Decision Support System for Surface Water Planning in River Basins

By K. Ito,[1] Z. X. Xu,[2] K. Jinno,[3] T. Kojiri,[4] and A. Kawamura[5]

Abstract: A decision support system (DSS) for the integration of hydrologic process modeling and risk evaluation of the surface water management alternatives in a river basin is developed. The DSS, named CTIWM, is aimed at supporting the testing and evaluation of water management policies and at facilitating integration of user-selected scenarios into planning strategies of the water resource system in the Chikugo River basin, a multipurpose multireservoir system. CTIWM uses a module library that contains compatible modules for simulating a variety of hydrologic processes. Different numerical models are invoked through a user interface menu, which facilitates communications between users and models in a friendly way. The source code was developed by using object-oriented programming techniques. The result shows that the use of DSSs may effectively improve the speed and quality of water management and give users more flexibility in analyzing different scenarios.

INTRODUCTION

Over the past centuries, global industrialization has led to the worldwide construction of reservoirs with different scales. With increasing water demand, the conflicts related to the operation of these hydraulic structures have dramatically increased during the past several decades. These conflicts have forced water managers to develop new management policies to achieve acceptable conflict resolution. Since the 1980s, with increased pressure on natural resources and growing awareness of environmental issues, the focus of water resources development has shifted toward integrated water management, where ensuring safe water supply and keeping water resources sustainable are the primary goals.

The aim of water resources planning and operation is to provide the necessary water supply with the required reliability to meet the customer's needs (Jamieson and Fedra 1996b). Because of the complexity of water resource systems, integrated water management in river basins is costly and time-consuming. Recently, new advances in computer technology have enabled widespread improvement in water resources planning and management. One of the new trends in the solution of water management problems has been to aggregate several models into an integrated software—a decision support system (DSS)—that focuses on the interaction between the user and the data, models, and computers (Davis et al. 1991; Andreu et al. 1996; Fredericks et al. 1998). DSSs for the study of water resources problems began to appear in the mid-1970s and have been widely discussed in the literature since the mid-1980s (Stansbury et al. 1991; Ford and Killen 1995; Dunn et al. 1996; Jamieson and Fedra 1996a,b; Reitsma 1996; Arumugam and Mohan 1997). Rapidly advancing computational ability, development of user-friendly software and operating systems, and increased access to and familiarity with computers among decision makers are the important reasons for this growth in the fields of both research and practice.

During the past several years, typical basinwide water resources management DSS developed by hydrologists include IRAS (Interactive River-Aquifer Simulation), RiverWare, TERRA (TVA Environment and River Resource Aid), NELUP (NERC-ESRC Land-Use Programme) DSS, DESERT (DEcision Support system for Evaluation of River basin sTrategies), AQUATOOL, Nile Basin Management, and WaterWare (Andreu et al. 1996; Dunn et al. 1996; Fedra and Jamieson 1996; Jamieson and Fedra 1996a,b). Most of those are generalized DSS software or packages and are flexible for application to different river basins. However, they are often not sufficient to accurately represent the site-specific features of river basins and the changing multiple objectives of the practical management scenarios because of the complex characteristics of catchments. To provide a site-specific modeling tool that can be applied to the Chikugo River basin for water resources planning applications, a site-specific DSS was developed by using the object-oriented programming techniques in this study. The feasibility of the DSS approach in basinwide water management is demonstrated by using a case study. The DSS, named CTIWM (CTI Water Management), was originally designed for assisting decision making in the planning of a complex river basin including multiple reservoirs, weirs, and water demand sectors. One of the aims of the CTIWM is to allow water managers direct access to the models through the graphical user interface. As the case study shows, the CTIWM model component, in association with the database contained within the system, provides a relatively straightforward procedure for analyzing the potential impacts of different water resources management policies on both the regional and the basinwide scale.

