IC ratio concept in distributed hydrological modeling for optimal performance

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Abstract General Circulation Models (GCMs) are one of the major data source in distributed hydrological modeling for gauged and un-gauged basins. However, the available grid resolution of GCM data should resemble to the need of hydrological model's spatial resolution, which largely depends on catchments size. Observing the behavior of spatial resolution in distributed hydrologic modeling, data requirement criterion with respect to catchments size is investigated by evaluating IC Ratio (ratio between input data resolution and catchments area), expecting massive use of GCM data and coupled atmospheric and hydrologic model in near future. A macro scale distributed hydrological model is developed using object oriented hydrological modeling system (OHyMoS) and test simulations are conducted for the case of Huaihe River Basin (132,350 sq. km.) in China and its two sub-basins Wangjiaba (29,844 sq. km.) and Suiping (2,093 sq. km.). A 10-minute spatial resolution data set is generated using the 1.25 degree GAME Reanalysis Data Version 1.1 referring the spatial pattern of 5-minute HUBEX EEWB Data; a field measurement based distributed data set. The newly created data has improved the modeling result. Later on, the generated 10-minute spatial data is converted to 20-minute, 30-minute and so on. Model performances are examined by feeding the generated forcing data into the model with the same parameters as before. A changing behavior of simulation result displayed a rapid improvement on model result with finer resolution. The improvement in model performance saturates afterward which suggests an existence of a threshold value of IC Ratio. Optimal simulation results are observed while the IC Ratios are around 1:10 ~ 1:20. Higher sensitivity in model performance due to spatial resolution is observed in smaller catchments in both presence and absence of routing models than that of larger catchments.

Keyword GCM data, Macro-scale distributed hydrological modeling, OHyMoS, IC Ratio, spatial resolution

INTRODUCTION

Hydrological models are evolved to get better understanding of surface runoff generated from complex watersheds. Several surface runoff models, which broadly can be classified as either Lumped-conceptual model or Distributed physically-based model, have already been tested and applied for this purpose. The lumped conceptual models are repeatedly proved unable to handle the spatial variability. Distributed models are developed, with a hope to obtain solution to the problems of lumped model, to represent the variability in physical watershed characteristics.

It is noticed that for many of the problem areas the need for the distributed models reflects a demand for predictive capability on the effects of man-induced impacts (Refsgaard & Abott, 1996) such as massive land-use changes, global warming effects and effects caused by natural reasons such as heavy rainfalls and droughts due to climatic fluctuations. The distributed models' strength to assess the effects of spatially variable impacts on hydrologic responses has made it an essential tool to analyze the hydrologic behavior of watershed with increased accuracy.

However, to use a distributed models is complicated by the need to establish a suitable spatial scale to be used in characterizing watershed conditions such as topography, drainage density, degree of soil saturation and rainfall properties or in a broad sense the input information to the model. The challenge in applying distributed models to large watersheds is to determine a scale at which spatial variability can be neglected, with average characteristics of a given area providing sufficient information for accurate modeling of basin runoff generation (Molnar, 2000). Probably this is one major reason to make distributed models not so popular in practical application.

Development of hydrological simulations for gauged and un-gauged basins frequently uses meteorological data inputs retrieved from global climatic scenario, which are provided by General Circulation Model (GCM). Unfortunately, the structure of GCMs is such that their space resolution is often too coarse and not adequate (Burlando, 2002) to describe variability in hydrologic processes components at the basin scale. Large efforts to produce finer resolution GCM data with greater accuracy have increased the possibility of extensive use of GCM data in distributed hydrologic models.

The available grid resolution of GCM data should resemble to the need of hydrological model's spatial resolution. Some criteria are necessary to determine a scale at which spatial variability can be ignored for a given area providing sufficient information with average characteristic of the area with respect to catchments size for accurate modeling of surface runoff generation. Shrestha et al. (2002) found that the results of distributed hydrological models are better while an IC Ratio (ratio between input data resolution and catchments area) is more than 1:10, which may serve as a criterion to evaluate suitable input data resolution.

This paper will illustrate the IC Ratio concept in distributed hydrological modeling by examining the model performance with different forcing data resolutions. Applying a macro scale distributed hydrological model, which uses the object oriented hydrological modeling system (OHyMoS) (Takasao et al., 1996), the study is conducted for three-basins in China, namely Huaihe River Basin (132,350 km^2), Wangjiaba (29,844 km^2) and Suiping (2,093 km^2).

BACKGROUND

Macro scale hydrological modeling is often practiced for a large river basin. An object oriented hydrological modeling system - OHyMoS (Takasao et al., 1996, Ichikawa et al., 2000) has eased a lot of tasks associated with the modeling procedure of water movement in a grid based analysis. For example, basin partitioning, hydrological process modeling for a sub-basin, linking sub-basin models together to make a total runoff model, processing channel network linkages to incorporate river flow routing, etc. involve a lot of heavy tasks, which now has been arranged in an automatic procedure

(Tachikawa et al., 2000). In this system a watershed basin is subdivided into grid boxes according to a grid system of a meso-scale atmospheric model outputs.

