AREAL MODELLING IN HYDROLOGY USING REMOTE SENSING DATA AND GEOGRAPHICAL INFORMATION SYSTEM

by F. Yoshino

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Cover: The figure is based on the SHE model (after Abbot et al., 1986)

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FOREWORD

Remote sensing and modelling techniques are advancing at a rapid pace and so are their applications to the science of hydrology. Recognizing the value of continuing its activities in the field of hydrological modelling, the Commission for Hydrology at its ninth session in 1993 appointed Mr F. Yoshino (Japan) as Rapporteur on Areal Modelling and Hydrological Forecasting. The Commission requested him "to evaluate and report on directions being taken and to be taken with regard to modelling to capitalize on the higher resolutions in time and space of data from automated surface sensors, remote sensors, and Geographical Information Systems (GIS)".

In 1996, at its tenth session, the Commission for Hydrology examined the report on this subject, prepared by Mr Yoshino with the assistance of Messrs M. Shiiba, K. Takara and T. Oki (Japan), and decided that it should be published in the World Meteorological Organization (WMO) Operational Hydrology Report Series.

It is with great pleasure that I express WMO's gratitude to Mr Yoshino and to those of his colleagues who contributed to this excellent report on a very complex subject.

(G.O.P. Obasi)
Secretary-General
SUMMARY

This report is concerned with areal modelling using newly developed techniques of remote sensing and Geographical Information Systems (GIS).

Hydrological processes vary spatially and temporally in the hydrological cycle. Traditionally, modelling of hydrological processes has treated the spatial and temporal variations of hydrological variables as spatially lumped with temporally varying processes.

However, the progress in remote sensing technology has made possible the acquisition of spatially distributed data on surface conditions, such as vegetation, land use, geological properties, and hydrological data such as precipitation or soil moisture. Also, topographical information and spatially distributed data with various statistics have been prepared electronically worldwide. The hardware as well as the software designed to analyse such multidimensional spatial information have been assembled as a GIS and have been used operationally or for studies in the field of hydrology and water resources.

The report consists of five chapters.

Chapter 1 outlines the contents of the report and classifies hydrological models for areal modelling.

Chapter 2 reviews the current status and problems of spatially distributed models and provides information on both distributed and physically-based models. The chapter addresses the parameters of physically-based models for unit areas. It includes examples of typical distributed models with tables for data requirements and the problems of distributed models.

Chapter 3 reviews hydrological applications of remote sensing data and their practical restriction and addresses remote sensing for modelling and remote sensing for observation of hydrological variables.

Chapter 4 discusses spatial modelling using GIS and application for hydrological modelling, with particular reference to model building by Digital Terrain Model (DTM). It addresses the analysis of the topographic features of catchments using the DTM.

Chapter 5 addresses the future prospects of areal modelling using remote sensing data and GIS. The chapter includes a list of new satellites with multiple remote sensors designed for observing the physical and biological characteristics of the Earth which are scheduled to be launched by the year 2000. It also addresses a new trend towards geoscientific information systems.

RÉSUMÉ

Ce rapport traite de la modélisation spatialisée au moyen de techniques nouvelles de télédétection et de systèmes d’information géographique (SIG).

Les processus hydrologiques varient dans l’espace et dans le temps à l’intérieur des cycles hydrologiques. Jusqu’à présent, on les modélisait en traitant les variations spatio-temporelles des variables hydrologiques comme étroitement liées dans l’espace à des processus variant dans le temps.

Les progrès de la télédétection ont cependant rendu possible d’acquérir des données réparties dans l’espace sur les conditions à la surface, telles que la végétation, l’aménagement des terres, les caractéristiques géologiques, ainsi que des données hydrologiques telles que celles relatives aux précipitations ou à l’humidité du sol. On a aussi élaboré par voie électronique dans le monde entier des informations topographiques et des données spatialement réparties avec divers jeux de statistiques. On a réuni sous la forme de SIG le matériel et le logiciel conçu pour analyser de telles informations spatiales multidimensionnelles et on s’en est servi en exploitation pour effectuer des études dans le domaine de l’hydrologie et des ressources en eau.

Le rapport est divisé en cinq chapitres.

Le Chapitre 1 en résume la teneur et classe par catégorie les modèles hydrologiques de modélisation spatialisée.

Le Chapitre 2 fait le point de la situation en ce qui concerne les modèles répartis spatialement, les problèmes qu’ils soulèvent, et donne des informations sur les modèles tant répartis qu’à base physique. Il traite de la paramétrisation des modèles à base physique pour des surfaces unitaires. On y trouve des exemples de modèles répartis classiques, avec des tableaux recensant les besoins en données et des problèmes qu’ils posent.

Le Chapitre 3 passe en revue les applications hydrologiques des données de télédétection, leurs limitations pratiques et les utilisations de la télédétection pour la modélisation et l’observation à distance des variables hydrologiques.

Le Chapitre 4 porte sur la modélisation spatiale à l’aide de SIG et sur son application en hydrologie, en insistant plus particulièrement sur le modèle numérique de terrain (DTM) et à son emploi pour analyser la topographie des bassins versants.

Le Chapitre 5 trace les perspectives d’avenir de la modélisation spatialisée à l’aide de données de télédétection et de SIG. Il contient une liste des nouveaux capteurs multiples qui serviront à observer les caractéristiques physiques et biologiques de la Terre depuis les satellites dont le lancement est prévu d’ici à l’an 2000. Il dépeint aussi une nouvelle tendance à l’emploi des systèmes d’information géoscientifique.
Настоящий отчет касается моделирования по площадям с использованием новых разработанных методов дистанционного зондирования и гидрогеографической информационной системы (ГИС).

Гидрологические процессы широко различаются в пространственном и временном плане в гидрологических циклах. Традиционно при моделировании гидрологических процессов пространственные и временные колебания гидрологических переменных рассматривались как пространственно сосредоточенные при меняющихся во времени процессах.

Однако прогресс в технологии дистанционного зондирования сделал возможным сбор пространственно распределенных данных по условиям на поверхности, таким, как растительные покрытия, землепользование, геологические свойства и гидрологические данные, такие, как осадки или влага в почве. Кроме того, топографическая информация и пространственно распределенные данные с различными статистическими шарами были подготовлены в электронном виде по всему земному шару. Аппаратное обеспечение, как и программное обеспечение, строится для того, чтобы анализировать такую многомерную пространственную информацию, было объединено воедино в виде ГИС и использовалось на оперативной основе либо при проведении исследований в области гидрологии и водных ресурсов.

Отчет включает в себя пять глав.
Глава 1 описывает содержание отчета и классифицирует гидрологические модели для пространственного моделирования.

Глава 2 рассматривает нынешнее состояние проблем пространственно распределенных моделей и предоставляет информацию как по распределенным, так и по физически обоснованным моделям. В этой главе рассматриваются параметры моделей, основанных на физических процессах, либо на площадях. Она включает примеры типичных распределенных моделей с таблицами для потребностей в данных и проблемах распределенных моделей.

Глава 3 рассматривает гидрологические применения данных дистанционного зондирования и их практические ограничения, а также рассматриваются вопросы дистанционного зондирования для моделирования и дистанционного зондирования для наблюдений за гидрологическими переменными.

Глава 4 излагает вопросы пространственного моделирования с использованием ГИС и применения гидрологического моделирования, с конкретной ссылкой на построение моделей с помощью Численной модели земной поверхности (ЧМП). В ней приводятся примеры гидрологических особенностей водосборов с использованием ЧМП.

Глава 5 рассматривает вопросы будущих перспектив моделирования по площадям с использованием данных дистанционного зондирования и ГИС. В эту главу включены перечень новых спутниковых многоспектральных дистанционных датчиков, созданных для наблюдений за физическими и биологическими характеристиками Земли и пределенных согласно памятным указаниям к 2000 г. В ней также говорится о новых тенденциях в системах информации по данным о Земле.

RESUMEN

El presente informe trata de la modelización zonal utilizando las técnicas más recientes en materia de teledetección y Sistemas de Información Geográfica (SIG).

Los procesos de los ciclos hidrológicos varían espacial y temporalmente. Habitualmente, en la modelización de esos procesos, las variaciones espaciales y temporales de los variables hidrológicas se han considerado como un todo espacial con procesos de variación temporal.

Sin embargo, los adelantos en la tecnología referente a teledetección han permitido la adquisición de datos distribuidos espacialmente sobre condiciones de superficie tales como la vegetación, el uso de la tierra, las propiedades geológicas, y datos hidrológicos como las precipitaciones y la humedad del suelo. Asimismo, se ha preparado de modo electrónico en todo el mundo información topográfica y datos distribuidos en el espacio con diferentes parámetros estadísticos. El material y programa informativos, diseñados para analizar esa información espacial de múltiples dimensiones, se han reunido para crear un Sistema de Información Geográfica y se han utilizado operativamente o para estudios sobre el terreno en el ámbito de la hidrología y los recursos hídricos.

El informe consta de cinco capítulos. En el Capítulo 1 se explica brevemente el contenido del informe y se clasifican los modelos hidrológicos para la modelización zonal.

El Capítulo 2 abarca un análisis del estado y los problemas actuales de los modelos distribuidos espacialmente y contiene información sobre modelos físicos y distribuidos. Incluye los parámetros de modelos físicos por unidades zonales, así como ejemplos de modelos distribuidos típicos con tablas para las necesidades de datos y los problemas de los modelos de distribución.

En el Capítulo 3 se hace un estudio de las aplicaciones de los datos de teledetección en la hidrología y su limitación práctica y se trata la teledetección para la modelización y la observación de variables hidrológicas.

El Capítulo 4 contiene una descripción de la modelización espacial utilizando el SIG y aplicaciones a la modelización hidrológica, con referencia particular a la creación de modelos con el Modelo Digital de Terreno (MDT). Aborda el análisis de las características topográficas de las cuencas utilizando el MDT.