RIVER BASIN DESCRIPTION AND PROBLEM STATEMENT

Study Area Description

The Chikugo is the fourth largest river in Japan. The river basin is located in Kyushu region, an island in Southern Japan, and has a catchment area of 2,860 km^2. The basin stretches 143 km from the Asogairin Mountain to the Ariake Sea. Major tributaries include the Kusu, Takase, Hanatuki, Ogoe, Kumanoue, Sada, Koishibaru, Kose, Takara, Houman, Tuetate, Tsue, Shirobaru, and Akaishi rivers. Land use varies from farmland to the highly urbanized industrial districts. The basin climate is subtropical humid, with an average annual rainfall of 2,000 mm. About 40% of the rainfall is received during the rainy season, from June to July, and another 25% falls during the typhoon season, from August to September.

Over the past several decades, the demand for water has dramatically increased as a result of population growth and

[1]Chief Engr., Dept. of Water Resour., CTI Engineering Co. Ltd., Tokyo 103, Japan.
[2]Sr. Res., R&D Headquarters, CTI Engineering Co. Ltd., Tokyo 103, Japan; presently, Dept. of Civ. and Envir. Engrg., Yamanashi Univ., Kofu 400-8511, Japan (corresponding author).
[3]Prof., Inst. of Envir. Sys., Kyushu Univ., Fukuoka 812, Japan.
[4]Prof., Disaster Prevention Res. Inst., Kyoto Univ., Kyoto 611, Japan.
[5]Assoc. Prof., Inst. of Envir. Sys., Kyushu Univ., Fukuoka 812, Japan.
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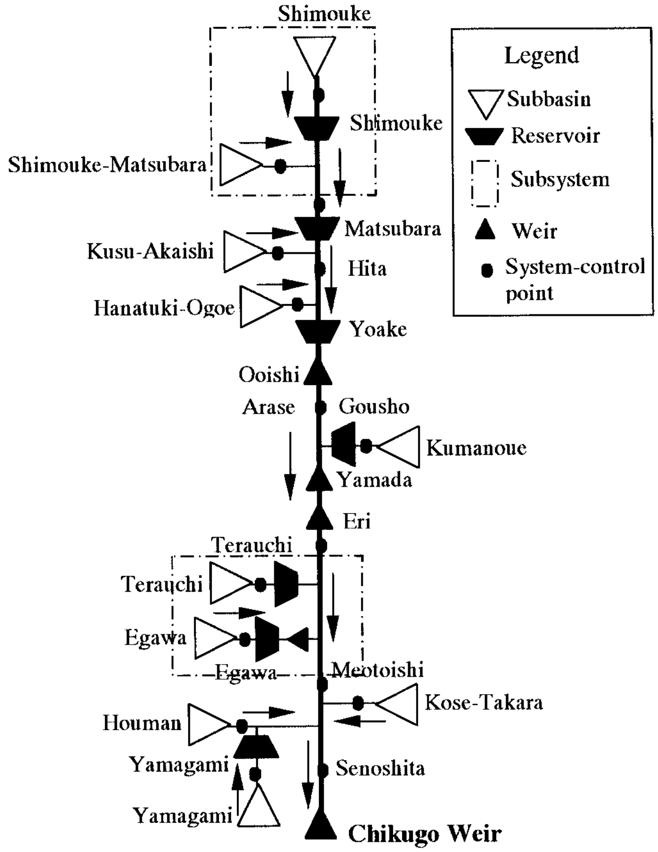

FIG. 1. Schematic Diagram of Chikugo River Basin

urbanization in the Chikugo River basin. The high demand for surface water and large seasonal variability of precipitation have led to the construction of reservoirs. Fig. 1 shows the existing reservoir and weir system, which includes the Shimouke, Matsubara, Terauchi, Egawa, Yoake, Gousho, and Yamagami reservoirs and five weirs. The Chikugo weir, which lies 23 km from the river outlet, plays an important role for the water supply at the downstream area of the river basin. It has a total storage of 5.5×10^6 m^3 and supplies 390,000 m^3 drinking water/day under water rights for Fukuoka and Saka prefectures and supplies necessary irrigation water during the drought season for these two prefectures.