The model consists of a runoff process model based on Xinanjiang model and Lumped stream kinematic-wave flow route model for each grid cells to constitute an element model. These element models are interconnected by data sending ports and data receiving ports defined as per the river network arrangement to construct the total simulation process. The model parameters are calibrated on the basis of field observation records inside Shigan River Basin, a sub-basin inside Huiahe River Basin, which is assumed to include the representative geomorphology of entire basin.

Using the grid precipitation and grid actual evapo-transpiration data obtained from the HUBEX-IOP EEWB data (termed EEWB data here after), a 5 minute spatial resolution data created in DPRI, Kyoto University (Tanaka et al 1999), discharges are successfully simulated (Tachikawa et al 2000). Using 2-dimensional forecast data of GAME Reanalysis (Version 1.1) with 1.25 degree resolution (termed GAME data here after), produced by Japan Meteorological Agency using 4 DDA-system including the GAME special observation off-line radio-sonde dataset, the discharges are successfully simulated again and observed that the simulation result with GAME data is better than EEWB data for large basin and just opposite for smaller basins (Shrestha et al., 2002). Magnitude errors in EEWB data are assumed as one of the reasons behind the large basin simulation error. Coarser resolution of GAME data is assumed as one of the reasons behind the smaller basin simulation error. Thus it has demanded some additional and closer investigations.

METHODS AND DATA

In this study, a finest resolution of 10 minute data is created by preserving the spatial pattern of EEWB data and magnitude of GAME data. EEWB data is created using interpolations of the ground observation points by considering both distance and direction of each observation station for precipitation field. It uses the simple bio-sphere with urban canopy (SIBUC) model to obtain the evapo-transpiration data field.

The reason behind following the spatial pattern of EEWB data is that it is created basically on the basis of ground observations. The EEWB data, with finest resolution among the available data until now, is therefore assumed to represent the spatial pattern better than any other data. On the other hand, GAME data is coarse and produced by an atmospheric model, which has given better simulation results in previous analyses, therefore its magnitude is assumed to be nearer to the actual data. The following two approaches are tested in the process of generating the 10 minute test data.

1. Multiplicative approach:
   This approach generates 10-minute disaggregated grid data by multiplying a factor based on the ratio between the original data and mean data. Thus the new data set is represented as:

   $$P_4 = P_1 * \frac{P_2}{P_3}$$

   Where P_4 = GAME 10-minute
   P_1 = GAME 1.25-degree
   P_2 = EEWB 10-minute
   P_3 = average of EEWB 10-minute

   The resolution of P_1 and P_3 are maintained same. If P_3 data field is zero, the P_4 value is simply assigned P_1 value of corresponding grid to avoid the chance of infinity error.

2. Arithmetic approach
   This approach simply adds or reduces the value from the averaged GAME 1.25-degree data on the basis of differences between the EEWB 10 minute data and its averaged figure. Thus the new data set is represented as:

$$P_4 = P_1 + P_2 - P_3$$

Here P_1, P_2, P_3 and P_4 represent the values as before. Sometimes, P_4 values may appear negative, which is forced to make zero. Thus, the accumulated value frequently appears to be higher than the original. A factor of ratio between the new accumulated value and original value is multiplied to all the data for maintaining the total input as same as that of the original data.

The arithmetic approach is found to yield better results for all test basins. Hence this approach is adopted to create the new experimental 10-minute data, which is used then to create 20-minute, 30-minute data and so on by passing an averaging window of (2 × 2), (3 × 3) and so on up to 150-minutes (2.5-degrees) respectively.

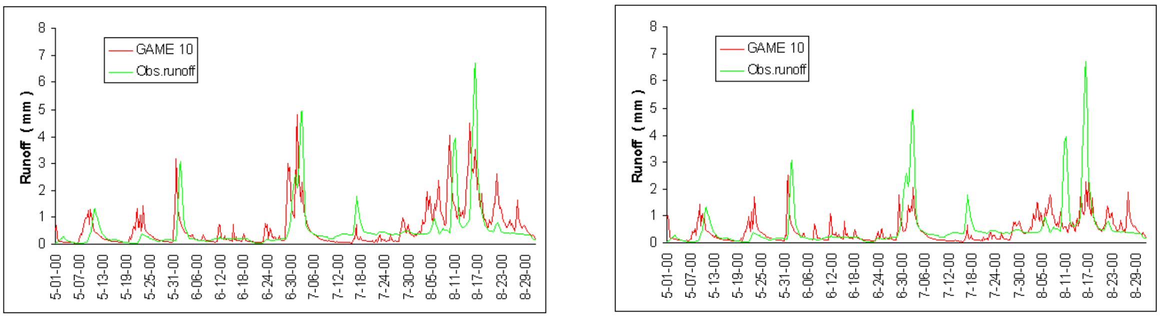
To see the effects of routing model in the simulation result, especially while the forcing data resolution differs, the experiment is conducted with and without routing model separately.

