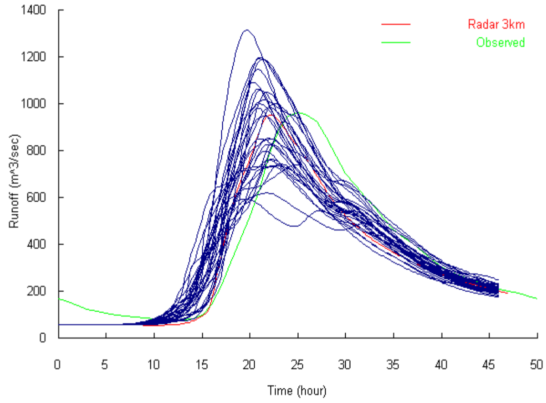

Fig. 10. Hydrographs at Inooka (1,589 km^2) obtained from the use of rainfall disaggregated by the RC method

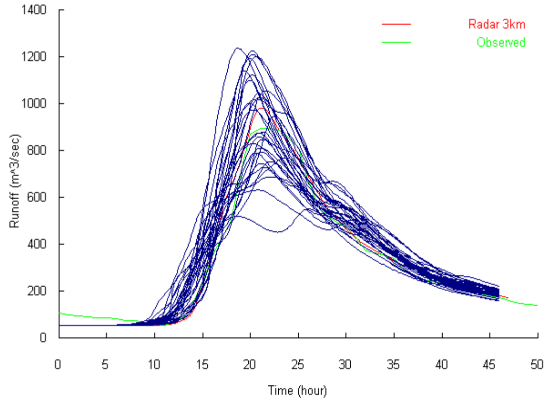

Fig. 13. Hydrographs at Kamo (1,469 km^2) obtained from the use of rainfall disaggregated by the RC method

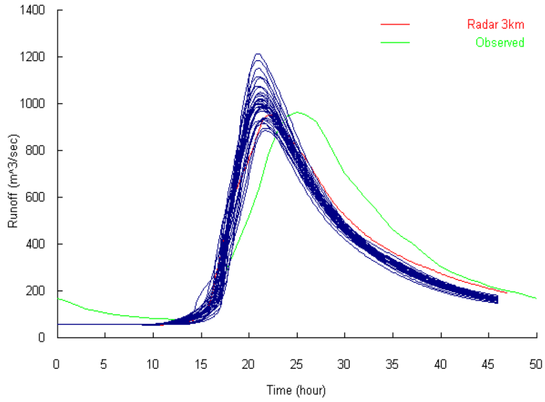

Fig. 11. Hydrographs at Inooka (1,589 km^2) obtained from the use of rainfall disaggregated by the RCHSA method

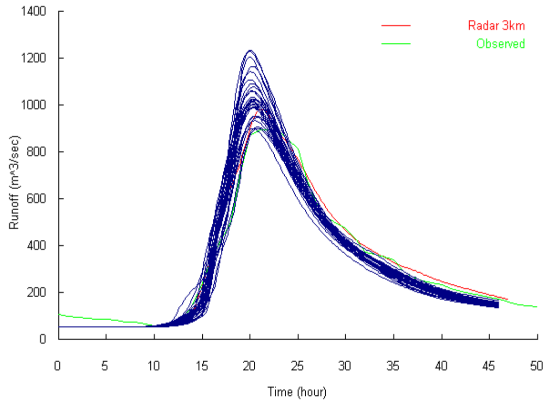

Fig. 14. Hydrographs at Kamo (1,469 km^2) obtained from the use of rainfall disaggregated by the RCHSA method

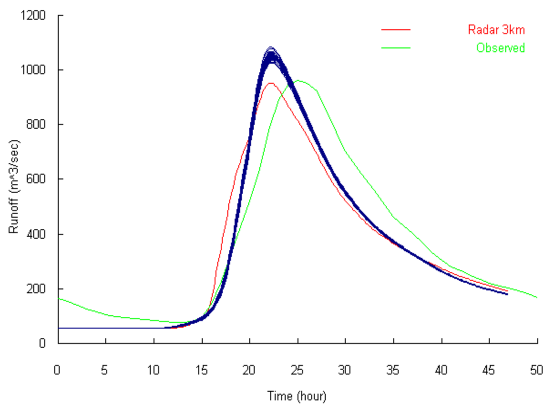

Fig. 12. Hydrographs at Inooka (1,589 km^2) obtained from the use of rainfall disaggregated by the STRaM method