El Capítulo 5 se refiere a las perspectivas futuras para la modelización zonal utilizando la teledetección y el SIG. Contiene una lista de los nuevos satélites que llevan a bordo múltiples sensores de teledetección diseñados para observar las características físicas y biológicas de la Tierra, cuyo lanzamiento está previsto para el año 2000. Aborda asimismo una nueva tendencia hacia sistemas de información geocientíficas.
CHAPTER 1
INTRODUCTION

1.1 Scope of the report

1.1.1 Background of the report

Hydrological forecasting using areal models is not widely applied in the field of operational hydrology. For this reason, the ninth session of WMO's Commission for Hydrology (CHy) appointed the author as Rapporteur on Areal Modelling and Hydrological Forecasting to investigate the subject. This report presents the result of this investigation.

It is necessary to point out that this report does not recommend the usefulness of specific models in operational hydrology. In the report, the present status of areal modelling is evaluated from technical considerations. Attention should be given to ensure the availabilities of lumped models in operational hydrology. It can also be said that distributed models are not widely used in the field of operational hydrology. Also, it is necessary to mention that the report includes a limited number of references, because of the large number of reference materials published in the field of hydrological modelling.

The aim of this report is: "to evaluate and report on directions being taken and to be taken with regard to modelling to capitalize on the higher resolutions in time and space of data from automated surface sensors, remote sensors, and Geographical Information Systems (GIS)."

It is necessary to clarify the term "areal modelling". What does the term "areal modelling" as used in this report mean? Areal modelling relates to the fields of meteorology and hydrology. From theoretical considerations, it may be possible to construct the model of the hydrologic cycle that integrates such elements as the atmosphere, precipitation, land surface process and ocean. In reality, however, it will be considerable time before such practical models are developed. Hence, it is appropriate to consider areal modelling separately for the meteorological and hydrological fields.

Precipitation forecasting is helpful in hydro-meteorological studies. However, precipitation forecasting is dealt with in a separate report entitled Precipitation Estimation and Forecasting (Operational Hydrology Report No. 46, WMO-No. 887) by Mr Collier, member of the CHy Working Group on Hydrological Forecasting and Applications for Water Management. Consequently, it was determined that the scope of this report be limited to the field of hydrology.

Generally in the hydrological field, models are classified into lumped and distributed models from the consideration of the treatment of the area considered. The typical example of areal models is the distributed model. In this report, therefore, the distributed models are analysed in the relation of applying remote sensing data and GIS.

Owing to advances in computer technology, computations involving large amounts of data have become possible. As a result, it has become possible to consider spatial distributions of hydrological variables for river runoff models. At the same time, the progress in satellite remote sensing technology has made possible the acquisition of data on surface conditions, for example vegetation, land utilization and geological conditions, or hydrological data such as precipitation or soil moisture.

Also, the topographical information and spatial distribution data with various statistics have been prepared electronically (in a manner that these can be processed using a computer) worldwide, while it has been made possible to collect data, such as that uniform in quality, and multidimensional and highly resolvable by means of satellite remote sensing. The hardware as well as the software designed to analyse such multidimensional spatial information with the use of an engineering work station (EWS) or a personal computer have been assembled as a GIS and used in practice or study in various fields. The field of hydrology and water resources is no exception.

For the above reasons, methods of using remote sensing data and GIS in spatial hydrological modelling are examined in relation to the construction of the hydrological models in this report.

1.1.2 Classification of hydrological models

The hydrological models are to be used to route the flow process of water, and runoff models are typical examples of hydrological models. The runoff models can be classified into two types: the first type considers water alone, and the second type both water and water-conveyed substances. The substances conveyed by water include soil, chemical substances, pollutants, etc. In this report, both types are discussed, however, there are less models that take into account the conveyed substances than those that focus exclusively on water. Emphasis is therefore placed on the former. Figure 1 shows the outline of the scope of the report.

![Figure 1 — Scope of the areal model to be covered by this report](image-url)
There are many types of runoff models and it is hardly possible to cover every type in this report. It is also difficult to systematically classify existing runoff models. An example of runoff model classifications is cited in Figure 2. As can be seen from the example, there are more than a few viewpoints from which these models can be classified. It is often the case that even from a single selected viewpoint, it is difficult to decide in which category a certain model should be included. Also, there are always boundary regions between individual categories.

Among the many types of runoff models, the distributed models can be explained as models that utilize high spatial resolution data obtained from remote sensors and GIS. However, the definition of the distributed models is not clear. Neither the definition nor the calibration of distributed models is well established (see Beven, 1989; Beven and Binley, 1992). Mathematically, a distributed model can be defined as a model where independent parameters include space and time coordinates. From certain points of view, the distributed models can also be referred to as the physically-based models (Beven, 1985).

In this report, however, the distributed models are discussed in a broader sense. It was decided that the distributed model be defined here as a model that deals with fluctuations in both temporal and spatial hydrological behaviours within a river basin. Meanwhile a model that deals only with temporal hydrological behaviour is referred to as a lumped parameter model.

1.2 Structure of the report

This report consists of six chapters.

Chapter 1 explains the scope of work and outline of the report.

Chapter 2 describes the current status and problems of distributed models. Firstly, in this chapter, the distributed models and physically-based models are defined more clearly. The parameters of physically-based models are discussed in relation with the calculated unit area of the model. When parameters are given to the model through the data from remote sensing or GIS, the magnitude of time and space resolution becomes important for the calculation. Secondly, the outline of a typical distributed model is presented, and lastly, problems of distributed models are reviewed.

In Chapter 3, spatial modelling using remote sensing and observed or estimated hydrological parameters by remote sensing are described. In this chapter, emphasis is placed on remote sensing from satellites.

The information required for building the distributed models can be classified as follows (see Figure 3): The information required for building the models and identifying the parameters can also be referred to as the information for modelling. The information for setting initial and boundary conditions is no other than quantitative hydrological data, such as precipitation and soil moisture. In view of the above considerations, Chapter 3 gives an account of the information obtained through remote sensing under separate headings, 3.4 — Remote sensing for modelling and 3.5 — Remote sensing for observing hydrological quantities.

Chapter 4 presents a description of spatial modelling using GIS and applications for hydrological modelling. The information acquired from GIS consists of the information for building the model and that for setting the parameters, as shown in Figure 3. In Chapter 4, a modelling method using GIS is described separately from the aspects of the

![Figure 2 — Classification of runoff models (Singh, 1988)](image-url)
information for model building (see 4.2 — Digital Terrain Models for hydrological application) and that for setting parameters (see 4.3 — Areal modelling of hydrological characteristics). As for the information for model building, a description is given with special attention to the Digital Terrain Model (DTM). The method of formulating DTM and of analysing the topographic features of catchment using DTM are reviewed.

Chapter 5 includes the future prospects of areal modelling using remote sensing data and GIS. In this chapter, satellites launched or scheduled to be launched during 1995-2000 are listed with the main sensors for hydrological use. Multiple remote sensing, which means multi-sensor observation of hydrological quantities, is one of the key issues of future hydrologic modelling because of the potential of observing hydrological quantities. Also, the new trend towards a geoscientific information system and the necessity of updating the GIS data are reviewed from the consideration of a four-dimensional GIS.

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CHAPTER 2
DISTRIBUTED RUNOFF MODELS

2.1 Distributed models and physically-based models

The precipitation-runoff process can be explained essentially as the movement of water in the catchment. It is therefore a natural consequence to express the physical process of water movement within a catchment by mathematical models and to solve these.

These models (i.e. runoff models in which the characteristics of the physical process of runoff are expressed with mathematical formulae which are then solved analytically or numerically) are called the physically-based models. Models which comprise physical objects (for example, methods in which scale models of catchment are produced and water is sprinkled on them) are referred to herein as physical models.

2.1.1 Kinematic wave model — a type of distributed model

One of the typical examples of physically-based models is the kinematic wave model. The kinematic wave model, which was introduced by Iwagaki (1955) and Sueishi (1955), is a technique to calculate the volume of runoff from rainfall by modelling the downward flow of stormwater along hillslopes as a sheet surface runoff and solving the model using the characteristic curve method.

Ishihara and Takasao (1959) have studied the basic characteristics of transformation from rainfall into runoff by using a kinematic wave model comprising a network of rectangular slopes and straight stream channels. They have clarified the relationship between the propagation time of stormwater and the time of peak discharge occurrence and introduced the indicators for the transformation effect along hillslopes and river channels, etc. Similar studies were also conducted by Wooding (1965a, 1965b, 1966).

Harley et al. (1970) developed a model which expressed a catchment by a network of many slopes and river channels and calculated the slope and river channel flows with a kinematic wave model. Figure 4 shows a conceptual basin model proposed by Harley et al. (1970). Similarly, models proposed by Engman and Rogowski (1974), Loague and Freeze (1985) and Loague (1990) also use basin models comprising slope blocks and river channels. These models allow for the influence of catchment topography by providing a network which comprises slopes and river channels.

Further, Kanemaru (1960), Woolhiser (1969) and Singh and Woolhiser (1976) proposed models which considered the effects of the difference in catchment topography (i.e. whether it is a converging type or diverging type). The kinematic wave model thus has evolved from a model of simplified fields to a model of combined networks to simulate the distributed character of runoff phenomena.

The basic formula of the kinematic wave model is expressed by partial differential equations incorporating space coordinates in addition to time as an independent variable. As the ‘flow’ of water is essentially a dynamic phenomenon which occurs

![Figure 4 — Basin model proposed by Harley et al. (1970)](image-url)
within space, its basic formula normally becomes a partial differential equation. In addition, a catchment usually includes many slopes and a river channel network which is formed by lateral inflows generated by runoff from the slopes. This means that a multi-stage, multidimensional combination of fields exists.

When the quantities which describe a phenomenon vary depending not only on time but also on space within a model (as in the case of the kinematic wave model), the model is called a distributed model.

2.1.2 Physically-based models

Freeze and Harlan (1969) indicated their intention to create a runoff system model which is a more generalized version of the kinematic wave model (i.e. a physically-based, digitally-simulated hydrologic response model). The concept proposed by them comprises the following steps:

(a) The various hydrological processes within a catchment can be expressed by a partial differential equation which is derived from the law of mass and momentum conservation;

(b) The initial and boundary conditions are given;

(c) Based on the assumption that the catchment can be expressed with a network of grid points, the partial differential equations are solved through the finite difference method for the given initial and boundary conditions.