RESULTS AND DISCUSSION

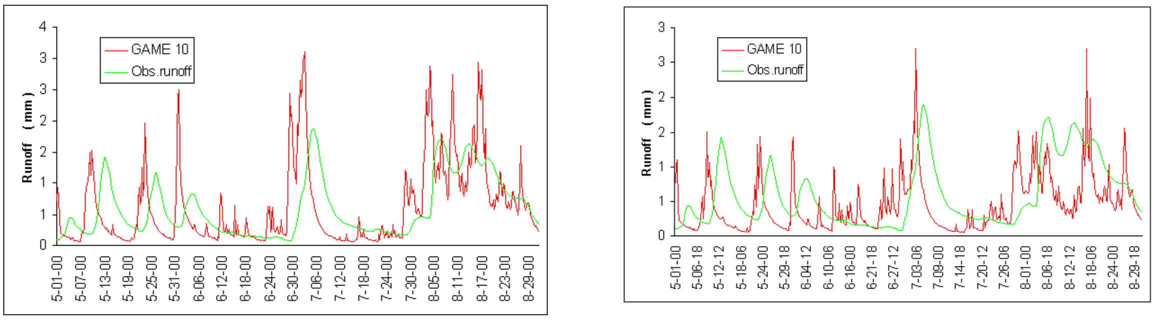
Simulation results with experimental data are found better than either of original data. They are compared against the observed discharge. The model performances are evaluated by using several indexes. The indexes used here to compare the hydrographs are Pearson's Moment Correlation Coefficients (PMC coeff.), Nash-Sutcliff's index of efficiency (NSI coeff.), Index of Agreement (IOA), Covariance, Root mean square error (RMSE), Mean bias, Volume error (VER), Unbalance, Peak flow error (QER), Peak time error (TER), Maximum difference at the same time (Max diff), Average absolute error (AAE) and Average absolute error within +/- 2 hour interval (AAE +/- 2hr). Indications about the model's performance with these indexes often coincide with very few exceptions. Therefore, some of the index parameters only mentioned in the discussions ahead. Some result hydrographs and the tabulated results are presented here.

Modeling without routing model

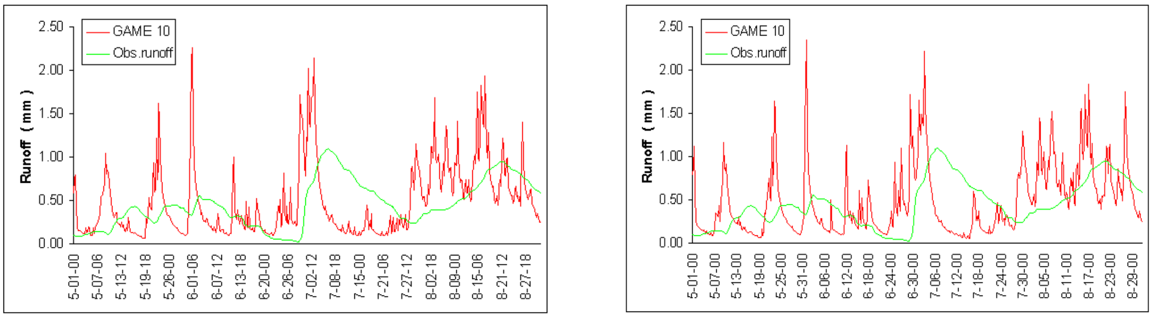
The simulation results without routing model do not display a good match at first look in all the cases except the result in Suiping with 10 minute-data (see fig.1). Mostly, the results are similar to the finding of Tachikawa et al. (2002) - too bad without routing model. Distributed hydrologic modeling without routing model should therefore not be practiced either in larger watersheds or with coarser resolution data. Routing model has significant influence in larger basins and with coarser data resolution. The results are too bad, so that it is doubtful to perform the comparisons between the performances; therefore, the attempt to evaluate the spatial resolution issues without routing model are abandoned then.



