Development of a macro scale distributed hydrological model using an object-oriented hydrological modeling system

Y. Tachikawa, Y. Ichikawa, K. Takara
Disaster Prevention Research Institute, Kyoto University, Uji 611-0011, Japan

M. Shiiba
Department of Civil Engineering Systems, Kyoto University, Kyoto 606-8501, Japan

ABSTRACT: A macro scale distributed hydrological modeling system using OHyMoS, Object-oriented Hydrological Modeling System (Takasao *et al.*, 1996, Ichikawa *et al.*, 2000) is developed. When a channel network data set and grid information on a meso-scale atmospheric model are given, the system automatically builds a distributed hydrological simulation model through a series of procedures. A watershed basin is divided into grid boxes; a sub-model composed of a runoff element model and a flow routing element model is set up for each grid box; sub-models are put together to build a total runoff simulation model by using functions of OHyMoS. The system is applied to the Chao Phraya River basin in Thailand (110,000 km^2) and a macro scale distributed hydrological model is constructed. River discharges at many hydrological stations are simulated and model performances are evaluated.

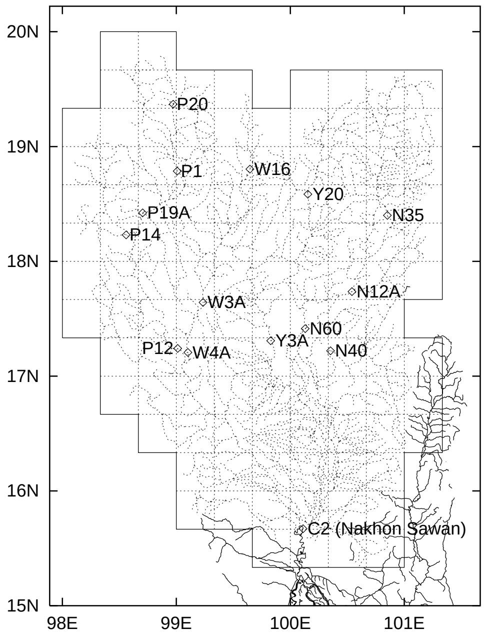
1 INTRODUCTION

To predict floods, droughts and future water resources for a large river basin, a macro scale distributed hydrological model is an indispensable tool. For modeling water movement of a large river basin, modeling procedures such as basin partitioning, hydrological process modeling for a sub-basin, linking sub-basin models together to make a total runoff model require heavy tasks. So, automatic procedures for processing hydrological modeling are necessary so that a model is transferable to various large catchments. In automatic modeling procedures, processing channel network linkages should be also included to incorporate a river flow routing model efficiently.

To satisfy such modeling requirements, a macro scale grid based distributed hydrological modeling system using OHyMoS, Object-oriented Hydrological Modeling System (Takasao *et al.*, 1996, Ichikawa *et al.*, 2000) is developed and applied to the Chao Phraya River basin in Thailand (110,000km^2). In the system, a watershed basin is subdivided into grid boxes according to a grid system of a meso-scale atmospheric model to incorporate atmospheric model outputs.

At first, a channel network data set is generated from the river network data sets stored in the DCW (Digital Chart of the World) and the GLOBE (Global Land One-km Base Elevation) data sets. The generated data set has a newly defined data format for efficiently building

Proc. of 4th International Conference Hydroinformatics 2000, Iowa, USA, 2000, CD-ROM, 8 pp.



Discharge Stations	Catchment Area(km^2)
P1	6,355
P12	26,363
P14	3,853
P19A	14,023
P20	1,355
W3A	8,985
W4A	10,507
W16	1,284
Y3A	13,583
Y20	5,410
N12A	15,718
N35	10,335
N40	4,340
N60	18,692
C2	110,569

Figure 1: Channel network and grid division for the Chao Phraya River basin. Dotted lines show the channel network above Nakhon Sawan (C2 station).

up a river flow routing model.

When the channel network data set and locations and sizes of a grid system of a meso-scale atmospheric model are given, a watershed basin is subdivided into grid boxes; a channel network is separated according to the grid boxes; for each grid box hydrological processes are modeled as a lumped runoff element model and flow routing is modeled as a lumped flow routing element model; and flow routing element models are linked together to make a total runoff simulation model. Hydrological modeling procedures are automatically processed by using functions of OHyMoS.