Figure 5 shows a conceptual diagram of the model suggested by Freeze and Harlan (1969). In this model, the topography of the catchment is directly expressed with a shape consisting of a grid-point series. The rainfall input, physical characteristics of field and spatial distribution of hydrological quantities are considered by giving different values for the grid points. The model suggested by Freeze and Harlan (1969) incorporates the model of basin topography as a series of allocated grid points, whereas in the kinematic wave model, the river channel network and shape of slope are explicitly considered to some degree.

One typical example of the models based on the concept developed by Freeze and Harlan (1969) is the SHE model (Abbott et al., 1986a, 1986b) jointly developed by the Danish Institute of Hydraulics, the British Institute of Hydrology and SOGREAH (a French research institute).

Models do not necessarily have to be solved by the finite difference method. For example, the finite element method is also a possible alternative. In the Institute of Hydrology Distributed Model (IHDM) version 4, a physically-based distributed model unsaturated-saturated flow in hillslope is solved by the finite element method (Beven et al., 1987). Thus many of the typical examples of physically-based models are distributed models utilizing numerical solutions of the finite difference and the finite element methods.

However, the physically-based distributed model requires very detailed input. Although this may be an ideal model, this model will not always be used because of the very large amount of detailed input necessary.

2.1.3 Distributed models with conceptual subsystem models

While physically-based distributed models surely provide the most promising style of runoff model, this is not to say that the
physically-based distributed model is the only possible style of runoff model. Nor has it been proven that this is an ideal style. Also, the conditions necessary for creating a complete physically-based distributed model have not been fully established.

It is essential to identify the problems surrounding the models and the conditions required. Therefore, it is important that a clear distinction be made between the terms 'physically-based' and 'distributed'. As explained in 1.1.2 above, being physically-based has traditionally meant being distributed. Depending on the components of the runoff system, however, it is possible that sometimes the models do not necessarily have to be represented by partial differential equations.

For example, when the rainfall interception by trees is considered, it is possible that some degree of macroscopic analysis (e.g. calculation of the volume of intercepted rainfall using the volume of stormwater retained by trees, rather than tracking the movement of water on the leaves and branches of trees) may be adopted. It is sometimes more appropriate to treat some of the component systems as a macroscopic, concentrated system than to consider all phenomena within each component in a microscopic manner. Therefore, a distributed model does not necessarily mean that all component systems within the model have to be that of a physically-based model.

In addition, spatial variation of rainfall and catchment characteristics can be appropriately treated by a number of tanks with varying parameters and input values (rainfall) in Sugawara's tank model. That is, by providing a number of lumped models with varying parameters, a model that incorporates the areal change in hydrological characteristics can be created. A distributed-type model that is at the same time of a conceptual nature can be formulated. Yoshino et al. (1990) developed a distributed model in which surface runoff, unsaturated flow, groundwater flow and river channel flow were modelled by means of linear and non-linear storage models. In deriving the storage models, the physical characteristics of flows were considered. The Xinanjiang model (Zhao, 1992) developed in China can be considered as a conceptual model of a distributed nature. The model calculates the quantity of soil moisture at each sub-catchment using a conceptual model of moisture balance and converts the runoff volume into discharge from the entire catchment by means of the unit hydrograph method or lag routing method.

As the distributed models include both physically-based models and conceptual models, therefore it can be said that the term 'physically-based' cannot necessarily be identified with the term 'distributed'. Rather, it is important to consider that the two models may be complementarily combined in one distributed model.

2.2 Purposes of runoff models and the role of physically-based distributed models

2.2.1 Purpose of runoff models

In order to assess the issues of distributed models, it is necessary to discuss the purposes and usage of the models.

Freeze and Harlan (1969) have identified the following four points as the purposes of the hydrological response models:

(a) To synthesize past hydrologic events;
(b) To predict future hydrologic events and to evaluate, for design purposes, combinations of hydrologic events occurring rarely in nature;
(c) To evaluate the effects of artificial changes imposed by humans on the hydrologic regime;
(d) To provide a means of research for improving our understanding of hydrology in general, and the runoff process in particular.

Of these, achievement of (a) and (b) does not necessarily require a physically-based distributed model. Especially in those cases where the hydrological phenomena within a catchment are of no importance and the main interest is to obtain a hydrograph for the outlet of catchment, the model does not have to be a distributed model. If the dynamic structure of the runoff model appropriately approximates a given curve with a multinomial, it is relatively easy to identify parameters so that they match the past runoff record, but when runoff is estimated for cases which were not used at the time of parameter identification, the accuracy of the result is normally deteriorated.

2.2.2 Spatial scale of models and the model parameters

Could these problems (2.2.1 (a) and (b)) be solved by using a physically-based model? Longue and Freeze (1985) made a comparison between a regression model, a unit hydrograph model and a physically-based model based on the Eng seamless Rogowski model. Engman and Rogowski (1974) in terms of runoff prediction performance and concluded that the unit hydrograph and physically-based models were almost of no use for runoff prediction.

Referring to this study, Longue (1990) said that this is not to say that simple models with fewer parameters are better. He mentioned, however, that successful application of a physically-based model depends on how to treat spatial variation of the parameters used. Through detailed field observations, Longue and Gander (1990) have shown that when spatial variation of the permeability coefficient is considered, a grid with intervals of 25 m is still too large. On the other hand, Bathurst (1986b) has reported that when he applied the SHE model (Abbott et al., 1986a, 1986b) to small basins in England with an adjustment made only to the vertically saturated hydraulic conductivity so that the hydrograph was accurately identified, and that with many other parameters determined, based on direct observation within the basins, other runoff hydrographs were relatively well predicted. The interval of grid was 250 m in Bathurst's application case (Bathurst, 1986b), which is very different from the scale of spatial variation in permeability coefficient that Longue and Gander (1990) obtained through observation. What does the permeability coefficient obtained by Bathurst (1986a) with grid intervals of 250 m indicate? The vertical grid interval was 0.05 m for vertical infiltration calculation. Does it make sense to use this kind of thin and wide grid to solve equations for an ordinary infiltration process? Beven (1989) argues that the current physically-based distributed models are categorized as conceptual models of the lumped type, because there has been no theoretical justification of ignoring the areal variation of hydrological parameters below 250 m grid.

While the rapid advance in computer technology has made it possible to make calculations for phenomena which occur within a catchment on a grid basis, in many cases the intervals of grid are much larger than the scale of the physically-based equations. It becomes necessary to change the original meaning of the physically-based equations so that the grid intervals and parameter values represent a set of model parameters. It will no longer be possible to consider that these parameters are physically-based constants that are independent of the grid intervals. Bathurst (1986b), in his analysis of the impact of parameter changes within the SHE model on the calculated hydrograph, indicates that the calculation results change substantially when the grid interval is changed from 250 m to 500 m.
CHAPTER 2 — DISTRIBUTED RUNOFF MODELS

Also, it is necessary to point out that the amount of this type of grid information required for a very large catchment is enormous and some of the hydrological data required are too sparse for models using such fine detail to be applied to very large catchments.

### 2.2.3 Runoff phenomena expressed by physically-based models

It is said that physically-based distributed models are designed in such a way that parameters are determined directly by observed data of physical quantities within the catchment, rather than adjusting parameters so that the record of runoff at the exit of the catchment can be reproduced with a sufficient accuracy.

In practice, however, the procedure for determining parameters has not been fully clarified. Although the basic equations are derived from conservation laws of mass, momentum and energy and hence are sort of laboratory-scale equations, they are applied to catchment-scale phenomena and computed with a grid interval of a scale at which the available computer can solve the catchment-scale phenomena.

Is it possible to obtain the physical constant values of this case through direct observation? Should we make observations at the sites of the grid points? Or should we use the mean values of the grid interval scale? Is it sufficient to use mean values only? Should we not consider the influence of areal variation? Is it not necessary to go back to the starting point and change the basic equations themselves? Unfortunately, these problems have yet to be solved.

According to Klemes (1992), scales discussed in hydrology are so close to those of human beings that it is harder to understand the physical process of the hydrologic cycle than more distant scales (see Figure 6). Humans first obtained knowledge of extremely large- or small-scale phenomena (such as atomic-scale and cosmic-scale phenomena) and then came to understand, for example, intermediate-scale phenomena such as molecular-level phenomena based on the knowledge obtained of atomic-level phenomena and on understanding phenomena of ordinary size, gradually reducing unknown factors. Klemes expects human's understanding of hydrology to develop in this manner. It seems that he is expecting a scaled-down approach based on the understanding of global-scale phenomena obtained through remote sensing.

It is considered that the third purpose of hydrological response models proposed by Freeze and Harlan (1969) (to evaluate the effects of artificial changes imposed by humans on the hydrologic regime) can be achieved properly by physically-based distributed models. This is possible only when the physically-based distributed models can represent catchment-scale hydrological phenomena as expected and the parameters are logically and quantitatively related to physical properties of the catchment. By applying the model with physical constants expressing future alteration of catchment, hydrological impacts can be appropriately predicted. However, if parameter change for the alteration of catchment is appropriately evaluated, lumped black box models can also be used for the estimation of runoff change.

It is possible that the models are in practice not different from conceptual models although the models may have been based on physically-based analysis. Therefore it is important not to give too much weight to the idea that the origin of the models is physically-based analysis.

Also regarding the fourth purpose of hydrological response models proposed by Freeze and Harlan (1969) (understanding of runoff phenomena within a catchment), it is considered that physically-based distributed models play a major role. In particular, by simulating phenomena that occur within a catchment using physically-based distributed models, it will become possible to verify the hydrological process with the observed areal quantities, such as remote sensing data, and this will lead to a better understanding of catchment phenomena. For example, it will be possible to compare the areal mean value and variance of state quantities calculated by physically-based distributed models with physical quantities obtained through remote sensing.

It can be argued that because “in principle”, the parameters of physically-based distributed models are determined by physical observation, the physically-based distributed models are more advantageous than the conceptual lumped models. However, as Beven (1989) has pointed out, the precondition “in terms of principle” has not yet been removed.

