

An Integrated Simulation System of Meteorological and Hydrological Models for Predicting Dam Water Availability

*Ryohji Ohba¹, Adil Bushnak², Toshiharu Kojiri³, Tomonori Matsuura⁴
and Haruyasu Nagai⁵*

1. Mitsubishi Heavy Industries, Japan
2. Bushnak Water Group, Saudi Arabia
3. Kyoto University, Japan
4. National Research Institute for Earth
Science and Disaster Prevention, Japan
5. Japan Atomic Energy Research Agency, Japan

Abstract

A Japanese national project team has developed an integrated simulation system to evaluate regional water cycles. The system consists of numerical models of rainfall, water discharge and ground water. These models numerically simulate the time-dependent relevant phenomena based on the conservation of momentum, heat and water.

The simulated results of rainfall amount, discharged water and ground water depth near Jeddah and Abha, Saudi Arabia are discussed in the present paper.

Keyword: Water Cycle, Rainfall, Meteorology, Hydrology, Climate Change

Introduction

The Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT) initiated a project in 2002 titled “Refinement of Numerical Modeling and Technology for Prediction of Global and Regional Water Cycles” (Global Water Cycle Project, <http://www.kakushin21.jp/kyousei/>) as a part of the Project for the Sustainable Coexistence of Humans, Nature and the Earth. The project was conducted between 2002 and 2006. The purpose of the project was

to create a master plan for the improvement of desert environments. Specifically, the project aimed for the creation of sustainable water cycles among the sea, land and atmosphere in coastal deserts such as the Asir region near the Red Sea. As the main contractor of the project, Mitsubishi Heavy Industries (MHI) organized an interdisciplinary project team consisting of Frontier Research System for Global Change (FRSGC), Kyoto University, Tottori University and Sophia University (see Fig. 1-1).

One of the findings of the project is that the annual variability of the sea surface temperature distribution of the Indian and Pacific Oceans, the Indian Ocean Dipole (IOD), and the El Niño-Southern Oscillation (ENSO) have the dominant influence on rainfall patterns through global-scale atmospheric teleconnection (Behera et al., 2005). In addition, the interaction between disturbances propagating from the Mediterranean Sea and moisture originating from the Red Sea was found to affect the severe regional rainfall events in Makkah and Asir regions. We have named this interaction and the resulting rainfall events the “Arabian Cyclone” (Chakraborty et al., 2006).