This paper is organized as follows. In section 2, a data structure and its format for representing channel networks are presented. In section 3, a method for building a hydrological simulation model for a large river basin based on the channel network data structure is shown. In section 4, some simulation results for the Chao Phraya River basin are presented. Finally, conclusions and further works are drawn in section 5.

2 DATA STRUCTURE AND FORMAT FOR CHANNEL NETWORK

The channel network of the Chao Phraya River is shown in Figure 1. To make the channel network data set, locations and connection relationships of river segments were derived from the DCW data sets. The GLOBE data sets were used to add elevation information of river segments to determine directions of water flow.

When a grid system is set over a watershed basin, the channel network data set is automatically separated according to the grid system and channel network

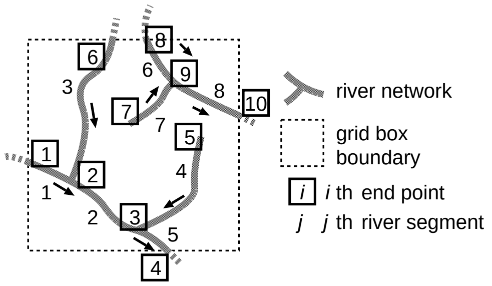


Figure 2: Schematic drawing of a channel network in a grid box.

data sets for each grid box are generated. For example, the Chao Phraya River basin is divided into grid boxes having $1/3 \times 1/3$ degrees as shown in Figure 1. Figure 2 shows an example of a grid box and Figure 3 is the data format of the channel network shown in Figure 2. The channel network structure is represented as combinations of river segments divided by endpoints composed of upper and lower ends of a channel network, confluences, and the intersections of a channel network and a grid box.

In an example of Figure 2, there are ten endpoints and eight river segments. In Figure 3, `[Map Number]` specifies relative locations of grid boxes. First column is the horizontal map number and second column is the vertical one. The `[Data]` section stores data of river segments. Each record has horizontal and vertical map number, endpoint number if the point is an endpoint (a negative value means that the endpoint is the lower end of the river segment), river segment number, identification number which specifies the location of the point within the grid box, the x, y and z coordinates of the point, and width of the point. If the value of the width is missing, zero is inputted.

```
[Comment]
This is a sample dataset.
[Data Format Name]
plain format V.2
[Coordinate System (map projection name)]
UTM 53
[Map Number (relative location of grid box)]
1 2
[Reference Coordinates (coordinates of origin)]
0.0 0.0
[Vertices of the Map (coordinates of corners of grid box)]
300.0 0.0
800.0 0.0
800.0 500.0
300.0 500.0
[Number of Endpoints]
10
[Data of Endpoints (coordinates of endpoints)]
1 300.0 210.0 345.0 4
2 400.0 170.0 330.0 0
3 550.0 60.0 425.0 0
4 330.0 0.0 365.0 1
5 710.0 270.0 369.0 0
6 500.0 500.0 382.0 3
7 550.0 300.0 410.0 0
8 580.0 500.0 403.0 3
9 640.0 400.0 397.0 0
10 800.0 320.0 381.0 2
[Number of River Segments]
8
[Data]
# river segment 1
1   2    1   1    4   300.0   210.0    345.0    0.0
1   2    0   1   -1   340.0   180.0   9999.0   10.0
1   2   -2   1    0   400.0   170.0    330.0    0.0
# river segment 2
1   2    2   2    0   400.0   170.0    330.0    0.0
1   2    0   2   -1   410.0   120.0   9999.0    0.0
1   2    0   2   -1   483.0    85.0   9999.0   12.0
1   2   -3   2    0   550.0    60.0    425.0    0.0
# river segment 5
1   2    3   5    0   550.0    60.0    425.0    0.0
1   2    0   5   -1   420.0    15.0   9999.0   15.0
1   2   -4   5    1   330.0     0.0    365.0    0.0
# river segment 3
1   2   -2   3    0   400.0   170.0    330.0    0.0
1   2    0   3   -1   410.0   200.0   9999.0   11.0
1   2    0   3   -1   450.0   320.0   9999.0    0.0
1   2    0   3   -1   475.0   470.0   9999.0    0.0
1   2    6   3    3   500.0   500.0    382.0    0.0
# river segment 4
1   2    5   4    0   510.0   270.0    369.0    0.0
1   2    0   4   -1   535.0   120.0   9999.0    7.0
1   2   -3   4    0   550.0    60.0    425.0    0.0
# river segment 7
1   2    7   7    0   550.0   300.0    410.0    0.0
1   2   -9   7    0   640.0   400.0    397.0    0.0
# river segment 6
1   2    8   6    0   580.0   500.0    403.0    0.0
1   2   -9   6    0   640.0   400.0    397.0    0.0
# river segment 8
1   2    9   8    0   640.0   400.0    397.0    0.0
1   2    0   8   -1   710.0   360.0    385.0    0.0
1   2  -10   8    2   800.0   320.0    381.0    0.0
```