### 2.3 Examples of distributed runoff models

#### 2.3.1 SHE model

It could be said that presently the most successful physically-based distributed model is the SHE (Abbot et al., 1986a, 1986b) model. One of the reasons for the success of the SHE model is that in this model each of the component models is modularized, and functions to integrate these modules are provided to make a flexible, upgradable total system. The SHE model is not just a runoff model, but a system for modelling runoff phenomena. By allowing each partial system model to be modified in this way, it becomes possible to incorporate research results for each partial system model into the system.

Another reason for the SHE model's success is that it has been constructed as a total system model which incorporates main hydrological processes, rather than as a system focused on a particular partial system. Because of this, the SHE model has become a realistic model that can be used to analyse actual water
resource problems. Figure 7 shows the structure of the SHE model. The SHE model is a physically-based model, which expresses the hydrological phenomena with partial differential equations of mass, momentum and energy conservation laws or uses experimental equations obtained from individual observation studies.

Orthogonal grids have been considered for the horizontal surface, and a field model consisting of columnar soil layers has been adopted for the vertical direction. Parameters and equations of mass, momentum and energy conservation laws or equations expressed the hydrological phenomena with partial differential equations. Calculation for a given storm event is performed after input/output functions for grid and contour data. However, at times it is said that it is very difficult to produce a hydrograph, because of its excessive data demands; because of this, it was a failure in the WMO Intercomparison of Snowmelt Runoff Models.

2.3.2 Institute of Hydrology Distributed Model (IHDM)

The Institute of Hydrology Distributed Model (IHDM) is a physically-based model which individually tracks subsurface flow, and overland and river channel flows on mountain slopes (Beven et al., 1987).

Mountain slopes are connected as a cascade and the subsurface flow is solved numerically by the finite element method. River channel flows and overland flows on mountain slopes are represented by kinematic wave equations and solved by difference equations. Calculation for a given storm event is performed after calculation of the preceding (upstream) runoff has been completed. Calver (1988) and Calver and Wood (1989) have made detailed analyses of the size of elements and time step for calculating flows on mountain slopes using the finite element method. Compared with the SHE model, it can be said that the IHDM emphasis is on tracking flows on mountain slopes. Table 2 lists the parameters required in the IHDM.

2.3.3 TOPMODEL

Beven and Kirkby (1979) and Beven et al. (1984) have proposed the TOPMODEL, a physically-based model which incorporates the concept of runoff contributing area proposed by Dunne and Black (1970). This model is based on the assumption that the runoff contributing areas change during a flood and the rain which falls within the runoff contributing areas immediately runs off as overland flow. The runoff contributing area is determined by the average level of underground water storage and topography. Beven and Kirkby (1979) say that the parameters can be determined by the data obtained from short-term observation on-site and topographic maps. Table 3 lists the parameters required in TOPMODEL.

Wood et al. (1988) have investigated the relationship between the size of a partial area and changes in runoff characteristics using TOPMODEL. They analysed partial areas at which the variance in catchment characteristics directly affects runoff characteristics and argued that a certain level of area (Representative Elementary Area) exists at which the distribution of catchment characteristics begins to cause a certain degree of influence on the total system.

2.3.4 Distributed models based on the Digital Elevation Model (DEM) — Models with conceptual subsystem

Takasao and Shiiba (1976) have proposed a model that simulates flows on mountain slopes and flows along river channel networks. They have shown that when calculating the runoff hydrographs from sub-catchments as in the case of the IHDM, a memory area equivalent to the number of the maximum order of the river channel is the minimum necessary to trace the hydrograph, if the order of calculations is correctly coordinated.

Liu et al. (1989) have produced a pseudo-river channel network from the DEM and proposed a model that traces the flows within the pseudo-river channel network based on the kinematic wave method. As more than two rivers may join in a pseudo-river channel network, Liu et al. (1993) have extended the scope of the method proposed by Takasao and Shiiba (1976) to propose a method for determining the order of routing that is applicable to those cases in which more than two rivers join.

Tachikawa et al. (1994) started from DEM and have proposed a method to represent catchments with an aggregate of triangle elements. By expressing catchments with an aggregate of triangle elements, it becomes possible to trace the flow paths and thus flow routing becomes easier. Figure 8 shows an example of the division of a catchment into triangle elements.
### Table 1 — Data and parameters required in the SHE model (Abbot et al., 1986b)

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameters/Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frame component</strong></td>
<td>Ground surface elevation, Impermeable bed elevation, Distribution codes for rainfall and meteorological source stations, Distribution codes for soil and vegetation types</td>
</tr>
<tr>
<td><strong>Interception component</strong></td>
<td>Drainage parameters, Canopy storage capacity (time varying), Ground cover indices (time varying)</td>
</tr>
<tr>
<td><strong>Evapotranspiration component</strong></td>
<td>Canopy resistance, Aerodynamic resistance, Ground cover indices (time varying), Ratio between actual and potential evapotranspiration as a function of soil moisture, Root distribution with depth</td>
</tr>
<tr>
<td><strong>Overland and channel flow component</strong></td>
<td>Strickler roughness coefficients for overland and river flows, Coefficients of discharge for weir formulae, Specified flows of water levels at boundaries, Man-controlled diversions and discharges, Topography of overland flow plane and channel cross-sections</td>
</tr>
<tr>
<td><strong>Unsaturated zone component</strong></td>
<td>Soil moisture tension/content relationship, Unsaturated hydraulic conductivity as a function of moisture content</td>
</tr>
<tr>
<td><strong>Saturated zone component</strong></td>
<td>Porosities or specific yields, Saturated hydraulic conductivities, Impermeable bed elevations, Specified flows or potentials at boundaries, Pumping and recharge data</td>
</tr>
<tr>
<td><strong>Snowmelt component</strong></td>
<td>Degree-day factor, Snow zero plane displacement, Snow roughness height</td>
</tr>
</tbody>
</table>

### Table 2 — Parameters required in the Institute of Hydrology Distributed Model (Beven et al., 1987)

<table>
<thead>
<tr>
<th>For each input zone:</th>
<th>For each soil type:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zo</td>
<td>SKX, SKZ, SA, SB, SC</td>
</tr>
<tr>
<td>Rs</td>
<td>THS, PSIO, PSI functions</td>
</tr>
<tr>
<td>α1, α2, α3</td>
<td></td>
</tr>
<tr>
<td>HVEG</td>
<td></td>
</tr>
<tr>
<td>ZPD</td>
<td></td>
</tr>
<tr>
<td>ZET</td>
<td></td>
</tr>
<tr>
<td>CMAX</td>
<td></td>
</tr>
<tr>
<td>RUTK, RUTB</td>
<td></td>
</tr>
<tr>
<td>CAl</td>
<td></td>
</tr>
<tr>
<td>PLAl</td>
<td></td>
</tr>
<tr>
<td>For each channel segment:</td>
<td>For overland flow on each hillslope:</td>
</tr>
<tr>
<td>BCH</td>
<td>BOF, OFC</td>
</tr>
<tr>
<td>CHC</td>
<td>Power in channel flow function, Roughness parameter in overland flow function</td>
</tr>
</tbody>
</table>
Table 3 — Parameters for the TOPMODEL
(Beven et al., 1984)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sd</td>
<td>maximum interception storage</td>
<td>sprinkling infiltrometer</td>
</tr>
<tr>
<td>Sc</td>
<td>maximum infiltration storage level</td>
<td>sprinkling infiltrometer</td>
</tr>
<tr>
<td>io</td>
<td>constant infiltration rate</td>
<td>sprinkling infiltrometer</td>
</tr>
<tr>
<td>OFV</td>
<td>overland flow velocity parameter</td>
<td>sprinkling infiltrometer</td>
</tr>
<tr>
<td>FC</td>
<td>field capacity</td>
<td>dilution gauging</td>
</tr>
<tr>
<td>m</td>
<td>subsurface flow parameter</td>
<td>dilution gauging and soil moisture analysis</td>
</tr>
<tr>
<td>qp</td>
<td>subsurface flow parameter</td>
<td>dilution gauging and soil moisture analysis</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>subcatchment topographic constant</td>
<td>topographic analysis</td>
</tr>
<tr>
<td>CHA</td>
<td>channel velocity parameter</td>
<td>dilution gauging</td>
</tr>
<tr>
<td>CHB</td>
<td>channel velocity parameter</td>
<td>dilution gauging</td>
</tr>
</tbody>
</table>

2.3.5 *The Modular Modelling System (MMS)*

The model was developed by the collaboration of the US Geological Survey and the Bureau of Reclamation (Leavesley et al.). This is one of the physically-based distributed models.

The Modular Modelling System (MMS) is an integrated system of computer software that is being developed to provide the research and operational framework needed to support development, testing and evaluation of physical-process algorithms, and to facilitate integration of user-selected sets of algorithms into operational physical-process models.

MMS uses a module library that contains compatible modules for simulating a variety of water, energy and biogeochemical processes. A model is created by selectively linking modules from the library using MMS model-building tools. A GIS interface is also being developed for MMS to support a variety of GIS tools for use in characterizing and parameterizing topographic, hydrologic and ecosystem features, visualizing spatially and temporally distributed model parameters and variables, and analysing and visualizing model results.

2.4 Perspectives concerning distributed runoff models

2.4.1 Basic equations for catchment scale

As discussed earlier in 2.2 above, one problem concerning the basic equations used in physically-based distributed models is that these equations are conservation equations at a point based on hydraulics or thermodynamics and therefore may not necessarily be suitable for dealing with catchment-scale problems.

There are two possible approaches for solving this problem. One is an approach that aims at discovering observable hydrological quantities in a catchment or global scale and analysing the processes of their change, rather than starting from experimental equations in a small partial area. It is considered that the problem of traditional conceptual models of catchment scale lies in the fact that they attempt to represent catchment phenomena by introducing imaginary quantities with no physical meaning. Observable hydrological quantities may turn out to be quantities observable by space-borne remote sensors.

The other is an approach of studying a scale-up method which utilizes knowledge obtained from mountain slope hydrology. For this purpose, variable hydrological characteristics in basin topography and physical parameters may be statistically expressed and basic equations may be combined. Variable terms are replaced with statistical relations during the integration process.