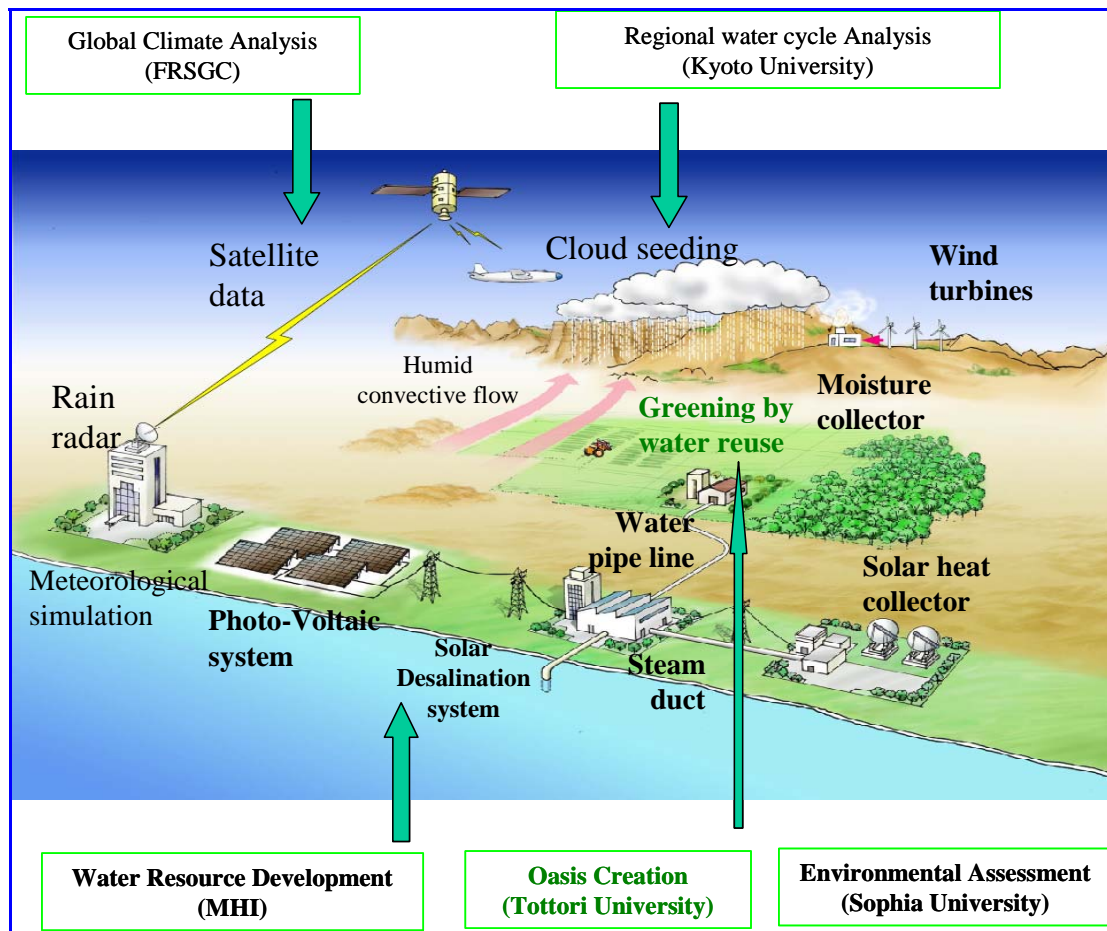


Fig. 1-1 Schematic of Global Water Cycle Project

In the Kingdom of Saudi Arabia, rainfall events are very rare and no river discharge data are available. Therefore, siting for a dam is a difficult task in this country.

The summary of the daily rainfall amount observed in Khamis Mushait (Fig. 1-2) shows:

- 1) Rainfall was observed only a few tens of days in spring, summer and winter.
- 2) Heavy rainfall occurs occasionally in spring and winter.

Khamis Mushait Rainfall during 2000

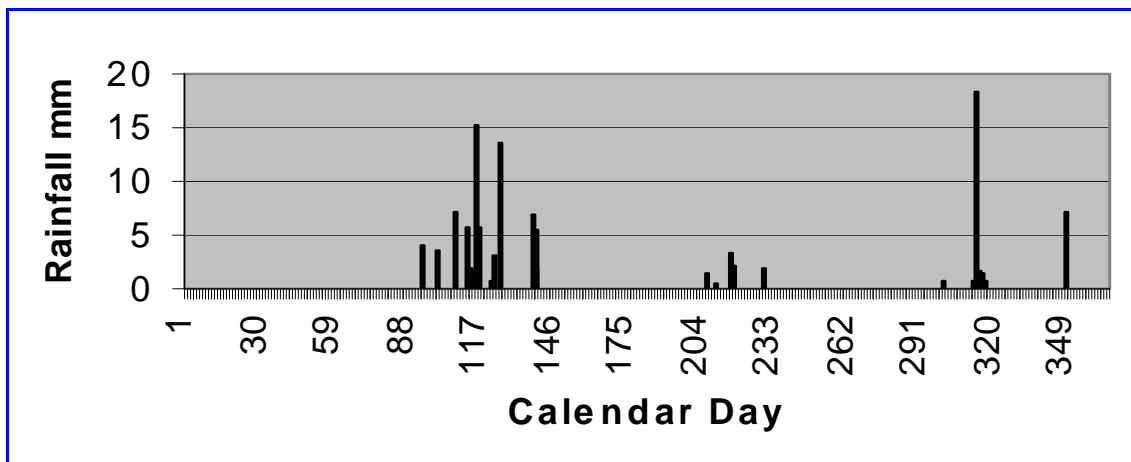
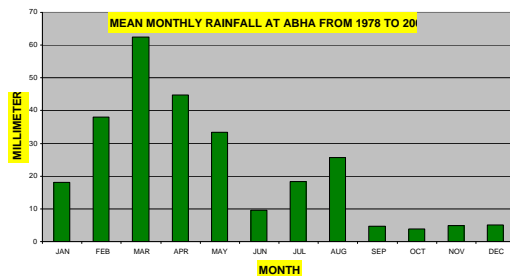


Fig. 1-2 Daily rainfall amount in Khamis Mushait in 2000

Comparisons of monthly rainfall between Abha and Khamis Mushait (Fig. 1-3) imply a heterogeneous spatial distribution of rainfall amount in the Asir region. The two cities are separated by approximately 30 km.

a) Abha



b) Khamis Mushait

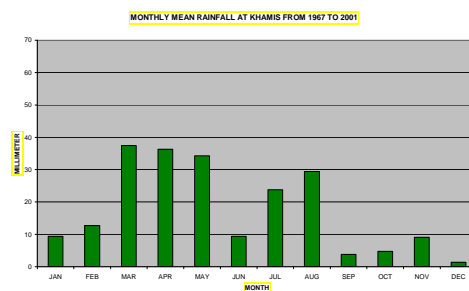


Fig. 1-3 Monthly rainfall averaged over approximately 30 years

There exist few meteorological observation sites in Saudi Arabia, and those that exist are situated mainly near big towns. Thus, meteorological

observations are sparse in the country. Accordingly, the use of meteorological data is limited for estimating the volume of water that can be stored in dams. Total annual rainfall can be as much as six times greater in high-rainfall years than in low-rainfall years (Fig. 1-4). This variability is attributable mainly to changes in the global-scale sea surface temperature distribution.