Figure 3: An example of a channel network data set.

3 BUILDING OF MACRO SCALE DISTRIBUTED HYDROLOGICAL SIMULATION MODEL

For each grid box, a sub-model composed of a runoff element model and a flow routing element model is constructed. The runoff element model represents hydrological processes within a grid box, which computes discharge to the channel network within the grid box. The flow routing element model gets discharge from the runoff element model and river

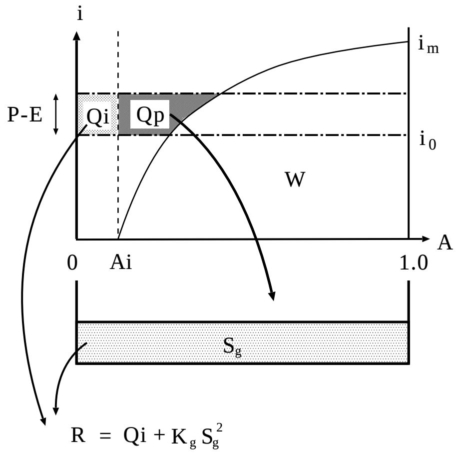


Figure 4: Schematic drawing of a simplified Xinanjiang model.

inflows from the upper reaches in the adjacent grid boxes, and it calculates river outflows to lower reaches within the adjacent grid boxes. When the channel network data set is separated into sub-network data sets for each grid box, connection relationships of sub-networks between grid boxes are also generated. By using the connection information, sub-models are linked together and simulated river discharges are passed through the sub-networks.

3.1 Hydrological process modeling within a grid box (runoff element modeling)

A simple hydrologic model (Nirupama *et al.*, 1996) based on the Xinanjiang model (Zhao, 1992) was used to model hydrological processes within a grid box, which takes into account a spatial distribution of soil water capacity.

As shown in Figure 4, runoff generation happens when the soil water storage reaches its capacity. The spatial distribution of soil water storage capacity i over a basin is defined as

$$i(A) = i_m \left\{ 1 - \left(1 - \frac{A - A_i}{1 - A_i} \right)^{1/b} \right\} \quad (1)$$

when $A_i \leq A \leq 1.0$. If $0 \leq A \leq A_i$, $i = 0$, where i_m is the maximum soil water storage height, A is the areal fraction of a basin which takes a value between 0 and 1, A_i is the impervious proportion of a basin, and b is a model parameter which determines the shape of the distribution of soil water storage capacity. From the impervious area runoff depth Q_i occurs, which is represented as

$$Q_i = A_i(P - E) \quad (2)$$

where P is precipitation, E is evapotranspiration. Runoff depth from the pervious area Q_p is given by the following equation when $i_m \leq i_o + P - E$,

$$Q_p = (P - E)(1 - A_i) - W_m + W \quad (3)$$

If $i_m \geq i_o + P - E$,

$$Q_p = (P - E)(1 - A_i) - W_m + W + W_m \left(1 - \frac{i_o + P - E}{i_m} \right)^{1+b} \quad (4)$$

where W is current soil water storage (in depth unit), i_0 is current storage height in unsaturated area, and W_m is the maximum water storage capacity over a basin (in depth unit) expressed as

$$W_m = \frac{i_m}{1 + b}(1 - A_i) \quad (5)$$

W is considered to be soil water storage which only contributes to evapotranspiration. Q_p is added to groundwater storage S_g and total runoff R is computed by

$$R = Q_i + k_g S_g^2 \quad (6)$$

Model parameters of the runoff element model are A_i, b, W_m and k_g.