At Suiping with 10 minute data With 2 degree data



At Wangjiaba with 10 minute data With 2 degree data

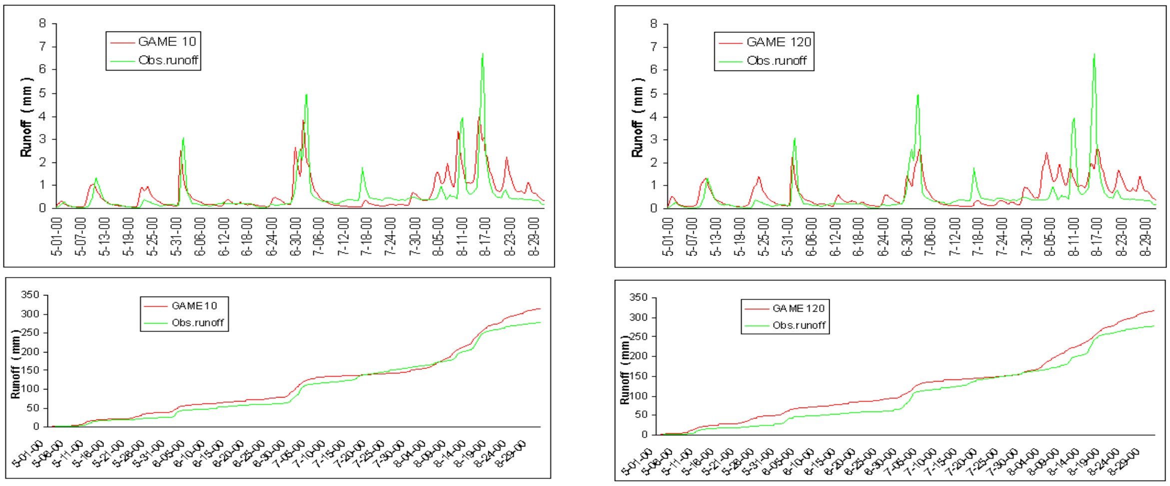


At Bengbu with 10 minute data With 2 degree data

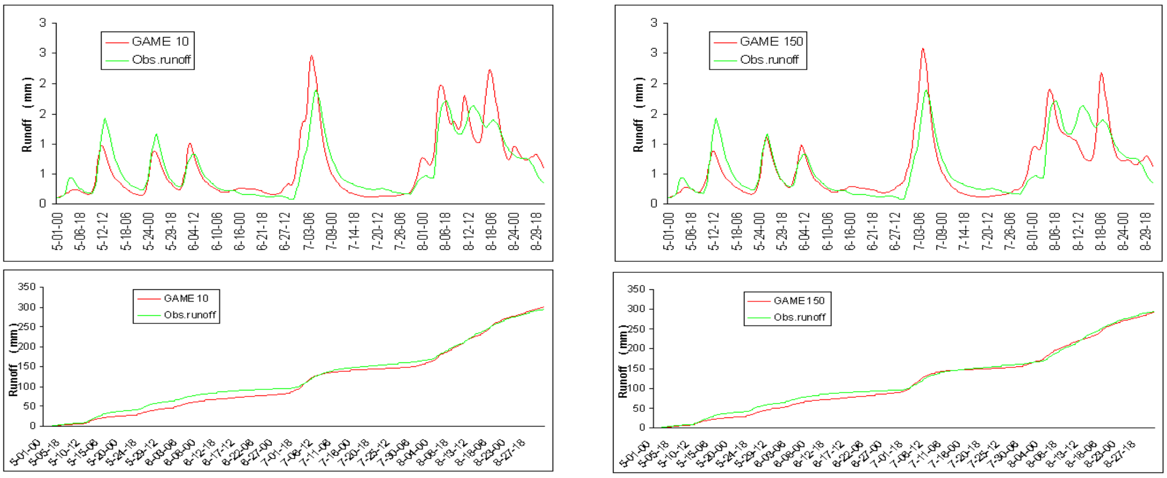
Figure1: The Hydrographs without routing model: Simulated vs. Observed.

Modeling with routing model

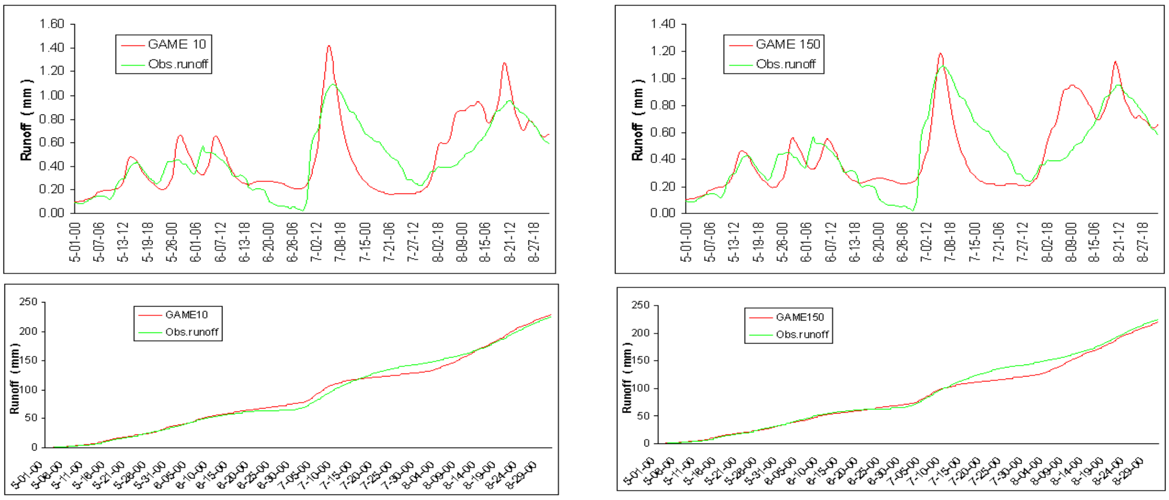
Inclusion of routing model yields good results in the simulation. The model performances are better and comparable against the observed discharge. Distinct changes in hydrograph are clearly visible at different spatial resolution data input. This change indicates the influence of the spatial resolution with a clear sign of worse simulation result at coarser input data resolution. A worth noting point is that the coarser resolution data applied here for simulation is nothing more than the spatially averaged value from the same finer resolution data, which just smoothens the spatial variability at a coarser scale. The total accumulated values are kept constant in all the analysis.