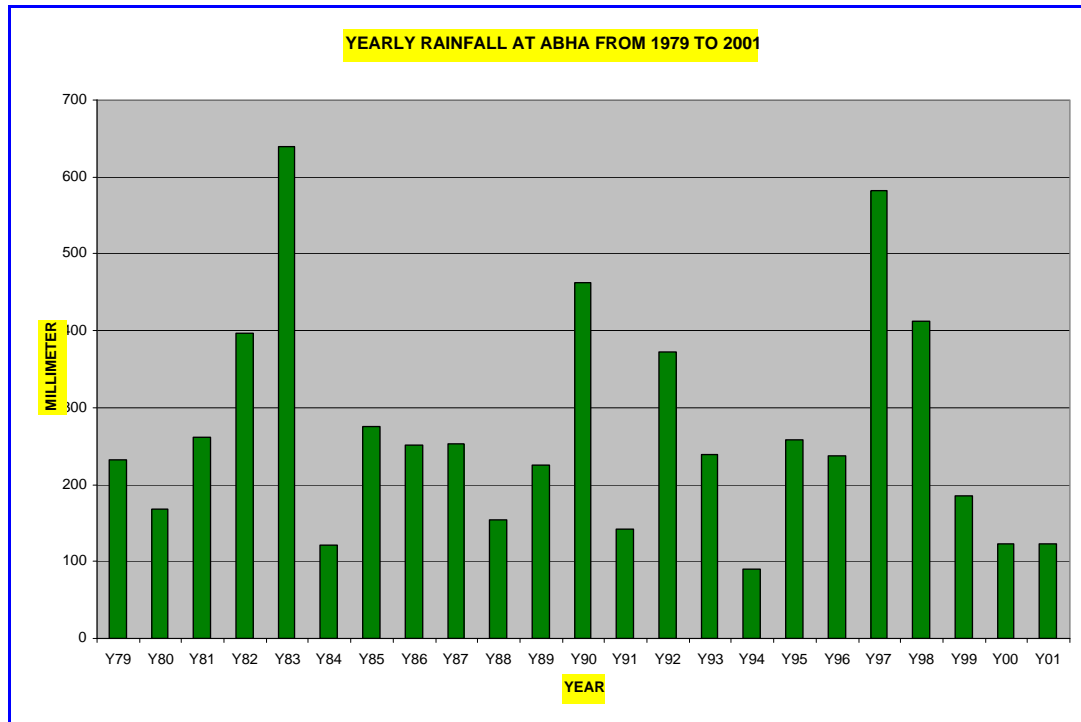


Fig. 1-4 Annual rainfall at Abha for 1979 – 2001

Based on simulation data, the IPCC (Intergovernmental Panel on Climate Change) predicted that year-to-year variation in rainfall amount will increase in the near future due to global warming (Fig. 1-5).

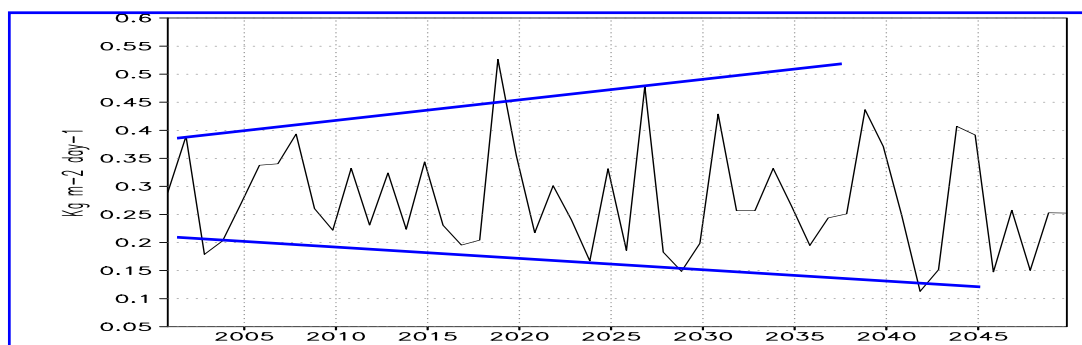


Fig. 1-5 Prediction of annual rainfall variation for 50 years with the influence of global warming (Ref.: the Canadian model, IPCC report)

2. Integrated simulation system (from rainfall to availability of dam water)

2.1 System components

The simulation system consists of simulation models for rainfall, water discharge and ground water. These models can numerically simulate the relevant phenomena continuously based on the conservation of momentum, heat and water (Fig. 2.1-1).