3.2 Flow routing modeling within a grid box (flow routing element modeling)

To model flow routing within a grid box, the lumped stream kinematic wave model developed by Shiiba *et al.* (1996) was applied. The model computes discharges from outlets without calculating flows of each computational cross-section by setting the assumption that river discharge varies linearly along each river segment at each time step.

Let $q_0(t)$ be a discharge change rate in space along river segments in a grid box, then the discharge of the j th river segment at a distance x from its upper end is given by

$$Q_j(x,t) = Q_j(0,t) + q_0(t)x \tag{7}$$

where $Q_j(0,t)$ is the inflow at the upper end of the river segment. The cross-sectional area at x is given by

$$A_j(x,t) = K_j\{Q_j(0,t) + q_0(t)x\}^{P_j} \tag{8}$$

where K_j and P_j are constants, so the water storage in the river segments within the grid box is expressed as

$$S(t) = \sum_{j=1}^{N} \int_0^{L_j} A_j(x,t)dx \tag{9}$$

where N is the number of river segments within the grid box and L_j is the length of the j th river segment. $A_j(x,t)$ is a function of $q_0(t)$, so $S(t)$ is a function of $q_0(t)$.

The continuity equation of river flow in the grid box is

$$\frac{dS(t)}{dt} = \sum_{j=1}^{MI} I_j(t) + R(t) - \sum_{j=1}^{MO} O_j(t) \tag{10}$$

where $I_j(t)$ is inflow into the j th inlet of the grid box, $O_j(t)$ is outflow from the j th outlet, MI is the number of inlets, MO is the number of outlets, and $R(t)$ is discharge from the runoff element model. Here, the summation of outflows from the grid box can be written as

$$\sum_{j=1}^{MO} O_j(t) = \sum_{j=1}^{MI} I_j(t) + q_0(t)\sum_{j=1}^{N} L_j \tag{11}$$

Substituting Equation 11 into Equation 10

$$\frac{dS(t)}{dt} = R(t) - q_0(t)\sum_{j=1}^{N} L_j \tag{12}$$

is obtained. From Equations 9 and 12, the value of $q_0(t+\Delta t)$ is obtained and outflow discharges are calculated using $q_0(t+\Delta t)$ and Equation 11.

Model parameters of the flow routing element model are K and P for each river segment. We assume a wide rectangular cross section, so K is a function of Manning's roughness coefficient n and channel width B.

3.3 Building a total runoff simulation model

OHyMoS, Object-oriented Hydrological Modeling System (Takasao *et al.*, 1996, Ichikawa *et al.*, 2000) is designed to connect element models and build a total hydrological simulation model systematically by using object-oriented programming techniques. In OHyMoS, basic common functions such as giving model parameter values, initialization of computational variables, data exchanges between element models and setting computation time steps for each element model are implemented as functions of the abstract base class. It is possible to set different time steps for each element model depending on the rate of a hydrological response. The system automatically accumulates calculated values before they are passed from one element model to another element model and calculated values are transfered when the lower element model requests the values.

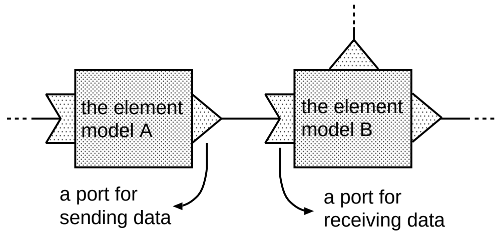


Figure 5: Data sending and receiving ports.

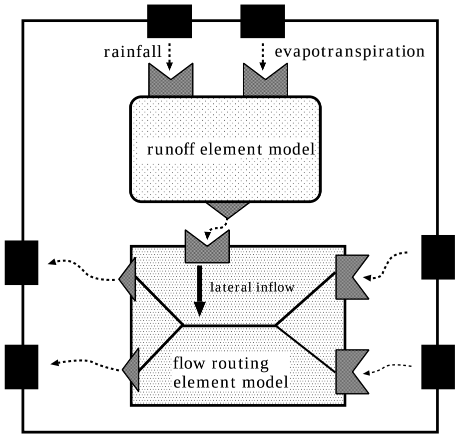


Figure 6: Structure of a sub-system model.