Comparison of hydrograph & water budget at Suiping with 10 minute and 2.0 degree data



Comparison of hydrograph & water budget at Wanjiaba with 10 minute and 2.5 degree data



Comparison of hydrograph & water budget at Bengbu with 10 minute and 2.5 degree data

Figure 2. The Hydrographs with routing model: Simulated vs. Observed.

Slight differences in the water budget, which are not detectable in graph scale, are observed. This should be due to the nonlinear soil-water interaction phenomenon of Xinanjiang model based runoff element process.

IC-Ratio and the results:

With the coarser resolution forcing data, one obtains poor model performance in the simulation result than that with the finer resolution. This result is obvious; in addition, it is expected to obtain variable model performances once the test basins are different. The constitutive relations for different flow processes that are function of the detailed geometry of flow pathways in different catchments are difficult to compare (Beven, 2002). Some indexes for example average slope, flow lengths, watershed relief etc. exist to represent the catchments features but they may not be compatible to test against forcing data resolutions. The concept of ratio between the input grid resolution and catchments size, termed as IC-Ratio (Shrestha et al 2001) may be generally useful index for investigating the phenomenon observed due to effects of resolution changes.

The finest resolution in this experiment is 10 minute spatial distance (approximately 13.5 km). The input data for Suiping basin (2093 km^2) varies from 10 minute to 2 degree resolution. Therefore the IC-Ratio value ranges from 1:11.77 to 1:0.08. Model performances are consistently better at 1:11.77 (called higher IC-Ratio values here) than near the ranges of 1:0.08 (lower IC-Ratio). Higher IC-Ratio corresponds to finer resolution and lower IC-Ratio corresponds to coarser resolution of input as catchments size remains constant.