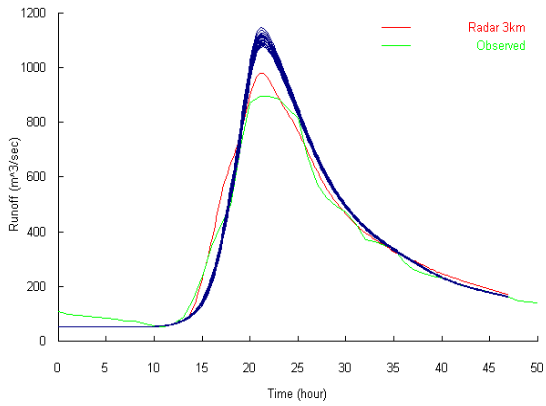

Fig. 15. Hydrographs at Kamo (1,469 km^2) obtained from the use of rainfall disaggregated by the STRaM method

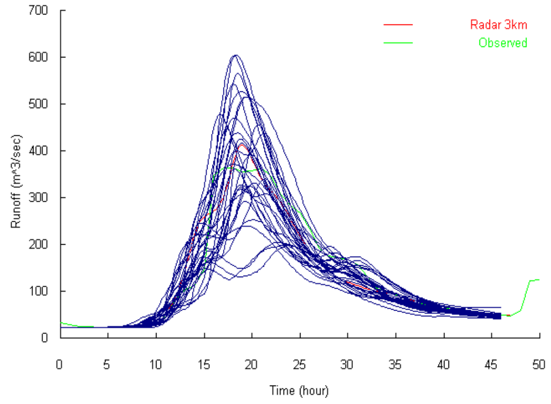

Fig. 16. Hydrographs at Ieno (476 km^2) obtained from the use of rainfall disaggregated by the RC method

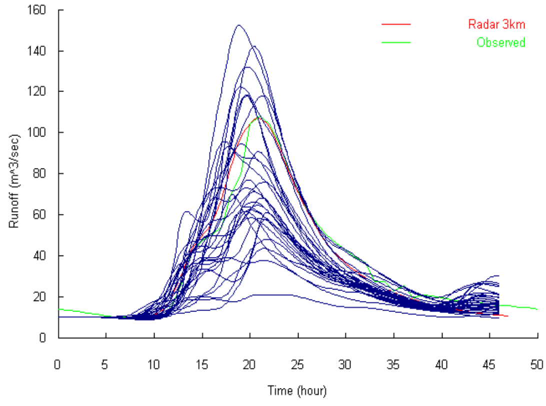

Fig. 19. Hydrographs at Ootori (156 km^2) obtained from the use of rainfall disaggregated by the RC method

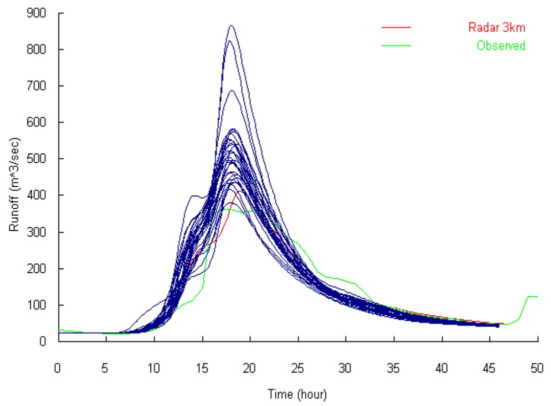

Fig. 17. Hydrographs at Ieno (476 km^2) obtained from the use of rainfall disaggregated by the RCHSA method

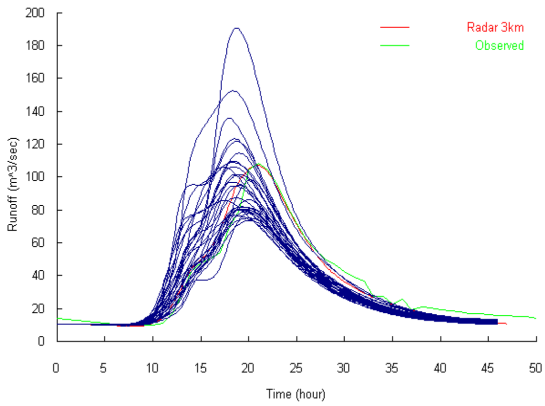

Fig. 20. Hydrographs at Ootori (156 km^2) obtained from the use of rainfall disaggregated by the RCHSA method

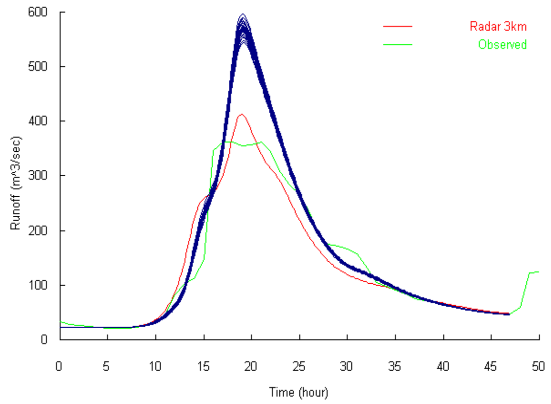

Fig. 18 . Hydrographs at Ieno (476 km^2) obtained from the use of rainfall disaggregated by the STRaM method