To use the functions of OHyMoS, a program code of an element model is made by using "inheritance" from the abstract base class. Each element model has a "data sending port" and a "data receiving port" through which computed values are sent or received. In Figure 5, the element model A sends data through a "data sending port" and B receives them through a "data receiving port". OHyMoS automatically controls data transfer according to the port connection relationships.

By using the functions of OHyMoS, rainfall-runoff processes within a grid box are modeled as a sub-system model shown in Figure 6. For each grid box, grid mean precipitation and evapotranspiration are inputted to the runoff element model through a "receiving data port", and discharge computed by the runoff element model is sent to the flow routing element model through a "sending data port". The flow routing element model receives the discharge from the runoff element model and inflows from the upstream flow routing element models in the adjacent grid boxes, and it computes the outflows to the downstream flow routing element models in the adjacent grid boxes.

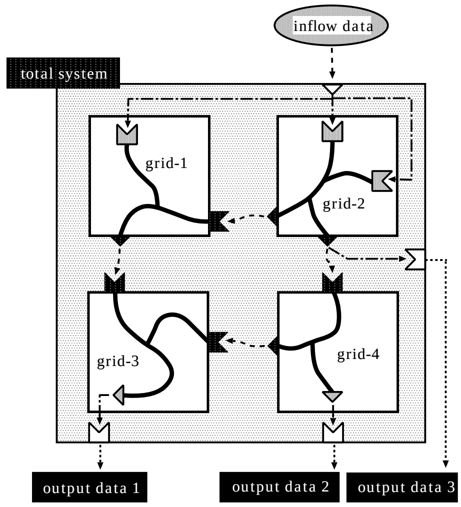


Figure 7: Connections of sub-system models to build up a total simulation model.

A total runoff simulation model is made up of the sub-system models. As shown in Figure 7, sub-models are linked together according to the channel network connection relationships to transfer the computed river discharge. When building the total simulation model, we do not need to consider the calculation order of the sub-system models be-

Table 1: Values of model parameters.

runoff element model			
A_i	b	W_m (mm)	kg (mm-s unit)
0.0	1.0	620.0	0.00011

flow routing element model		
B (m)	n (m-s unit)	P
100.0	0.05	0.6

cause OHyMoS controls accumulation and transfer of computed values and they are passed depending on the requests of the sub-system models.

4 APPLICATION AND DISCUSSION

The Chao Phraya River basin was divided into grid boxes with $1/3 \times 1/3$ degrees as shown in Figure 1. Table 1 shows the values of model parameters used in the element models. Model parameters were identified at the watershed having the P20 station(1,355km^2) and applied to all the element models. A reason to determine model parameters at the watershed is that its catchment area is nearly equal to the size of one grid box.

By using observed precipitation data, model performances were evaluated. Precipitation values given to each grid box were obtained by simply averaging the precipitation values observed within each grid box. There were no observed or simulated evapotranspiration data sets, so evapotranspiration values were determined from precipitation and discharge data sets and supposed to be the same value every day.

A simulation period is from April 1, 1987 to March 31, 1988. The basin average rainfall is shown in Figure 8. Some simulation results are shown from Figure 9 to Figure 12. The results at P19A station (Figure 9), N40 station (Figure 10) and Y3A station (Figure 11) show good agreement with the observed discharges. These discharge stations are located at the upper reaches of the Bhumiphol dam and the Sirikit dam. Simulations for other stations at upper reaches of the dams

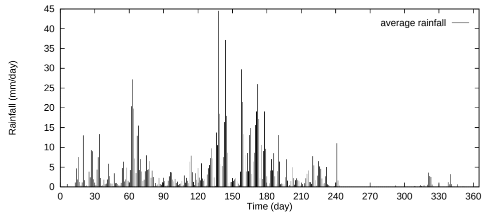


Figure 8: Basin average precipitation.