For example, the following method can be used. A catchment is considered as an aggregate of basic partial units. Such a unit is applied to Sub-catchment A in Figure 9. The scale of this unit is a scale that corresponds to the Representative Elementary Area suggested by Wood et al. (1988), and phenomena which can be captured with this scale directly affect the whole catchment-scale phenomena. For example, suppose that the location of Sub-catchment A within the catchment is important in considering the whole catchment-scale phenomena. At this whole catchment scale, hydrological quantities are considered to be geometrically distributed. On the other hand, the hydrological parameters within Sub-catchment A are probability distributed, which means that the distribution of hydrological parameters within the catchment is important rather than the location. It is important to find a scale that forms the boundary between geometrically-distributed and probability-distributed scales in this fashion.

2.4.2 Promotion of flexible model construction technologies

The runoff system comprises many components and the time and space scales of each component also vary. It is important to be able to prepare a variety of models for these components and construct a total model by flexibly combining them, even for
studying the modelling of specific component systems. Given such tools, it becomes possible to examine the meaning which a component system model has on the catchment scale.

The SHE model is one of the systems which has this capability. By using object-oriented language, which has developed rapidly in recent years, it will be possible to construct a more flexible modelling framework (Takasao et al., 1993). Given such a framework, it will become possible to provide basic functions such as the setting of model constants, reading of initial values and setting of calculation time intervals in the basic framework to allow those parts unique to individual models to be flexibly described. This will reduce the burden of modelling. Of course, the functions prepared in this way should not restrict flexible construction of models and also it is important, for example, to provide functions to enable direct communication between models.

2.4.3 Assessment of the impacts of human activities on the hydrologic cycle

In discussing water resource problems, it is no longer possible to ignore the impacts of human activities. Those models which can analyse only the hydrological phenomena within the natural catchments in mountainous areas are losing their practical values because practical cases increasingly require the analysis of the impact of operation of hydraulic structures within catchments and the impact of agricultural withdrawal or recycling water from rice fields on an overall hydrologic cycle. For example, Watanabe and Maruyama (1993) treat agricultural water withdrawal and recycling water as a component of the water circulation system. It is important to promote this type of approach and construct models in which the impacts of human activities on the hydrologic cycle can be considered. Naturally, a distributed model capable of simulating changes in runoff phenomena due to urbanization cannot be constructed without a model that can represent the hydrologic cycle of urban areas.

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CHAPTER 3
APPLICATION OF REMOTE SENSING TO HYDROLOGICAL MODELLING

There are many reference books and materials in the field of remote sensing for hydrological applications. Also, the technology of remote sensing is now rapidly progressing. This chapter has been prepared as a brief introduction to avoid duplication with other appropriate materials. This chapter is mainly prepared from the book by Engman and Gurney (1991) and the reviews by Schultz (1988) and Blyth (1993) in line with the author's views.

3.1 Hydrological use of remote sensing data

Satellite remote sensing technology has been improved in recent years, and it has been possible to observe the terrestrial conditions (vegetation, land use, mineral resources, etc.) as well as hydrological data (precipitation, soil moisture, etc.).

According to Blyth (1993), there are three methods of utilizing the remote sensing data, as follows:

(a) Design for hydrological observation networks;
(b) Extraction of physical characteristics in the river basin, such as topography of watershed, land use, etc. which do not change or change but only seasonally;
(c) Estimation of changeable physical properties of hydrological parameters, such as soil moisture, precipitation amount, etc.

Blyth (1993) classifies the primary hydrological variables into three types: the catchment input such as precipitation (rain, snow and dew); catchment storage such as surface water, snow and ice cover, vegetation moisture, soil moisture and groundwater; and catchment output such as stream flow, groundwater flow and evaporation. Included in the secondary variable are solar radiation, albedo, surface temperature, air temperature, air humidity, atmospheric pressure, wind speed, wind direction and water quality. These shall be used for the estimation of evaporation or study of snow.

At present, some of the hydrologic variables can be estimated by the combined use of hydrologic models and remote sensing, while others can be expected to be estimable at some time in the future. These include:

Flux: Precipitation, evapotranspiration, vapour advection, sensible heat flux;
State variables: Accumulated snow, soil moisture content, water vapour, storage in lakes, land surface temperature, air temperature, snow surface temperature;
Field variables: Topography, river network, soil cover, aerodynamic roughness, albedo.

One of the important aspects for the application of remote sensing is the necessity of accurate ground truth data. Remote sensing data must be checked by the ground observed data. It is sometimes very difficult to obtain the appropriate ground truth data.

3.2 Practical restrictions on satellite remote sensing

3.2.1 Outline of usable satellites and sensors

The remote sensing satellites which are now generally used are listed in Table 4. Attention should be paid to the repeat period, which is the time it takes the satellite to view the same point on Earth.

The observation width (swath width) of sensors is shown in Table 5. In general, the higher space resolution of the sensor coincides with the narrower range of observation. This means more than just a limited field of observation, but attention must be paid to the fact that this corresponds to a smaller number of observations at the same spot.

In other words, with the high space resolution sensor, the same spot can be observed occasionally, whereas the sensor (as with a geostationary weather satellite) used for frequent observations (e.g. every hour) has, in general, a low space resolution. Therefore, it is no easy task to monitor from outer space extremely small objects such as water surfaces and embankments along a small stream which are subject to abrupt hourly changes during flooding.

3.2.2 Other restrictions

There are two points other than the repeat period to which attention should be given in the practical application of remote sensing data:
(a) Purchasing cost;
(b) Time delay in acquisition.

Regarding the cost involved, data which are not subject to change in time may be obtained from several satellite image sheets in a year, and the funds required can be generally provided for without difficulty. In the case of hydrological observation or monitoring, however, it will be necessary to acquire several images a day and this will result in a sizeable expenditure.

The same is true of the time delay in data acquisition. Such acquisition of data required for the investigation of a disastrous flood which has passed could take a long time. But in such cases as real-time forecasting, it will be necessary either to receive images directly from the satellite or to acquire satellite image data on-line from a satellite data centre.

3.3 Fundamentals of satellite remote sensing

In this section, the fundamental subjects which are considered to be the minimum requirements in application of satellite remote sensing for hydrological modelling are reviewed briefly.

<table>
<thead>
<tr>
<th>Satellite name</th>
<th>Orbit</th>
<th>Altitude</th>
<th>Angle of inclination</th>
<th>Repeat period</th>
</tr>
</thead>
<tbody>
<tr>
<td>LANDSAT</td>
<td>Sun-synchronized</td>
<td>705 km</td>
<td>98°</td>
<td>17 days</td>
</tr>
<tr>
<td>SPOT</td>
<td>Sun-synchronized</td>
<td>522 km</td>
<td>99°</td>
<td>26 days</td>
</tr>
<tr>
<td>ERS-1</td>
<td>Sun-synchronized</td>
<td>785 km</td>
<td>99°</td>
<td>3, 35, 176 days</td>
</tr>
<tr>
<td>MOS-1(b)</td>
<td>Sun-synchronized</td>
<td>909 km</td>
<td>99°</td>
<td>17 days</td>
</tr>
<tr>
<td>JERS-1</td>
<td>Sun-synchronized</td>
<td>568 km</td>
<td>99°</td>
<td>44 days</td>
</tr>
<tr>
<td>NOAA</td>
<td>Sun-synchronized</td>
<td>833 km</td>
<td>99°</td>
<td>—</td>
</tr>
<tr>
<td>DMSP</td>
<td>Sun-synchronized</td>
<td>833 km</td>
<td>99°</td>
<td>—</td>
</tr>
<tr>
<td>GMS</td>
<td>Geostationary (140 E)</td>
<td>35 800 km</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 4 — Satellites generally used for remote sensing.
### Table 5 — Sensors with applicable data

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Wavelength/Frequency</th>
<th>Space resolution</th>
<th>Observation range</th>
<th>Loaded satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSS</td>
<td>0.5-1.1 μm, 4 bands</td>
<td>80 m</td>
<td>185 km</td>
<td>LANDSAT</td>
</tr>
<tr>
<td>TM</td>
<td>0.45-2.35 μm, 6 bands</td>
<td>30 m</td>
<td>185 km</td>
<td>LANDSAT</td>
</tr>
<tr>
<td>HRV/VX</td>
<td>10.4-12.5 μm</td>
<td>120 m</td>
<td>185 km</td>
<td>LANDSAT</td>
</tr>
<tr>
<td>HRV/PA</td>
<td>0.50-0.89 μm, 3 bands</td>
<td>20 m</td>
<td>60 km x 2</td>
<td>SPOT</td>
</tr>
<tr>
<td>AMI</td>
<td>5.3 GHz (SAR mode)</td>
<td>30 m</td>
<td>100 km</td>
<td>ERS-1</td>
</tr>
<tr>
<td>AMI</td>
<td>5.3 GHz (wave mode)</td>
<td>5 km</td>
<td></td>
<td>ERS-1</td>
</tr>
<tr>
<td>AMI</td>
<td>5.3 GHz (wind mode)</td>
<td>50 km</td>
<td>500 km</td>
<td>ERS-1</td>
</tr>
<tr>
<td>MESSR</td>
<td>0.5-1.10 μm, 4 bands</td>
<td>50 m</td>
<td>100 km x 2</td>
<td>MOS-1</td>
</tr>
<tr>
<td>VTR</td>
<td>0.5-0.7 μm</td>
<td>0.9 km</td>
<td>1500 km</td>
<td>MOS-1</td>
</tr>
<tr>
<td>VTR</td>
<td>6.0-12.5 μm, 3 bands</td>
<td>2.7 km</td>
<td>1500 km</td>
<td>MOS-1</td>
</tr>
<tr>
<td>MSR</td>
<td>23.8 GHz</td>
<td>31 km</td>
<td>317 km</td>
<td>MOS-1</td>
</tr>
<tr>
<td>OPS/VNIR</td>
<td>0.52-0.86 μm, 3 bands</td>
<td>18 x 24 m</td>
<td>75 km</td>
<td>JERS-1</td>
</tr>
<tr>
<td>OPS/SWIR</td>
<td>1.60-2.40 μm, 4 bands</td>
<td>18 x 24 m</td>
<td>75 km</td>
<td>JERS-1</td>
</tr>
<tr>
<td>JERS/SAR</td>
<td>1.275 GHz, HH polarization</td>
<td>18 m</td>
<td>75 km</td>
<td>JERS-1</td>
</tr>
<tr>
<td>ACHR</td>
<td>R/2</td>
<td>0.58-12.50 μm, 5 bands</td>
<td>1.1 km</td>
<td>2700 km</td>
</tr>
<tr>
<td>TOVS-HIRS/2</td>
<td>0.69-14.96 μm, 20 bands</td>
<td>20 km</td>
<td>2200 km</td>
<td>NOAA</td>
</tr>
<tr>
<td>TOVS-MSU</td>
<td>50.31-57.95 GHz, 4 frequencies</td>
<td>110 km</td>
<td>2347 km</td>
<td>NOAA</td>
</tr>
<tr>
<td>TOVS-SSU</td>
<td>15 μm, 3 bands</td>
<td>147 km</td>
<td>736 km</td>
<td>NOAA</td>
</tr>
<tr>
<td>VISSR</td>
<td>0.50-0.75 μm</td>
<td>1.25 km</td>
<td></td>
<td>GMS</td>
</tr>
<tr>
<td>VISSR</td>
<td>10.5-12.5 μm</td>
<td>5 km</td>
<td></td>
<td>GMS</td>
</tr>
<tr>
<td>SSM/1</td>
<td>19.35 GHz</td>
<td>70 x 45 km</td>
<td>1400 km</td>
<td>DMSP</td>
</tr>
<tr>
<td>SSM/1</td>
<td>22.235 GHz</td>
<td>60 x 40 km</td>
<td>1400 km</td>
<td>DMSP</td>
</tr>
<tr>
<td>SSM/1</td>
<td>37.0 GHz</td>
<td>38 x 30 km</td>
<td>1400 km</td>
<td>DMSP</td>
</tr>
<tr>
<td>SSM/1</td>
<td>85.5 GHz</td>
<td>16 x 14 km</td>
<td>1400 km</td>
<td>DMSP</td>
</tr>
</tbody>
</table>