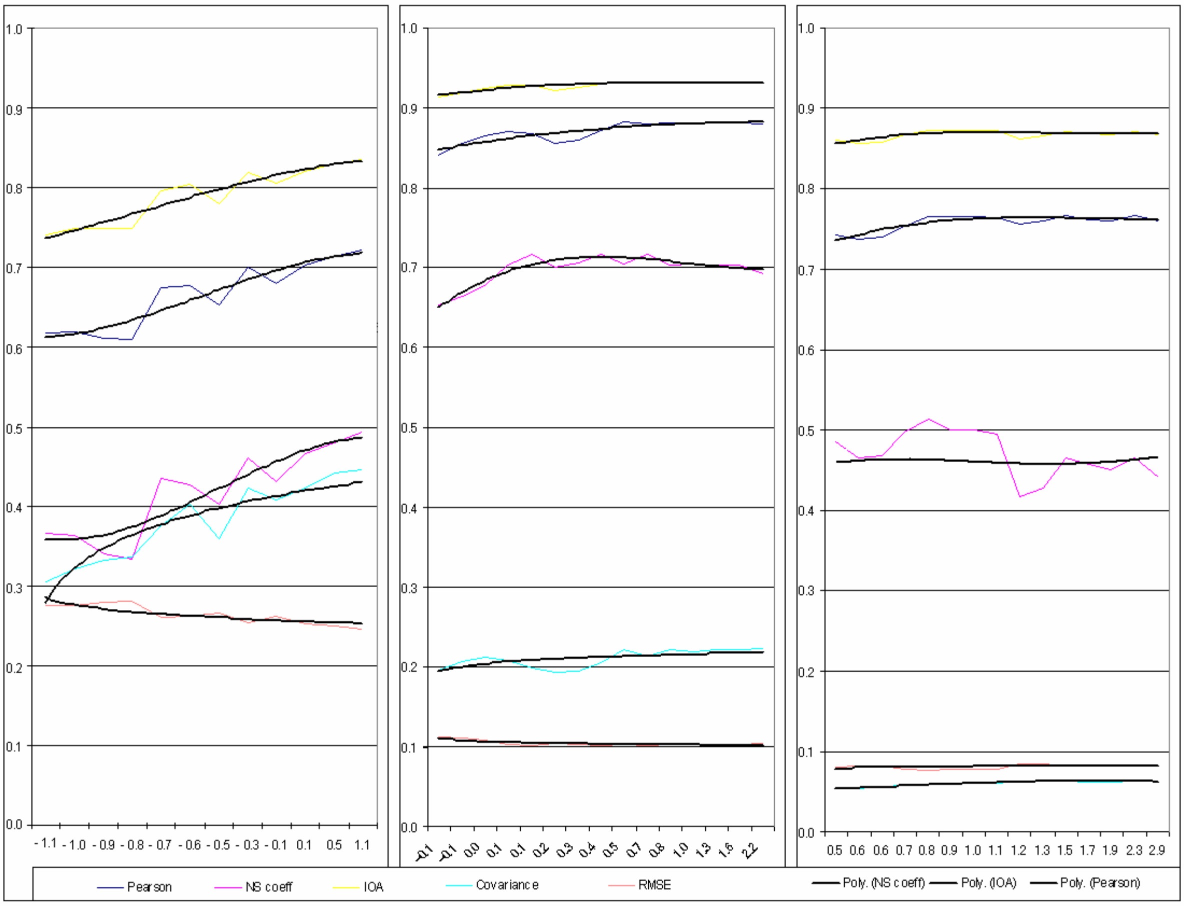


Figure 3. The model performances of Suiping, Wangjiaba, and Bengbu at different IC Ratios

The IC-Ratio values for Wangjiaba basin (29844 km^2) and Bengbu basin (132350 km^2) vary from 1:167.8 to 1:0.75 and 1:744.5 to 1:3.3 respectively. Model performances are better while IC-Ratio values are higher in both these cases also.

The trend of change in model performance from the graphs presented (see fig.3) clearly shows that the smaller basin has higher sensitivity in response to the forcing data resolutions. The rate of change in performance is higher in Wanjiaba than that in Bengbu. Similarly, the rate of change in performance is higher in Suiping than that in Wangjiaba. This indicates that the resolution issues need more attention for the smaller basins than the larger ones. This indication seems quite natural because, in larger basins, the larger heterogeneous parts may be represented as homogenous parts than in smaller basins.