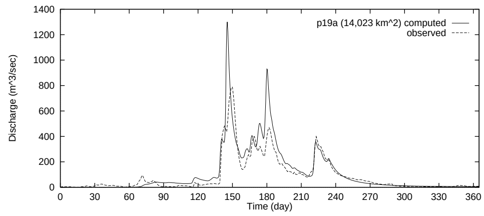


Figure 9: Simulated discharge at the P19A station.

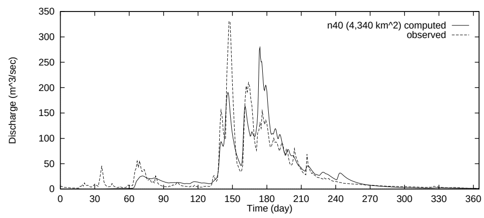


Figure 10: Simulated discharge at the N40 station.

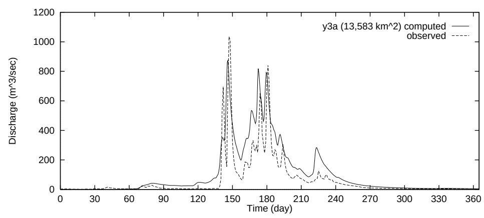


Figure 11: Simulated discharge at the Y3A station.

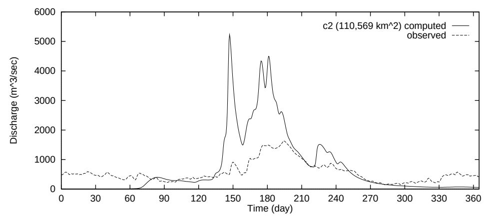


Figure 12: Simulated discharge at the C2 station.

also showed good results. However at the stations located at the lower reaches of the dams, there were significant differences between simulated discharges and observed ones. Figure 12 shows computed discharge at the outlet of the study area. This shows that dam controls give a great effect on a hydrological cycle.

5 CONCLUSIONS AND FURTHER WORKS

A macro scale distributed hydrological modeling system using OHyMoS was developed. When a channel network data set and grid information on a mesoscale atmospheric model are given, the system divides a watershed basin into grid boxes; a sub-model is set up for each grid box; and a total runoff simulation model is built by using functions of OHyMoS. The system was applied to the Chao Phraya River basin in Thailand (110,000 km^2) and a macro scale distributed hydrological model was constructed.

The simulation results showed good agreements with the observed discharges at the discharge stations along the upper reaches of the dams. The difference between simulated discharge and observed one at the lower reaches of dams suggests that it is quite important to incorporate the effect of dam control to the simulation system. The next version of the model will include the effect of human activities on a hydrological cycle, such as dam controls, reservoir regulations, water intakes for irrigation.

Acknowledgments : The hydrologic data used in this paper were obtained through the GAME-Tropics project. A part of this work has been supported by the Grants-in-Aid for Scientific Research, Nos. 10044156 (PI: Prof. S. Ikebuchi) and 11694141 (PI: Prof. K. Takeuchi) by the Ministry of Education, Science, Sports and Culture of Japanese Government (Monbusho).

REFERENCES

Ichikawa, Y., M. Shiiba, Y. Tachikawa and K. Takara, "Object-oriented hydrological modeling system", Submitted to HydroInformatics 2000.

Nirupama, Y. Tachikawa, M. Shiiba and T. Takasao, "A simple water balance model for a mesoscale catchment based on heterogeneous soil water storage capacity", Bulletin of Disaster Prevention Research Institute, Kyoto Univ., 45, pp. 61-83, 1996.

Shiiba, M., Y. Ichikawa, S. Ikebuchi, Y. Tachikawa and T. Takasao, "Scale-up of a runoff model using GIS and an object-oriented hydrological modeling system", IAHS Publ. 235, pp. 63–70, 1996.

Takasao, T., M. Shiiba and Y. Ichikawa, "A runoff simulation with structural hydrological modeling System", *Journal of Hydroscience and Hydraulic Engineering*, Japan Society of Civil Engineers, 14(2), pp. 47–55, 1996.

Zhao, R. J., "The Xinanjiang model applied in China", *Journal of Hydrology*, 135, pp. 371–381, 1992.