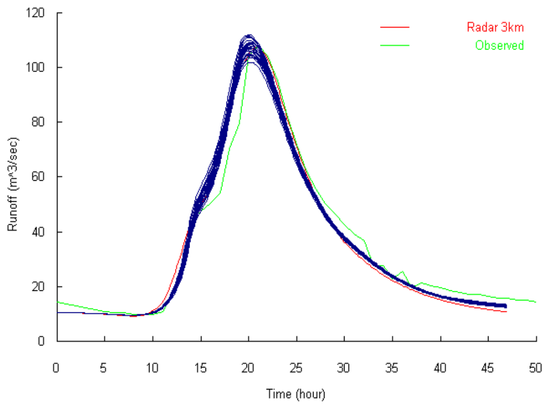

Fig. 21. Hydrographs at Ootori (156 km^2) obtained from the use of rainfall disaggregated by the STRaM method

The widespread bandwidth of ensemble hydrographs obtained from the use of rainfall disaggregated by the RC method and RCHSA method reveals the higher uncertainty associated with the disaggregated rainfall field. The narrowest bandwidth of the ensemble hydrograph obtained from rainfall disaggregated by the STRaM method proves the robust characteristics of the disaggregation method, which is plausible in a wide range of catchments sizes.

While the simulation results are better and more robust by the use of STRaM method, a considerable amount of bias is evident in the catchments other than Ootori. In an ideal case, the biases measure adverse properties of the disaggregated rainfall field to the radar rainfall. It might however explain a different perspective as we see the rising and falling limbs of hydrographs simulated by the disaggregated rainfall (using the STRaM method) are better matched to the observed hydrograph than that yielded by the radar rainfall. Recalling tremendous uncertainties in the methods of converting the radar reflectivity to the rainfall rates, the bias noticed here might have an unknown inter-relations. As we zoomed the rainfal structure in and out through the scaling processes (the aggregation and disaggregation) of the radar rainfall field, a significant changes might have occurred in the disaagregated rainfall field that could have resulted the simulated hydrographs better than the one obtained using the radar rainfall. In this regard, the bias noticed in the hydrographs using the disaggregated rainfall can be a positive achievement if the bias leads the simulation results toward an improved accuracy. This phenomenon is prominently visible in Figure 12, 15 and 18.

6. Conclusion

Bridging the scale gap has been an attractive research motivation in hydrology, which expects to overcome the limitations of the scale-mismatch via scale-transformation. The results obtained from a disaggregation model becomes useful only if it can properly describe the sub-grid scale variability. Testing the disaggregated rainfall in hydrological modeling is the best way to examine the rainfall structure as far as the runoff simulation is concerned.

Our simulation results seek to prove three hypotheses: (1) that hydrological simulation has significantly high sensitivity to the structure of input field particularly the rainfall (2) that the response to the structure of rainfall field tends to damp as the catchment size grows (3) that the disaggregated rainfall can simulate significantly tiny catchments when improving the space-time structure adequetely. In addition to that, the results have indicated possibility of self correcting the rainfall field, though this requires extensive investigation to confirm.

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淀川流域を対象とした分布型流出モデルへのダウンスケール降水量データの適用

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要 旨

淀川流域を対象として構築した広域分布型流出モデルを用いてダウンスケールした降水量データを検証する。降雨データをダウンスケールする方法として，β lognormal モデルを用いたマルティプリカティブランダムカスケード法(RC)，階層統計的配置法(HAS, Hieratical Statistical Arrangement)を導入したランダムカスケード法，ランダムかスケート法に移流モデルを導入した STRaM(space-time rainfall modeling)法の 3 種の手法を用いる。これらの手法をもちいて，それぞれ空間分解能 48km，時間分解能 100 分の降水量データを空間分解能 3km，時間分解能 10 分にダウンスケールする。生成した降水量データを分布型流出モデルへの入力データとし，大鳥居(156 km2)，家野 (476 km^2)，加茂 (1469 km^2)，飯岡 (1589 km^2)での計算流量を，3km，5 分分解能のレーダー雨量計を用いた場合の計算流量と比較してダウンスケールしたデータを検証する。その結果，STRaM を用いた場合の流量シミュレーション結果が，他の 2 つのダウンスケール手法に比べて極めてレーダー雨量を用いた場合のシミュレーション結果に近いことが分かった。

キーワード: ダウンスケール，降水量データ, 分布型流出モデル，RCHSA 法，STRaM 法