Problem Statement

In the Chikugo River, water is used mainly for supplying agriculture, municipalities, and industries. In addition, hydroelectric power is produced and flood control is a concern in the basin. A water transfer to the neighboring areas exists as well. Over the past several decades, growing industrial and urban development in the Chikugo River basin has placed severe demands on available water supplies. The main water resources management problem in the Chikugo River basin is to meet the continuing increase in demand without adversely affecting the natural environment. Presently the estimated water demand is 46.0×10^6 m^3/month to supply agricultural (56.5%), industrial (15.3%), and domestic water needs (28.2%). Besides this water demand, a minimum downstream release also must be maintained to avoid the intrusion of saltwater into the estuary during dry season. The rational operation for these reservoirs and weirs and the integrated water resources management within objectives such as hydropower generation, water supply, and water quality in the Chikugo River basin have received special attention from government officials and the public for many years. However, integrated water management of this multireservoir system is by no means an easy task because the uncertain inflow and reservoir storage must be allocated for multiple purposes.

Planning decision on integrated water resources management refers to the complex decisions made by reservoir and power plant operators and refers to the activities within a set of rules, regulations, and standards. Automating the process with a DSS could effectively improve the surface water resources management in the Chikugo River basin. This is also the target of this study. The CTIWM is designed as a computer-aided tool for developing improved basinwide and regional strategies for river management, reservoir operation, and drought contingency planning. The DSS permits basinwide forecasts of streamflow and water demand and ideally will lead to improved reservoir operation.

CTIWM DESIGN AND MODULE DEVELOPMENT

CTIWM Design

The CTIWM DSS has been developed to organize the immense volume of data, to support the modeling effort, and to prepare output of model results. Its main functions include (1) retrieve and process rainfall, water demand, and streamflow data; (2) estimate basin average rainfall and forecast runoff; (3) simulate reservoir operation; (4) estimate water demand; (5) forecast regulated flows basinwide; and (6) perform risk analysis for short- and medium-term planning to decide, for instance, the appropriate time to apply restrictions and the extent of water supply. The utility of the CTIWM may be summarized under three headings:

- Description: A wide variety of temporal and relational data, describing the characteristics of the river basin, are stored in the system. These data can be employed and manipulated by means of a user interface.
- Forecast: A range of models is developed within the CTIWM that can perform the simulation of the river basin under a wide range of scenarios. These models may be executed through the integration of models, database, and user interface.
- Presentation: The system provides concise, visual statements in the graphical and tabular form of model results to illustrate the consequences of different water resources management strategies.

A careful review of the available hardware and software technology was made. Several mainframe- and minicomputer-based shells and computer languages were examined but rejected because of high expense, low flexibility, and lack of the required modeling capability. It was decided to use a personal computer because it offers great flexibility, high potential for system growth and expansion, ease of use, and much lower costs. The Microsoft Visual C++ and Fortran PowerStation were chosen because mixed-language programming is possible between these two languages, i.e., Fortran object modules and libraries created with Fortran PowerStation can easily be linked into C++ programs. This functionality provides very useful benefits, making it possible to call the model coded in Fortran from the menu and dialog items developed by using C++, and many existing Fortran codes presently used can be easily incorporated into the CTIWM system. Because this environment is object-oriented, new models will easily be incorporated into the existing CTIWM and the models included in the CTIWM can easily be modified if necessary. The disadvantage for doing so is that much effort is required for developing the user interface and database in comparison with using an existing shell or software.