#### 3.3.1 Observation wavelength

By remote sensing, the radiation or reflection of electromagnetic waves from the object is measured in general and the properties and physical conditions of the object are evaluated. The object has different electromagnetic wave characteristics, depending on the wavelengths of electromagnetic waves used, and the difference is used for the evaluation of the object's characteristics.

Wavelengths used in remote sensing are:

(a) **Visible ray**: wavelength 0.4-0.7 micro m;
(b) **Infrared ray**: wavelength 0.7-14 micro m;
(c) **Microwave**: wavelength 1 mm-1 m.

With visible rays, spectral reflectance of rays from the object is measured, while with infrared rays as well as with passive microwave sensors, the temperature or emissivity is measured. In the case of active sensors, the conditions including surface configuration of the object are measured. In other words, "RS (remote sensing) sensors never measure hydrological data," as stated by Schultz (1988) very appropriately.

In general, the data measured by sensors with different wavelengths are often combined to evaluate the characteristics of the object.

This is because the same plants have different reflectance characteristics to different colours such as red, green and blue and the differences in spectral reflectance characteristics are used to classify the vegetation. The same principle is true of the classification of different rocks and minerals, and a plural number of sensors are likewise used in classifying soil cover and land use with the differences in spectral reflectance characteristics.

#### 3.3.2 Quantitative observation

In satellite remote sensing by means of electromagnetic waves, a quantitative observation is not easy as it is affected greatly by the atmosphere. The reason for this phenomenon is that there are numerous carbon dioxide, water vapour, ozone and other absorptive electromagnetic wave substances as well as dispersive substances contained in the atmosphere. When their contents vary from time to time or from place to place, different reflectance or radiance characteristics are obtained from the same object observed. In this connection, a variety of studies for the correction of atmospheric effects have been made. For example, surface temperature, which is considered to be the most fundamental quantity, can be estimated with the accuracy of about plus/minus half a degree on the surface of the body water. On the other hand, the accuracy is not as high with land surface temperature. In the case of precipitation or atmospheric moisture which can only be measured indirectly, the current status of the accuracy in satellite remote sensing is at the point where 'there is a good correlation' rather than to say 'it can be used for measurement'.

#### 3.3.3 Qualitative observation

Remote sensing can easily be seen as an extension of aerial photogrammetry. For instance, the classification by image analysis, extraction of time changes using images at different periods, monitoring of specific objects and three-dimensional surveying have all been derived from aerial photogrammetry. In satellite remote sensing, generally speaking, images are received...
in digital form and it takes time to prepare these for processing. Once this is automated, it will be quick and easy to quantitatively evaluate the qualitative results of observations. For example, digital processing can easily convert a qualitative classification on urban land use to a qualitative index such as urbanization indices.

3.4 Remote sensing for modelling

3.4.1 Application of remote sensing data to modelling

The runoff process is extremely affected by topography in the river basin and soil cover, in particular. Hence, exact hydrological modelling requires that information within the river basin at all times. However, as an on-site investigation or aerial photogrammetry is costly and requires a large number of personnel, an investigation is not always frequently conducted, even in areas where abrupt changes take place resulting from urbanization or development.

The technique classifying land use is one of the most advanced areas in the application of satellite remote sensing, and it can be said that this technique has almost been established. The classified land use is reflected as a difference with the roughness coefficient or runoff rate in the runoff model. One of the fundamental issues is to clarify the corresponding relations between the roughness coefficients or runoff rate and the land use classifications, but there has been no observation of their relations nor verification due to the wide range of data scattering. However, it is possible now with the use of satellite remote sensing information to estimate such a relation as an increase in the impervious area rate or a decrease in the concentration time and an increase in the peak discharge as a result of urbanization. The satellite method and also detailed models such as the SHE model will always be useful for predicting changes caused by land use change.

It is also possible to observe the terrain in the river basin using visible and near-infrared images and synthetic aperture radar images. These images can be applied in extracting the networks of river channels. The acquisition of this information is not necessarily required in the midst of a flood. The latest satellite remote sensing information for the topographic analysis is available in the hydrologic model. Consequently, any problem with the repeat period can be solved. Further, there is no problem with space resolution since the space resolution of 10-20 m is considered to be sufficient to clarify land use or to analyse the terrain in the entire river basin. In this connection, the land use classification and terrain analysis by satellite remote sensing are most suitable to hydrological modelling. For instance, the images of the same region at different periods are acquired and their chronological changes are applied to river management. This will have the following applications:

(a) Extraction of river channels and terrain analysis: application for modelling of catchment topography;
(b) Classification of land use, soil cover, vegetation, soil properties: qualitative judgment of land surface conditions;
(c) Estimation of soil moisture distribution: quantitative estimation of properties of terrestrial conditions.

3.4.2 Terrain analysis of river basins

The terrain in the river basin can be measured in the same manner as stereo aerial photogrammetry. Rodríguez et al. (1988) have stated that in the case of SPOT-2, which is capable of acquiring terrain data at a high resolution of 10 m, contour lines can be drawn at a high resolution of more than 10 m in ideal conditions.

However, there are many cases in which aerial photogrammetry is more advantageous in obtaining detailed terrain information. Therefore, it is necessary to select an appropriate remote sensing platform with the sizes of river basins taken into account. In general, it is difficult to obtain an accurate altitude of the tree-covered ground from remote sensing information.

3.4.3 Soil cover classification

Remote sensing of land use has been seriously studied from the early stage of remote sensing. Regarding the application to hydrological modelling, Rango et al. (1983) have indicated that it is possible to classify land use using Landsat images with almost the same 95 per cent accuracy as with employing the conventional technique.

In addition, Schultz (1988) has pointed out that the observation by SPOT or Landsat 5 makes it possible to obtain hydrological data with a high space resolution such as soil type, soil cover, vegetation, land use, drainage density, etc.

There are many types of runoff models available for which land use classification maps obtained by remote sensing are used. The first and most famous one is perhaps the SCS model by Ragan and Jackson (1980). The curve number for the SCS model has been identified from such factors as soil type, soil cover, vegetation, land use, etc., and the runoff volume has been estimated from the precipitation. In this method, however, a space distribution of the remote sensing data is thoroughly integrated, so that such space resolution is not taken advantage of. On the other hand, there has been an instance (Jackson et al., 1977) of the ratio of impervious districts, obtained from the Landsat data, linked with the runoff coefficient for application to the distributed runoff model. This resulted in a reduced cost.

There is a runoff model by Groves and Ragan (1983) which is capable of incorporating the physical constants estimated from remote sensing data. This model is also characterized by the use of GIS for data management.

Kite and Kouwen (1992) studied a watershed modelling using land classifications using Landsat images. They compared the results between using a lumped hydrological model and using a version of the same model applied to different land uses within sub-basins. A hydrological model was applied separately to each land cover class in each sub-basin, and the resulting hydrographs were routed to the sub-basin outlet and then through lower sub-basins. The final hydrographs were compared to those obtained using the model on the basin as a whole. They found that using a semi-distributed model gives goodness of fit statistics that are better than the lumped basin approach. The land class dependent parameter values found through optimization confirm the physical variations in storage and infiltration rates that would be expected in a mountain basin.

3.4.4 Vegetation

Vegetation indices are defined using the visible, near-infrared channel and are referred to as the volume of vegetation. As a mean of application to hydrological modelling, a study has been under way to determine how to relate vegetation indices to photosynthesis (transpiration).

3.4.5 Geological properties in river basins

Geological properties in the river basin are estimated from remote sensing by using the spectral reflectance characteristics of the surface of the Earth. The information on the geological properties in the river basin is used in monitoring the groundwater in the river basin. Generally speaking, the result of these photographic interpretations is referred to prior to an outdoor investigation (Revezon et al., 1983).
3.4.6 Physical parameters of soil

It is difficult to obtain directly physical parameters of soil but they can be estimated from the classification of soil covers and vegetation due to their close relation with each other. Schultz and Barrett (1989) have estimated the seasonal changes in infiltration capacity on a 94-km² river basin in Germany by using a vegetation index obtained from the Landsat TM data and applied to the rainfall runoff model.