Table 1: A summary of model performance indexes values for all the basins

IC Ratio (1 : X)		PMC coeff	NSI coeff	IOA	Cova- riance	RMSE	Mean Bias	VER	Un- bal	QER	TER	Max diff	AAE	AAE +/- 2hr
0.08	S	0.62	0.37	0.74	0.31	0.28	-0.0135	-14.31	39.78	-61.6	-5	4.99	0.92	0.67
0.10	S	0.62	0.36	0.75	0.32	0.28	-0.0137	-14.59	40.56	-54.1	3	4.52	1.02	0.73
0.12	S	0.61	0.34	0.75	0.33	0.28	-0.0143	-15.16	42.13	-51.9	-5	4.50	1.06	0.76
0.15	S	0.61	0.33	0.75	0.34	0.28	-0.0140	-14.82	41.21	-50.6	-5	4.49	1.07	0.77
0.18	S	0.67	0.44	0.80	0.38	0.26	-0.0135	-14.33	39.85	-53.2	8	4.43	0.89	0.62
0.24	S	0.68	0.43	0.80	0.40	0.26	-0.0120	-12.78	35.52	-46.3	3	4.38	0.76	0.53
0.33	S	0.65	0.40	0.78	0.36	0.27	-0.0138	-14.68	40.82	-56.5	3	4.51	0.96	0.68
0.47	S	0.70	0.46	0.82	0.42	0.25	-0.0136	-14.41	40.06	-44.6	8	4.03	0.82	0.56
0.74	S	0.68	0.43	0.81	0.41	0.26	-0.0126	-13.33	37.07	-45.6	3	4.31	0.77	0.53
0.75	W	0.84	0.65	0.91	0.20	0.11	0.0006	0.56	-1.65	37.5	3	0.99	0.40	0.31
0.86	W	0.86	0.66	0.92	0.21	0.11	-0.0009	-0.92	2.69	38.8	3	1.01	0.39	0.30
0.99	W	0.86	0.68	0.92	0.21	0.11	-0.0017	-1.71	5.03	35.1	3	1.05	0.39	0.30
1.17	W	0.87	0.70	0.93	0.21	0.10	-0.0019	-1.94	5.71	28.1	2	0.92	0.40	0.31
1.31	S	0.70	0.47	0.82	0.42	0.25	-0.0135	-14.35	39.89	-45.4	3	4.01	0.83	0.57
1.39	W	0.87	0.72	0.93	0.20	0.10	-0.0012	-1.21	3.57	21.4	2	0.89	0.39	0.31
1.68	W	0.86	0.70	0.92	0.19	0.10	-0.0008	-0.78	2.30	22.5	3	0.88	0.40	0.31
2.07	W	0.86	0.71	0.92	0.19	0.10	0.0000	0.03	-0.09	28.1	3	0.87	0.39	0.31
2.62	W	0.87	0.72	0.93	0.21	0.10	-0.0004	-0.36	1.07	30.2	3	0.92	0.39	0.31
2.94	S	0.71	0.48	0.83	0.44	0.25	-0.0132	-14.00	38.92	-41.8	3	3.84	0.79	0.53
3.31	B	0.74	0.49	0.86	0.06	0.08	0.0018	2.35	-5.30	8.1	3	0.51	0.54	0.48
3.43	W	0.88	0.70	0.93	0.22	0.10	-0.0026	-2.60	7.65	31.6	3	1.00	0.39	0.30
3.80	B	0.74	0.47	0.86	0.05	0.08	0.0018	2.33	-5.24	6.9	2	0.55	0.54	0.49
4.41	B	0.74	0.47	0.86	0.06	0.08	0.0017	2.22	-5.01	7.0	2	0.53	0.54	0.48
4.66	W	0.88	0.72	0.93	0.21	0.10	-0.0015	-1.47	4.32	30.7	3	0.97	0.39	0.30
5.17	B	0.75	0.50	0.87	0.06	0.08	0.0013	1.71	-3.84	10.9	2	0.47	0.54	0.49
6.15	B	0.77	0.51	0.87	0.06	0.08	0.0019	2.54	-5.71	14.2	2	0.44	0.53	0.48
6.71	W	0.88	0.70	0.93	0.22	0.10	-0.0020	-2.00	5.87	30.7	4	1.03	0.38	0.29
7.44	B	0.77	0.50	0.87	0.06	0.08	0.0005	0.72	-1.61	16.9	3	0.44	0.54	0.49
9.19	B	0.77	0.50	0.87	0.06	0.08	0.0003	0.42	-0.94	17.6	3	0.44	0.54	0.49
10.49	W	0.88	0.70	0.93	0.22	0.10	-0.0012	-1.21	3.56	32.5	4	1.05	0.38	0.29
11.63	B	0.76	0.50	0.87	0.06	0.08	-0.0002	-0.24	0.55	18.9	3	0.44	0.55	0.50
11.77	S	0.72	0.49	0.84	0.45	0.25	-0.0125	-13.23	36.78	-40.7	3	3.79	0.76	0.51
15.19	B	0.76	0.42	0.86	0.06	0.08	-0.0032	-4.25	9.58	26.2	4	0.49	0.58	0.52
18.65	W	0.88	0.70	0.93	0.22	0.10	-0.0017	-1.67	4.90	30.6	4	1.02	0.38	0.29
20.68	B	0.76	0.43	0.87	0.06	0.08	-0.0032	-4.25	9.57	29.9	4	0.47	0.58	0.52
29.78	B	0.77	0.47	0.87	0.06	0.08	-0.0008	-1.03	2.32	28.8	4	0.43	0.56	0.50
41.97	W	0.88	0.70	0.93	0.22	0.10	-0.0020	-2.00	5.87	30.7	4	1.03	0.38	0.29
46.53	B	0.76	0.46	0.87	0.06	0.08	-0.0009	-1.22	2.74	27.7	4	0.44	0.56	0.50
82.72	B	0.76	0.45	0.87	0.06	0.08	-0.0011	-1.46	3.30	27.6	4	0.44	0.56	0.50
167.87	W	0.88	0.69	0.93	0.22	0.11	-0.0023	-2.28	6.71	31.0	4	1.05	0.38	0.29
186.12	B	0.77	0.47	0.87	0.06	0.08	-0.0008	-1.03	2.32	28.8	4	0.43	0.56	0.50
744.47	B	0.76	0.44	0.87	0.06	0.08	-0.0015	-1.98	4.46	29.5	5	0.44	0.56	0.51

Optimal performance and IC Ratio

The obtained results unanimously argue that the model's performance depends upon forcing data resolution. However, demanding very high resolution data is not a solution in response to this phenomenon. Minimum data, minimum parameter and minimum calculating load to obtain best simulation results make the distributed hydrological model easier and popular to apply elsewhere.

Improvement rate of the model performance has a tendency to saturate at some points. The rate of improvement is higher while the IC Ratio is lesser than 1:10. When the IC Ratio values reach higher than the 1:20, the improvement rates of the model performances are not much significant. This behavior is believed to follow the trend line of S-shape curve with its point of inflection near to 1:10 (Shrestha et al., 2002).