CTIWM Module Development

Menus and options in each section of the CTIWM allow the user to perform either model-execution or data-display operations. The subsections of it include Drought, Flood, and Quality. The suboptions under the Model option in each subsection control the simulation and risk assessment models. In the same manner, the Input option allows the user to input the data available and the Output option allows the user to access the graphical analysis of simulation results. The option Help provides an on-line help facility when using the system. The classes Input, Model, and Output are composed of different subclasses. For example, Reservoir is a subclass of Input in which the attributes include variables for storage, release, industrial water supply, and domestic water supply and the corresponding objects include Egawa-Reservoir, Terauchi-Reservoir, and Shimouke-Reservoir. Each object or reservoir is described using values of various attributes.

The CTIWM is designed with a range of simulation capabilities as well as data input and output analysis functionality. The user is first asked to select purposes: drought, flood, or water quality. Then the user needs to input necessary data: rainfall, water demand, reservoir storage, etc. Input can be made from the keyboard, and lengthy sets of time series data for streamflows and demands can be inputted by means of text files with the same label as the object. Moreover, the data input, including any modification, is under the surveillance of a knowledge base built into the system, which warns the user when abnormal data values are entered in addition to checking the hydrologic consistency of the scheme. This is of great help in avoiding errors in the execution of the models.

Once the data are imported, the CTIWM model can be executed from the interface. Model subclasses include Simulation, Quality, and Risk, and the corresponding objects include AR-Model, ARMA-Model, ARMAX-Model, Tank-Model, and LP-Model. With the Output, users can plot both observed and forecasted data on the screen or with a printer. A graphical module has been developed in the CTIWM. It allows the user to obtain graphical representation of the results, for each result of the simulation, in the form of either time series or mean monthly values. Both tables and graphs can be printed immediately at the touch of a button on the graphical interface.

APPLICATION EXAMPLE: RISK ANALYSIS FOR WATER SUPPLY

Water Supply System Description

During the past several decades, Kyushu Island has experienced dramatic urbanization and industrialization. The Fukuoka region, the political and cultural center on Kyushu Island, recently has experienced serious water shortages. As the nearest large water source, the Chikugo River is the major water source for the cities of both Fukuoka and Dazaifu. They withdraw water from the river at Egawa Reservoir, Terauchi Reservoir, and the Chikugo weir. From the intake at the Chikugo weir, Fukuoka and Dazaifu withdraw 139,800 and 6,700 m^3 water/day from the Chikugo River under an entitled agreement, fulfilling 33 and 41.6%, respectively, of the cities' domestic water demands. Several serious droughts occurred in both cities during the past decade. In the city of Fukuoka, the most recent drought started in July 1994, during which the water restriction continued for 330 days. The other serious drought began in September 1992 and continued for 5 months. The complex task of water resources management is the responsibility of the local water authorities, who supervise the daily distribution of water in accordance with water-right priorities and intercity compacts.