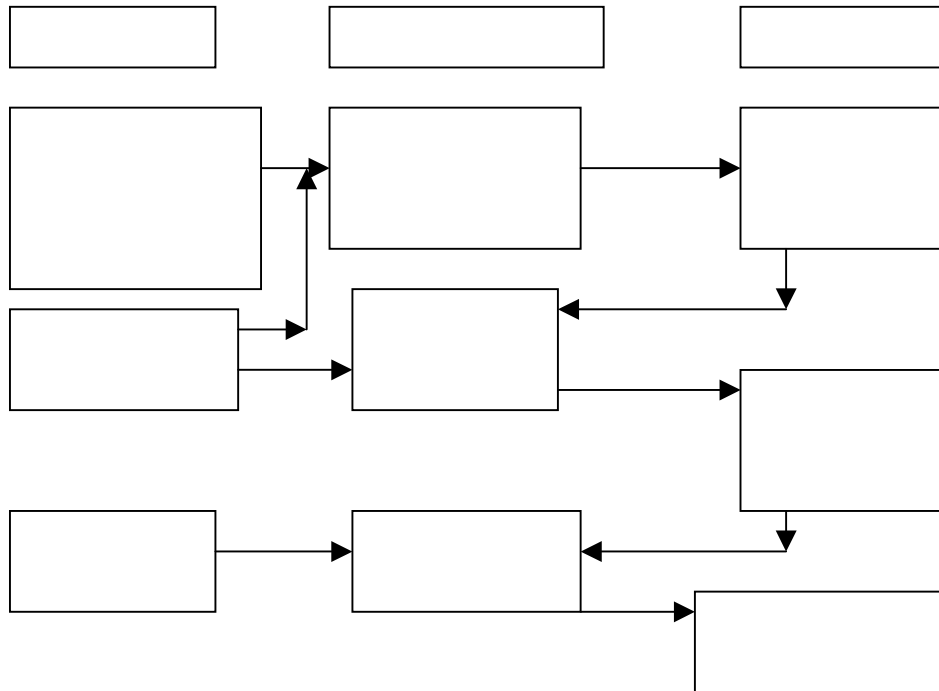


Fig. 2.1-1 Flow chart for the simulation of rainfall, discharged water and ground water distributions

2.2 Meteorological model

Meteorological models such as MM5 and RAMS can simulate meteorological variables including temperature, wind velocity, humidity and rainfall both in time and space. The mesh size of these models is as fine as approximately 1km (Ter Maat et al., 2006). As an example, Fig. 2.2-1 shows comparisons of satellite-observed and numerically simulated horizontal distributions of clouds.

a) Satellite Image by EUMETSAT



b) Numerical simulation by RAMS

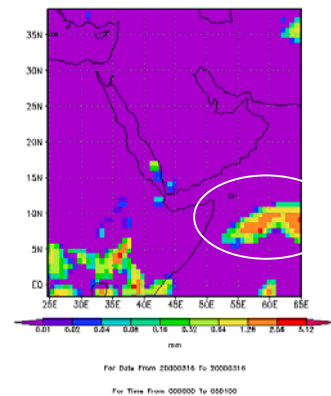


Fig. 2.2-1 Comparison of satellite-observed and simulated cloud distributions

The three-dimensional distributions of clouds and rain were simulated for observed events from 9 to 12 November 2000 (Fig. 2.2-2). This result shows increased rainfall on mountaintops in Ethiopia and the Asir region due to the topographical effect. Simulation of meteorological phenomena over a one-year period by the high-speed parallel computer, “Earth Simulator” of Japan requires computational time of approximately one month.

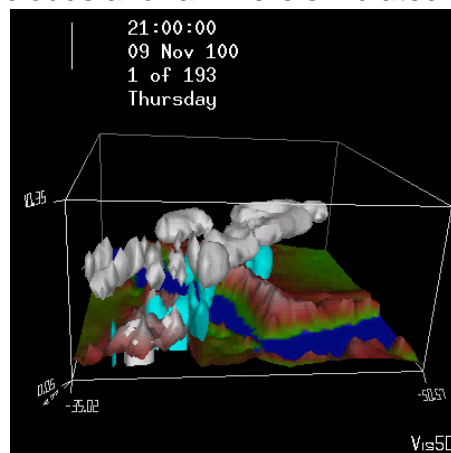
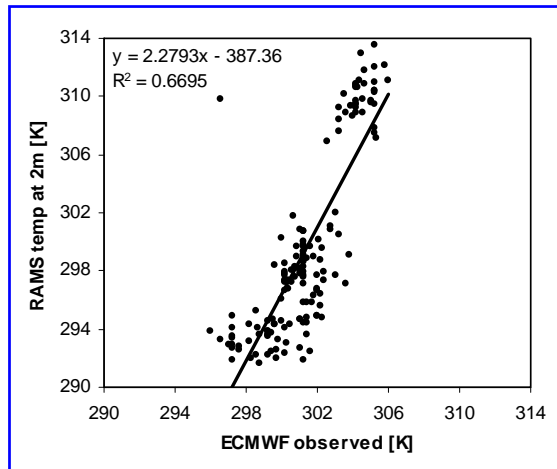


Fig. 2.2-2 Simulated results of cloud (white) and rainfall (blue) around the Red Sea in November 2000