Furthermore, with the use of a passive microwave sensor, the information on roughness that is important to model the flows in channels or over slopes can be obtained. In consideration of impractical observation due to clouds, it will be better to use the active microwave sensor such as the synthetic aperture radar (SAR), combined with the visible, near-infrared information.

3.4.7 Snowmelt runoff modelling

Snowmelt runoff procedures using remote sensing have followed two distinct paths, either empirical relationships or numerical modelling. The choice of approach depends somewhat on the available data and to a great extent on the detail in output desired.

One of the most direct approaches is to relate the satellite snow cover area on a given date to the seasonal runoff. A number of models for forecasting and simulating snowmelt runoff have been developed or have been modified from existing models to incorporate satellite-derived snow cover data.

The Snowmelt Runoff Model (SRM) (Martinec et al., 1983; Rango (1995)) is a simple degree-day model that requires remote sensing input in the form of basin or zonal snow cover extent. The model is designed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major runoff factor. Using Landsat and NOAA-AVHRR data, the model has been tested successfully on over 60 basins worldwide in the simulation and forecast modes. Model variables are derived from actual observations of temperature, precipitation and snow covered area. Model parameters can either be derived from measurements or estimated by hydrological judgement taking into account the basin characteristics, physical laws, and theoretical or empirical relationships.

3.5 Remote sensing for observing hydrological quantities

3.5.1 Water level and discharge

The final output of hydrological modelling with the flow volume is the monitoring of the water level in the stream. Quite often, however, there are only several points for observing the water level within a wide river basin and these are certainly too few to cover the propagation of a flood wave in the entire river basin. It will be epoch-making if the water level and the discharge can be measured by satellite remote sensing, as the cost and the personnel involved in the maintenance of water-level and discharge observation stations are enormous.

However, there are several problems. First, one of the problems is that of the electromagnetic wave does not propagate through the water and is absorbed. This is clear from the fact that there are instruments for measuring the water level using surface scattering of the ultrasonic wave or microwave, but there is no remote sensor designed to measure the depth of water or discharge. Therefore, it is considered difficult to measure the depths of water using ordinary remote sensors.

On the other hand, it is possible in principle to measure the water level. Microwave altimeter which can measure the distance to the ground surface based upon the time of microwave transmission along the path has been in practical use. Moreover, the accuracy of observation is very high, ranging from about several centimetres to 10 cm and is considered to be sufficiently accurate for observing the water level in the river. However, there are several problems with its practical application. One is that it is hard to extract only the water level in the river as the instantaneous field of view is about 2 km. Another problem is the repeat period.

However, Mason et al. (1990) have indicated the possibility of monitoring the changes in water level of the lake covering a wide water surface with an accuracy of 25 cm. In addition, Richards et al. (1987) have indicated that it is possible to detect the flooding of rivers utilizing the L band HH polarization.

There is a possibility to observe the water level using a visible sensor. Once it is known how high the water climbs the gentle slopes of the bank, then the water level is known based on the same principle as staff gauge. However, the problem with the repeat period is still left unsolved.

It is difficult to measure the discharge directly. In principle, the surface flow velocity may be estimated from the dust floating on flowing water by using stereo photography. From the standpoint of satellite remote sensing, however, there still exists a problem with the space resolution or repeat period, and in this respect, it will be more practical to apply airplane remote sensing.

3.5.2 Precipitation

The remote sensing of precipitation varies with the sensors to be used. First of all, discussion will be on rainfall observation by radar. Marshall and Palmer (1948) have approximated the exponential function of the distribution of raindrops in size and linked the radar reflectivity factor to the rainfall intensity by an empirical formula. In other words, it is expressed as \( Z = B R^\beta \), in which \( B \) and \( \beta \) are the parameters which are determined by the distribution of raindrops in size and the storm characteristics. They are not only variable with the types of rainfall (Fujitara, 1965), but they are known to be changeable abruptly in the midst of a rainfall (Waldvogel, 1974). Consequently, a quantitative observation with a high accuracy is considered to be possible, when calibration is made using data from ground observation (Oki et al., 1992). When a multi-wavelength or multi-polarization radar is used, such variability can be reduced, contributing to more accurate observation (Yoshino et al., 1989). With its ability to observe the distribution of rainfalls with a space resolution of about 1 km in several minutes, the rainfall radar can be used not only for input data in runoff models, but for extending the lead time for runoff forecasting through a precipitation forecast on the basis of the radar information (Krajewski et al., 1993; Pessoa et al., 1993; Einheit et al., 1990). In addition, Gal-Chen (1978) has devised a retrieval method of initial values and boundary conditions for a mesoscale forecast model by using the Doppler radar and a study in that direction has been in progress (Greets and Hobbs, 1991).

At present, the only satellite with an active microwave sensor is the TRMM satellite launched jointly by Japan and the USA (Simpson et al., 1988). The frequency of the sensor will be 13.8 GHz, and a vertical distribution of the radar reflectivity factor \( Z \) can be obtained. Thus, it is expected to contribute to improving the accuracy of observation by the rainfall radar on the ground. The space resolution on the ground is 4 km with a swath of about 220 km in width. In order to observe the diurnal variation, it will have a non-synchronous orbit with the sun. It is scheduled to make one or two observations on a daily basis with the range of observation of about plus/minus 35 degrees of latitude. In addition to the method of estimation using the \( Z - R \) relationship, Meneghini et al. (1983) have proposed a method using the rainfall attenuation of the reflected waves from the surface of the sea.
Next, there is a method using a passive microwave sensor. Today, an algorithm to estimate an amount of precipitation has been under study using the SSM/I instrument on DMSP, and it is known that the amount of precipitation can be estimated with a fairly high accuracy (Jameson, 1991). The application to hydrology is accompanied by a problem with space resolution. It depends on the wavelength of the microwave sensor. The horizontal scale is about several tens of kilometres. Since the horizontal resolution of the passive sensor is large, the influence of a spatial variation of rainfalls becomes large on the accuracy of observation within an instantaneous field of view (Chiu et al., 1990). At present, the frequency of observations is once or twice a day.

Lastly, there is a method using a thermal-infrared sensor. This method of using the microwave sensor directly uses the information on water drops in the atmosphere regardless of being active or passive. The method using a thermal-infrared sensor applies an empirical relationship such that the clouds having a high rainfall intensity tend to reach a high altitude (low temperature at the top) (Adler and Negri, 1988). Nevertheless, the sensor can be placed on a geostationary weather satellite for hourly observation and, therefore, the estimation of an amount of precipitation using a thermal-infrared sensor has been in practice. During the daytime, when it is possible to use visible information, an effort is exerted to improve the accuracy of estimation by removing thin clouds with a high altitude at the top from visible images. The space resolution of visible and near-infrared sensors is high at 1-5 km but the accuracy of observation is not as high as the others. It is applied to a time scale roughly equivalent to a volume of precipitation on a monthly basis (Arkin and Ardanuy, 1989). These methods have an advantage in estimating precipitation amounts on the ocean as opposed to a combination of the ground weather observation data with remote sensing data to estimate the amount of evaporation rather than to use the latter alone. For instance, solar radiation and downward long-wave radiation can be detected in the remote sensing image. However, with the damp snow, the vertical distribution of snow water contents cannot be estimated, if the slope gradient and the roughness of the surface are corrected in the remote sensing image. However, with the damp snow, the vertical distribution of snow water contents cannot be obtained, and it should be verified whether the active sensor can be applied to a depth of 10 m in dry snow.

Soil moisture itself can be observed by the active microwave sensor (synthetic aperture radar). The observation of soil moisture is derived from the changes in dielectric constant caused by the degree of dryness, and the emissivity drops from 0.95 to about 0.6 according to the soil moisture, while backscattering is enhanced by about 10 dB (Schumuge, 1990). This type of research has begun recently. Hydrologically appropriate results have been gained, showing that the decreased average soil moisture in the images (becoming dry) coincides with an increase in the number of non-rainy days and the valley becomes wetter than the ridge (Nakaegawa et al., 1993).

Moreover, Price (1982) had developed a method to estimate surface temperature changes from the magnitudes of change of diurnal surface temperature changes, based upon the principle that the heat capacity is subject to changes by soil moisture.

The problem lies in the fact that the information on soil moisture contents in the river basin immediately before a flood cannot necessarily be obtained due to the repeat period of the satellite. One of the measures to overcome this problem is to forecast the soil moisture condition in the river basin all the time by using a river basin water budget model, and to calibrate the soil moisture contents by intermittent satellite observation.

In addition, one of the indirect methods to estimate the soil moisture content in the river basin is a method using the albedo of vegetation and the reflectance of the bare surface. It will be desirable to adopt several available methods.

Engman et al. (1989) adopted the storage type model to compare the observed areal soil moisture contents by airplane microwave observation.

### 3.5.5 Snow accumulation and snowmelt

Snowmelt is a primary reason for flooding in early spring. It seldom causes enormous damage quickly but its effect lasts a relatively long time. Sizable damage to river facilities and structures sometimes occurs in the long run and it is important to forecast the snowmelt runoff.

Measurement of the snow covered area is easy, once the cloudy area can be subtracted from the image obtained by remote sensing. However, a heavily clouded area in the image occurs at a critical moment in early spring and the snow area cannot always be observed in every repeat period of the satellite. The snow cover can be detected by an extremely high reflectance (albedo) in the visible and near-infrared sensors as compared with the surface area without snow. It is easy to discriminate between snow and clouds if the fifth band (1.57 micro-m) of Landsat/7M is used (Dozier, 1984).

Conversion from the snow cover to snow volume is made possible by considering the dependence of snow depth and snow density on the altitude. Some microwave sensors can directly observe the accumulated snow water volume. However, the microwave sensor of a passive type may not be applied to the basins of a small river covering a distance of less than several tens of kilometres and an area of about 1 000 km², as opposed to the fact that the snow cover can be estimated using a visible sensor with a high space resolution. With an active sensor, there are possibilities of estimating the water volume of snow accumulation, if the slope gradient and the roughness of the surface are corrected in the remote sensing image. However, with the damp snow, the vertical distribution of snow water contents cannot be obtained, and it should be verified whether the active sensor can be applied to a depth of 10 m in dry snow.