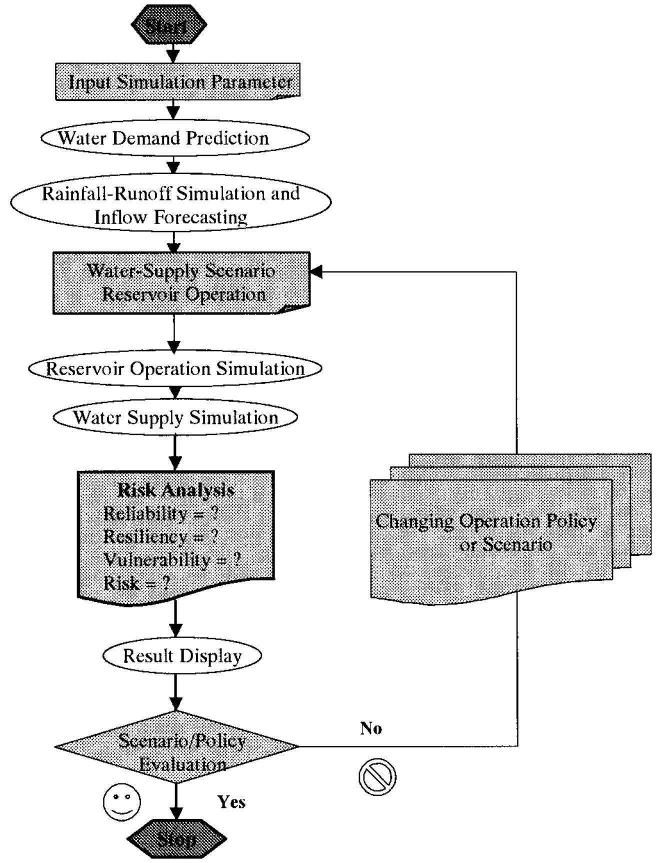

FIG. 2. Flowchart of Risk Analysis for Water Supply

Risk Analysis for Water Supply System

The CTIWM is an integrated software that has several functions to assist water resource planning in the Chikugo River basin. One of these functions is the risk analysis for subbasins or water supply regions. As one example of the applications, this section uses CTIWM to analyze the water supply risk for the cities of Fukuoka and Dazaifu. As shown in Fig. 2, the risk of water supply is estimated according to the following steps: (1) retrieve available rainfall observations from the database; (2) forecast water demand using time series models corresponding to different strategies; (3) estimate average rainfall hyetograph for each subbasin; (4) forecast inflow hydrograph and simulate the daily operations of reservoirs and weirs; (5) estimate water supply available at various sources; and (6) execute risk models to estimate reliability, resiliency, vulnerability, and an integrated risk index using the results of Steps 2 and 5 (Jinno et al. 1995).

During the development of a DSS, a commonly asked question is, Who will be the user of the system? The study presented in this technical note has received attention from local water authorities. However, the planning and operation of the Chikugo River were jointly made by several organizations presently. No single office is responsible for the basinwide management. Because the CTIWM has not yet been adopted by users as designed, results of its practical performance cannot be reported nowadays. Application was made with historical data and the use of the CTIWM is described with a subsystem of the Chikugo River system in this technical note.

Risk Analysis Example

The 1992 drought was a serious water shortage event for the Fukuoka region. As part of the risk analysis results, Fig. 3 presents the risk for the drought that occurred in the city of Fukuoka in 1992. It simulates the reservoir operations under