Prediction accuracy of the Earth Simulator was evaluated using meteorological data for the Asir region (Fig. 2.2-3).

a) Temperature



b) Wind velocity

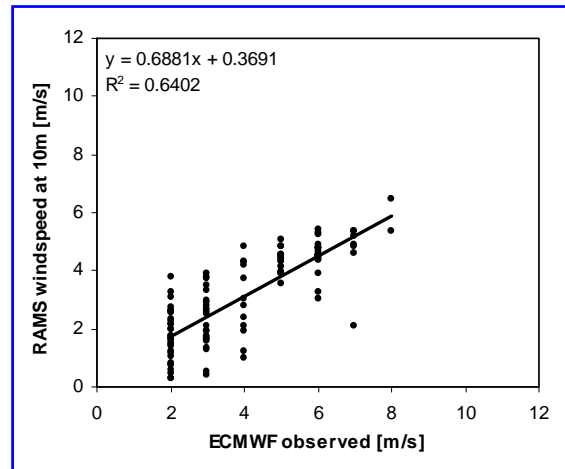


Fig. 2.2-3 Comparisons of hourly observations and simulation results by RAMS for Gizan between 21 February 2000 and 30 March 2000

Because of the significant spatial and temporal variation of rainfall, comparison of the rainfall amount simulated by a numerical model to that observed at one point in space is inherently limited. With the awareness of this limitation, the monthly values of rainfall observed in-situ are compared to those simulated by MM5 (Fig. 2.2-4). Fig. 2.2-4 also includes the monthly values of rainfall that were evaluated by TRMM satellite data over a square of a few kilometers (Ueda et al., 2005).

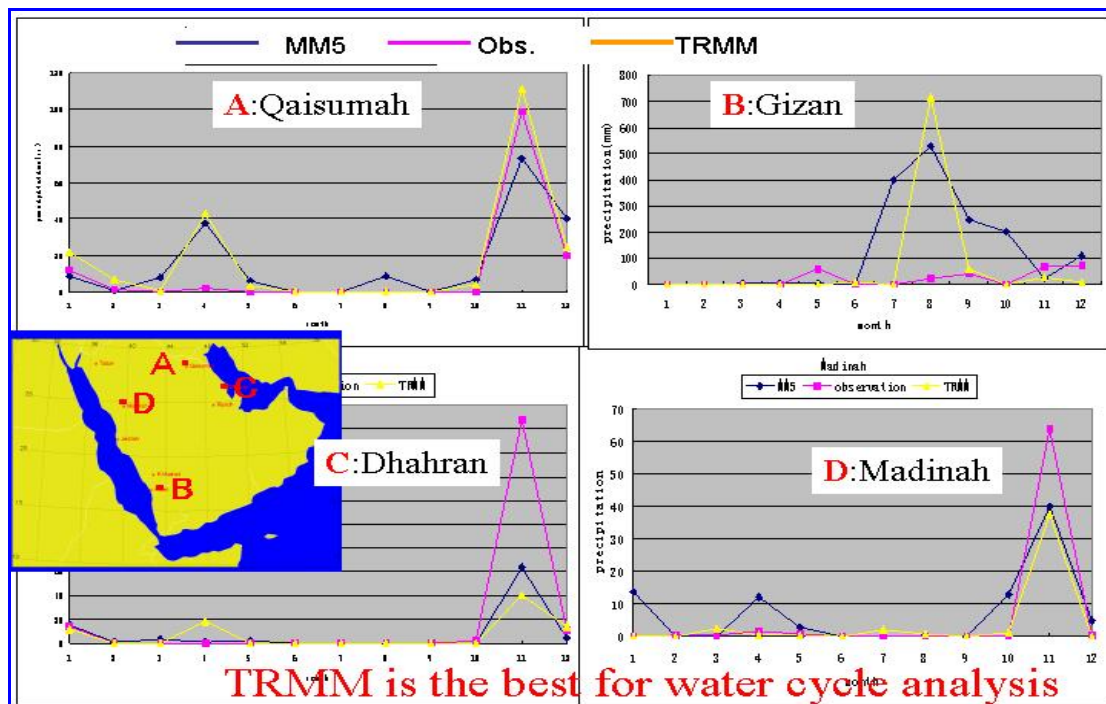


Fig.2.2-4 Comparisons of the monthly surface precipitation (blue: simulation by MM5, pink: in-situ observation, yellow: satellite observation by TRMM)

2.3 Hydrological model

Hydrological models can simulate the spatial and temporal patterns of water discharge due to rainfall. The simulation takes into consideration the effects of topography and ground condition within a mesh size as fine as 1km (Fig. 2.3-1). The simulated distribution pattern of rainfall is complex (Fig. 2.3-2) and was validated using satellite-based flood water data (Fig. 2.3-3).