Looking the trend of RMSE values, the errors are found to stay stable after the IC Ratio 1: 20 or near this value. Similar behavior is displayed from the covariance between the observed and simulated discharges. Thus, on the basis of all these result, the optimal performance should lie within IC Ratio 1:10 ~ 1:20.

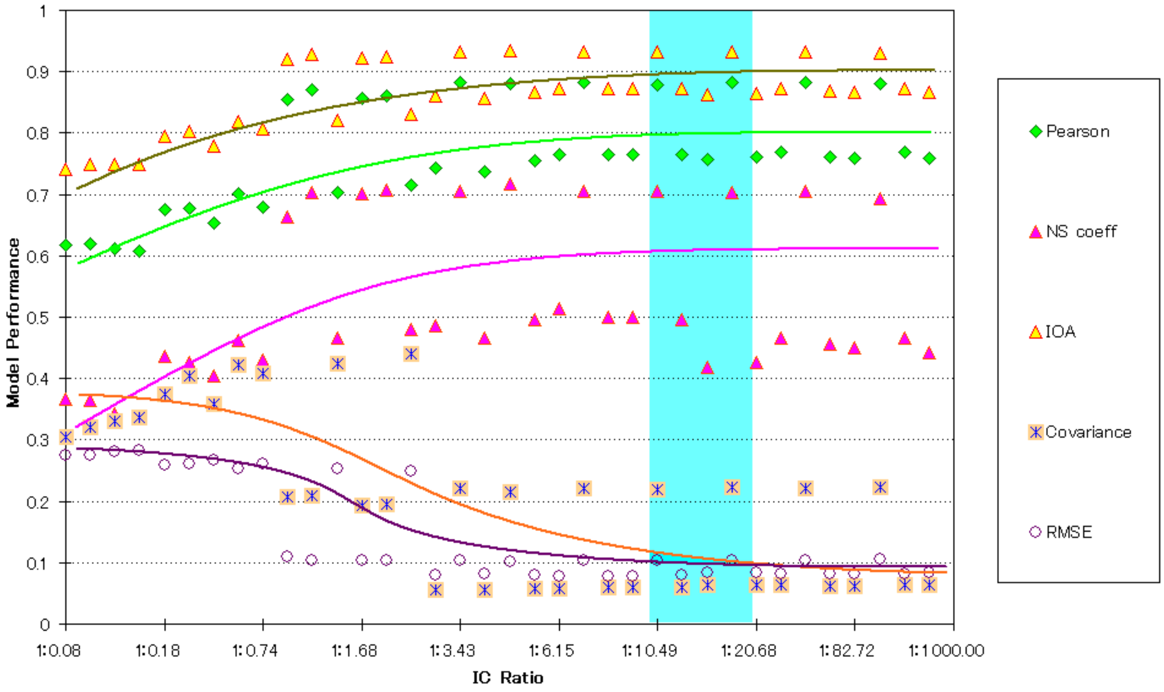


Figure 4. Model performance vs. IC Ratio

The IC Ratio figure (1:10 ~ 1:20) mentioned here in fact represents a marginal value of IC Ratio to obtain the simulation result at a satisfactory level. This mean, the simulation result with IC Ratio lower than 1:10 ~ 1:20 may not yield nice result. With higher IC Ratio values for example 1:100, the result will always come better but, at the cost of high resolution data and calculation. The interesting part is that, slight improvements are expected in the results even with the decision of choosing high resolution data such as 1:100 or 1:200.

In an un-gauged basin, where hydrologists need to start work from beginning, a lot of unknowns are expected to encounter at an attempt of distributed hydrological modeling. Heavy tasks involve in defining the model parameters, modeling scales, data acquisitions, etc. Probably in such case, the idea of IC Ratio may be very useful to set up model framework at early stage.

CONCLUSION

In distributed hydrological modeling, the model's performance is believed to be better than the lumped-conceptual type of modeling. This greatly depends upon the quality of modeling, which refers to the quality of modeling technique, model parameters and input data. Talking about the input data, its quality is associated with accuracy and resolution issues. The ratio of input data resolution and catchments area, called as IC-Ratio, can be an index to evaluate the suitability of data resolution in distributed hydrological modeling.

In this experiment, 3 catchments, ranging from small (2,093 km^2) to large (132,350 km^2) size, have been taken to study the data resolution effects in the discharge simulation results. Smaller catchments are found more sensitive than the larger catchments indicating that, the resolution issues need more attention for the smaller basins than the larger one.

The simulation results deteriorate sharply when the IC Ratio is kept lower than 1:10. The improvement rate in model performance is small after increasing the IC Ratio values higher than 1:20. A marginal IC Ratio value of 1:10 ~ 1:20 seems to be appropriate to obtain optimum performance in the results of distributed hydrological modeling viewing the need of efforts to process the high resolution data.

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