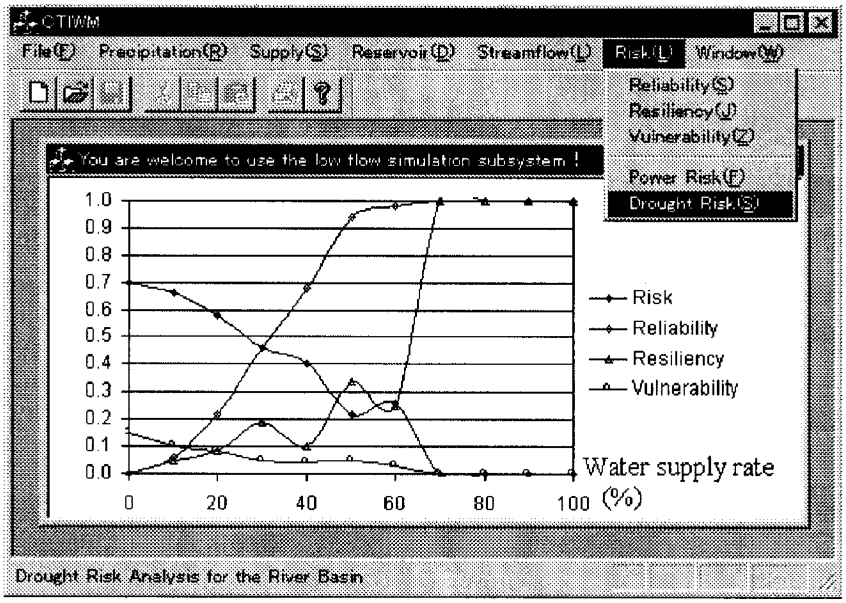

FIG. 3. Risk Analysis for Water Supply in City of Fukuoka

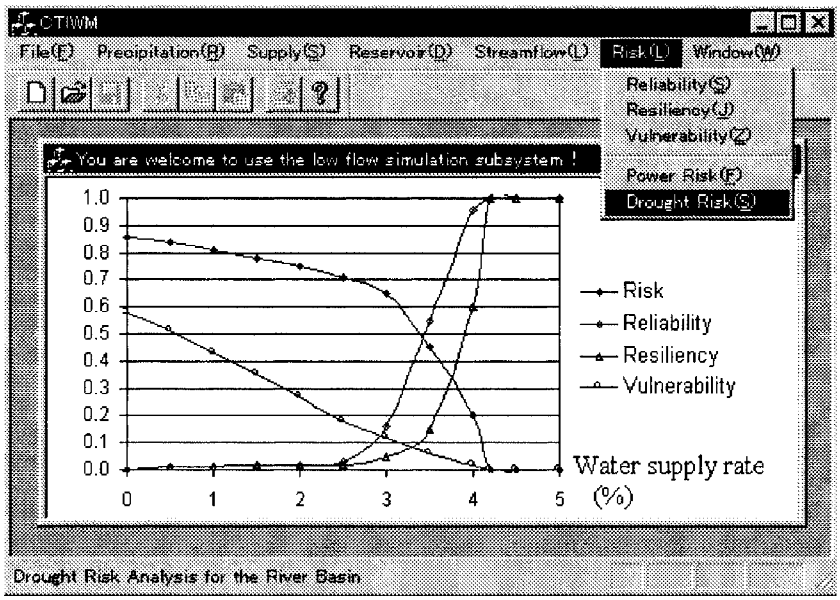

FIG. 4. Risk Analysis for Water Supply in City of Dazaifu

conventional operating policy and the water supply to the city for different water supply rates under water-right priorities. The water supply rate means the ratio of water transfer from the Chikugo River to the simulated areas. It predicts that, if reservoirs are operated perfectly, the water supply in the city of Fukuoka may decrease to zero even if only 70% of the predetermined water is withdrawn from the intake at the Chikugo weir. That means the water supplied to Fukuoka may be reduced by 7,000–12,000 m^3 and transferred to other cities or small communities without effect on the water supply in Fukuoka, but with dramatic decreases in the damage due to the water shortages in other cities. For example, the city of Dazaifu has the right to withdraw 6,700 m^3 water/day from the intake at the Chikugo weir. This quantity of water is actually only about 3.7% of the amount withdrawn from the intake at the Chikugo weir by the Fukuoka region. Fig. 4 shows the risk results under conventional operation in the city of Dazaifu. It can be seen that, if the water taken from the intake at the Chikugo weir increases by 0.7%, from 3.7 to 4.4%, the risk due to the water shortage in Dazaifu may decrease to zero. In other words, during the 1994 drought, if the city of Fukuoka had transferred 1% of its water right to the city of Dazaifu, Dazaifu would have had no shortage of water and that transfer would have had no effect on the water supply in Fukuoka.

CONCLUSIONS AND FUTURE WORK

The DSS technique holds great potential for better applications in integrated water management of river basins. The CTIWM may be used to assist managers in the simulation and evaluation of water management strategies. The example application for water supply risk analysis in the Fukuoka region shows that the CTIWM may improve the integrated surface water management in river basins by automating the time-consuming simulation task. Incorporated models allow a wide range of potential management scenarios to be simulated and evaluated, providing managers with the ability to develop and test alternative water resources management strategies.

Recently, the fast growth of geographic information systems has opened the door for DSS developers to take an active role in the processing of spatially distributed databases. The closer integration of geographic information systems with existing

DSS techniques will provide insight into water resources management within a spatial context, thereby enhancing integrated water resources management. As one area of future development, CTIWM will be improved so as to be able to quickly process this kind of distributed hydrologic data.

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