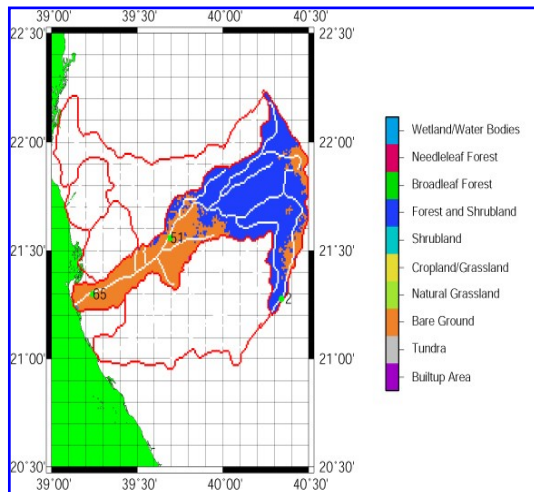


Fig. 2.3-1 Classification of surface types simulation

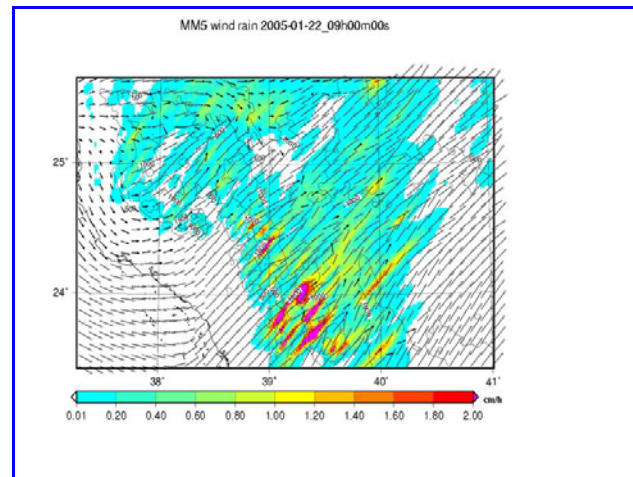
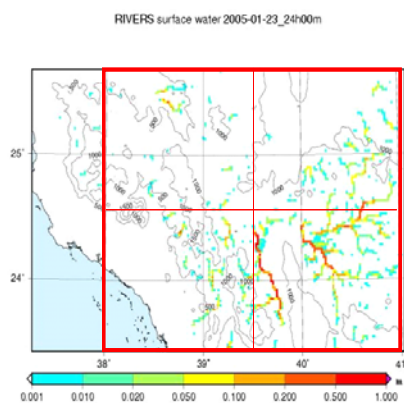


Fig.2.3-2 Simulated distribution of used for rainfall rate

a) Simulated results



b) Satellite-based observation

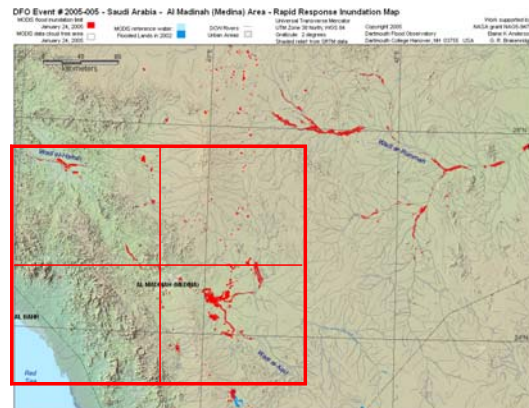
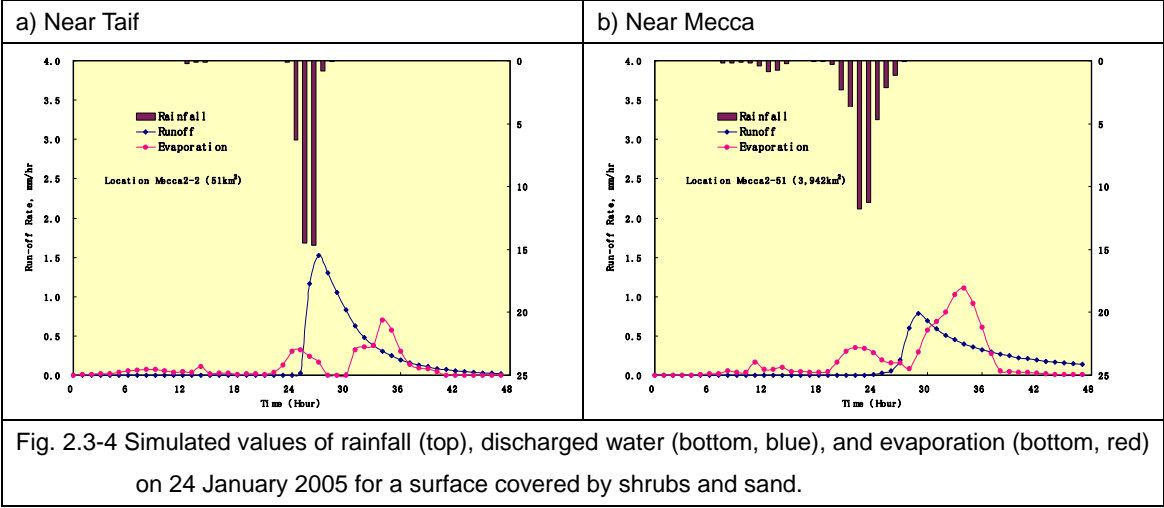


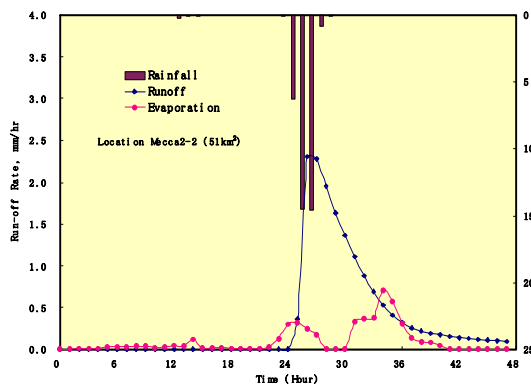
Fig. 2.3-3 Comparison between simulated and satellite-observed flood water distribution for 24 January 2005 (red squares outline the same region in both figures).

The volume of discharged water was calculated from the rainfall amount simulated by the meteorological model under three kinds of ground surface conditions: mix of sand and shrubs (Fig. 2.3-4), sand only (Fig. 2.3-5) and

shrubs only (Fig. 2.3-6). The volume of water available to a dam can be estimated by integrating the values of discharged water over a period of 1 year or longer.



a) Near Taif



b) Near Mecca

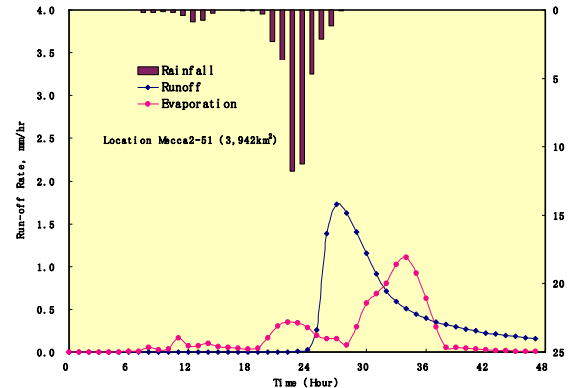
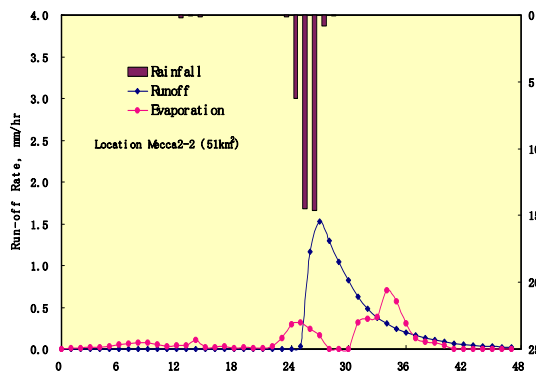


Fig. 2.3-5 Simulated values of rainfall (top), discharged water (bottom, blue), and evaporation (bottom, red) on 24 January 2005 for a surface covered entirely by sand

a) Near Taif



b) Near Mecca

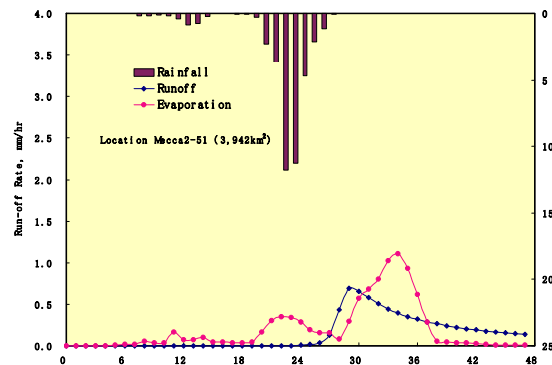


Fig. 2.3-6 Simulated values of rainfall (top), discharged water (bottom, blue), and evaporation (bottom, red) on 24 January 2005 for a surface covered entirely by shrubs.

The present simulation led to the following findings:

- 1) The rate of water discharge was small for the shrub-covered surface, attributable to the high water retentivity of the shrubs.
- 2) The rate of water discharge was higher in Taif than in Mecca because of the larger rainfall in Taif than in Mecca.

2.4 Ground water model

Conventional lumped models are based on the rainfall and river water amounts observed at limited locations and times. The present ground water model can simulate the temporal and spatial variations of ground water depth, storage in dams, and recharge by rainfall. The mesh size of the model is

approximately 1 km (Nawahda et al., 2004). The schematic of this simulation is shown in Fig. 2.4-1.

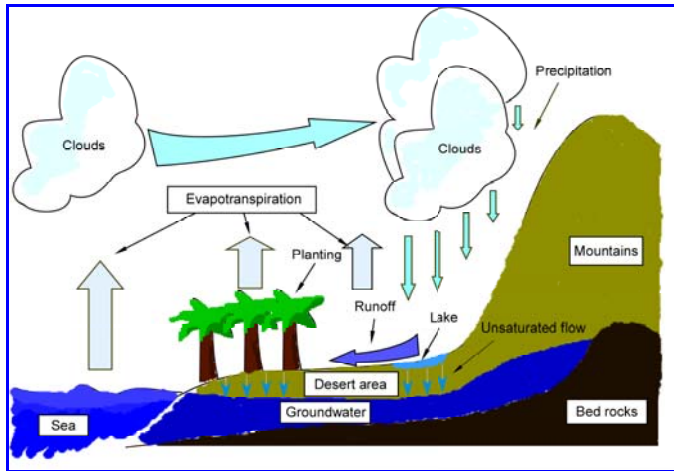
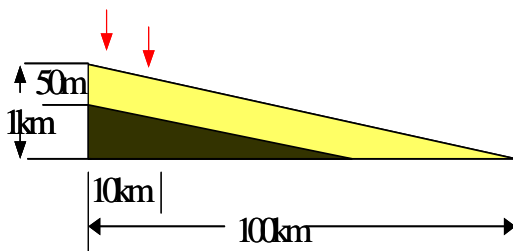


Fig.2.4-1 Overview of the ground water model

The ground water depth was simulated using topographical and rainfall conditions similar to those of the Asir region. The simulation was performed with the following assumptions: 1) a filtration layer existed to a depth of 50 m below the ground surface along the slope of the Asir Mountains; 2) rainfall of 24 mm/day occurred within the area 10 km from the mountain tops (Fig. 2.4-2a) on the first day of January, March, October and December; 3) The initial value of the ground water depth was 5m from the bottom of the filtration layer.

The preliminary simulation results show that the ground water depth in the rainy area near the top of the mountains increases with the rainfall of each month (Fig. 2.4-2b). However, it takes more than one year for the ground water to penetrate into the lower altitudes along the surface layer of the mountain slopes.

a) Topography and rainfall condition



b) Ground water depth

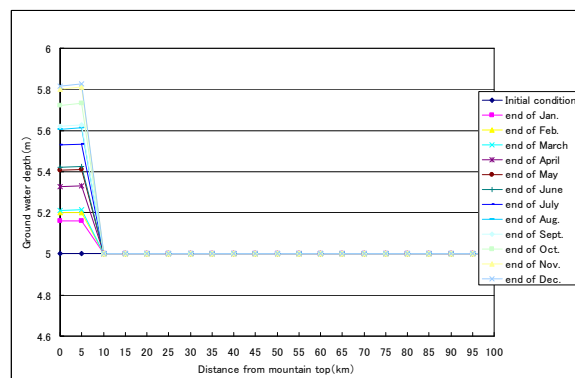


Fig. 2.4-2 Simulation of the ground water depth with the assumption of 24 mm/day on the first day of January, March, October and December near the tops of the Asir Mountain

Conclusions

The conclusions of the present study can be summarized as follows:

- 1) Meteorological models such as MM5 and RAMS can accurately simulate meteorological conditions including temperature, wind velocity, humidity, and rainfall in time and space.
- 2) Hydrological models can accurately simulate water discharge due to rainfall in time and space by taking into consideration the effects of topography and ground surface conditions.
- 3) The volume of water available at a dam can be estimated over a one-year period or longer, using the integrated simulation system of meteorological, hydrological and ground water models.

Acknowledgment

This work was conducted as a Japanese national project titled Global Water Cycle Project, sponsored by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT).

References

- 1) Behera, S. K., J. J. Luo, S. Masson, S. A. Rao, H. Sakuma, and T. Yamagata, 2005: A CGCM study on the interaction between IOD and ENSO, J. Climate (accepted).
- 2) Chakraborty, A., S. K. Behera, M. Mujumdar, R. Ohba, and T. Yamagata, 2006: Diagnosis of tropospheric moisture over Saudi Arabia and influences of IOD and ENSO, Mon. Wea. Rev. (in press).
- 3) Nawahda, A., T. Kojiri, and S. Ikebuchi, 2004: Distributed runoff model linking surface with groundwater processes, Annuals of the Disaster Prevention Research Institute, Kyoto University, No.47C
- 4) Ter Maat, H. W., R. W. A. Hutjes, R. Ohba, H. Ueda, B. Bisselink, and T. Bauer, 2006: Meteorological impact assessment of possible large scale irrigation in Southwest Saudi Arabia, Global and Planetary Change
- 5) Ueda, H., et al. 2005: Meteorological simulation for the improvement of environment by greening of desert, Second Oman-Japan Symposium: Preservation of Environmental and Water Resources amid Economic Development