It has been known that the amount of snowmelt can be well estimated by means of an empirical approach called the degree-day method. However, it is rather difficult to estimate a
large volume of melted snow caused by the transport of latent heat from the moist air to the snow surface in the wake of a low atmospheric pressure; hence, it is desirable to use a heat-balanced approach. In this approach, it is expected that satellite remote sensing will make it possible to estimate snow surface temperature, radiation balance and so forth.

A snow map of the northern hemisphere was produced by Chang et al. (1987) to detect the snow cover using the SMMR data of Nimbus-7, for which a low radiance of dry snow in the microwave sensor has been applied.

In connection with the depth of snow, Srivastav and Singh (1991) have reported the effectiveness of observation through a multi-frequency, multi-polarization passive microwave sensor. With the passive microwave sensor, only the estimation of the snow moisture of dry snow is possible, but Chang et al. (1991) have estimated the average volume of snow moisture in the river basin available for use with an ordinary snowmelt runoff model using the SMMR data at night in an area covering 3 400 km².

3.6 Remote sensing inputs for hydrological models

3.6.1 Necessity of transfer function between ground truth and remote sensing data

As already mentioned, hydrological models that are to be applied at the basin scale require parameters that link the hydrological characteristics in the basin. Although the hydrological variables are accurately measured by the conventional point measurements, they are not obtained in the spatial variability except by remote sensing. Remote sensing provides the means of sampling the spatial variability of hydrological elements, but has limits of observation accuracy and time resolution.

Therefore, in the application of remote sensing of hydrological variables, it is most advantageous to combine both ground-based and areal measurements. Remote sensing of the hydrological variables provides an indirect measurement. The hydrological variables are estimated by using some form of transfer function. Ground data are used to adjust or calibrate the transfer function to ensure convergence of the remotely sensed and point data.

The full advantage of remote sensing lies in the ability to provide up-to-date basin characteristics and the spatial variability of hydrological data for inclusion in distributed parameter models as opposed to lumped parameter models. Applications requiring simple transfer functions are likely to achieve true operational status more rapidly than those having complex relationships between the remotely sensed signal and the hydrological variable.

3.6.2 Hydrological models application

The trend in hydrologic modelling has shifted from simple lumped, linear, deterministic models to more complex distributed, non-linear, stochastic models.

Moore (1993) reports that the availability of data obtained by radar on rainfall distributed on a square grid has provided a stimulus to develop new rainfall runoff models configured to make better use of data in this form. He has developed the radar grid-square model for real-time flood forecasting. His study presented results for two basins served by two different C-band radars. While the basin located in hilly terrain in northwest England showed variable results with both radar and rainfall performing best in different storms, the performance of the grid model using radar data proved consistently superior for the basin in southern England.

Although the application of remote sensing data in hydrology offers numerous advantages over conventional data, the advent of remote sensing caused some confusion among the modellers since the remotely sensed data could not be used directly in existing models. For this reason, Schultz (1993) listed the following three items:

(a) The input data consist of electromagnetic information instead of hydrometeorological data;
(b) The resolution in time and space is at times higher, at times lower than necessary due to the available sensors;
(c) There was no information available in order to transform the electromagnetic signals into hydrological information with the aid of a model.

However, during the last two decades the development of hydrological models designed for acceptance and processing of remotely sensed data has been observed. Schultz (1993) also noted that "the structure of hydrological models using remote sensing data depends to a certain degree on the scale of the system under construction".

According to Schultz (1993), good hydrological models have a structure which does not change from region to region. Only the "model parameters" are different in different regions and have to be recalibrated for each region separately. In the case of physically-based distributed system hydrological models, many model parameters depend on the characteristics of the hydrological system, e.g. the basin characteristics, aquifer characteristics and river reach characteristics.

"Model input" data can also be estimated with the aid of remote sensing. For instance, for the computation of snowmelt, the snow cover area is a relevant model input; for the estimation of evapotranspiration, radiation and temperature values are relevant model inputs; and for the estimation of rainfall (as input to rainfall runoff models), cloud top temperature values are relevant model inputs.

In the modelling of hydrological processes there is usually never a direct mathematical relationship between the electromagnetic signal and the hydrological variable. Usually, a more complex transformation of the electromagnetic signals is necessary, often combined with terrestrial information in order to estimate hydrological variables. Sometimes data from different channels or from different platforms and sensors have to be used in combination with terrestrial data.

As in the case of conventional hydrological modelling practices, the structure of the hydrological model using remote sensing data is usually a function of the scale of the system under consideration. About the relationship between areal scales and hydrological models, Schultz (1993) stated as follows: in the case of microscale (< 100 km²) hydrological models, the structure of the model should subdivide the hydrological systems into area elements of pixel size, if the available spatial resolution of remote sensing data is to be fully utilized. In the case of mesoscale (100 to 10 000 km²) hydrological models, the number of area elements has to be reduced considerably as compared to the microscale models. Currently there are many operational models available for both microscale and mesoscale and some of which use remote sensing information are under development. However, no physically satisfactory models are available for the macroscale (> 1 Mkm²) except for more lumped system approach models.

REFERENCES

CHAPTER 3 — APPLICATION OF REMOTE SENSING TO HYDROLOGICAL MODELLING


Moore, R., 1993: Application of weather radar data to hydrology and water resources, WMO, Regional Association VI (Europe), Working Group on Hydrology, 26 pp.


4.1 Hydrologically oriented Geographical Information Systems

For engineering purposes such as flood control and water resources management, it is necessary to accurately understand the time and space distribution of various hydrological parameters in river basins and to assess suitably the status of their distributions. The preparedness of various spatial data and the development of GIS are making it possible to incorporate areal information in analysing hydrological environments in the river basin with relative ease. Until the 1980s, designing a hydrological model (e.g. runoff model) had been regarded as a sort of art. This was because the work involved, which included the description of the hydrological conditions of river basins or numerical calculation of hydrological data, was the task of only a well-trained hydrologist or an experienced engineer. There is no doubt that prepared spatial data coupled with GIS have been changing the status. The GIS makes it possible to input, edit, superpose or update all types of spatial information.

A "hydrologically oriented" GIS has the functions to store, manipulate and display geomorphological data related to the basin landscape domain resulting in an appropriate set of operational tools oriented to solve hydrological problems; databases are the fundamental skeleton over which information analysis can be performed.

As it is useful for planning and decision-making, the GIS can be effectively utilized for various types of analyses, plans and management. As a matter of fact, GIS has begun to be used in various fields of hydrology and water resources. Included among them, for instance, are terrain analysis, soil cover classification, runoff analysis, disaster prevention, waterfront landscaping, management of water supply and drainage facilities, and paleohydrology and paleoclimatic analyses. As the GIS is becoming more efficient and less expensive day by day, it will be used in a wider range of applications.

Since there are several reference books available which deal with GIS in a concrete and appropriate manner (e.g. Burrough, 1988; Star and Estes, 1990; Antenucci et al., 1991; Maguire et al., 1991a, 1991b), any further discussion will be omitted. In the following sections, some examples of the applications of GIS will be briefly reviewed.

4.2 Digital Terrain Models for hydrological application

4.2.1 Digital Terrain Models and Digital Elevation Models

A model which describes the spatial information on terrain in the river basin (area) is referred to, in general, as the "Digital Terrain Model or DTM." In particular, a model related to elevation data is called the "Digital Elevation Model or DEM".

The network of data included in DEM can be classified roughly into three categories. The most common is a square-grid network (a network of elevations with rectangular grids or meshes). Such data of a square-grid network may be classified into that of a raster type. On the other hand, those data which deal not with the square-grid network but with the boundaries of river basins and the coordinates of location and elevations of river courses may be classified into the vector-type data. The network of data called triangulated irregular network (TIN) represents the three-dimensional coordinates of the vertices of triangles with the river basin covered up with triangles of all sizes, while a network of terrain data plotting the points of the same elevation (i.e. contour-based) is called a contour-based network.

In recent years, the analyses of terrain and runoff in river basins using DTM are often made in hydrology. In these analyses, DTM is used in analysing river channels and slopes of river basins, and the resulting terrain model is used to obtain the parameters of characteristic quantities for physically-based distributed runoff models. At this point in time, the question arises as to the accuracy of DTM. In this section, the technical status of producing DTM will, first of all, be reviewed.

4.2.2 Digital Terrain Model production method

Weibel and Heller (1991) made a comprehensive review of the methods of production of such a DTM, methods of evaluation of quality, methods of DTM visualization, and the application of DTM to civil engineering, planning and resources management, global science, military purposes and so forth.

There are three methods available to produce DTM, that is, the ground survey method, the photogrammetric measurement method and the cartographic method derived from existing maps. Petrie has made a comparison of these methods as shown in Table 6 (Petrie and Kennie, 1990).

The ground survey method is very accurate but is time-consuming and rather difficult from an economic standpoint due to its wide coverage. In cases where the elevation at each point is plotted with the use of a plotter of photogrammetric measurements, a high accuracy can be obtained.

Petrie and Kennie (1990) have evaluated quantitatively various DTM production methods based on photogrammetric measurements and their degrees of accuracy as shown in Table 7.

There are three methods of production of DTM on the basis of existing maps: one uses the geographical map which is read by a digitizer; another uses the lines on the map which are traced semi-automatically; and the other is the map automatically traced with the use of a scanner. In all methods, the accuracy is low with DTM obtained on the basis of medium- and small-scale maps. With the photogrammetric measurement method, for instance, the average square error of DEM is approximately 7 m at intervals of 7.5 minutes corresponding to a geographical map on a scale of 1/24 000, whereas the mean square error of DEM obtained with the contour lines read by the digitizer from the geographical map is allegedly 7–15 m (Petrie and Kennie, 1990). The results of DEM are highly dependent on the accuracy of the source map.

Many software packages have been developed in the areas of ground surveys and civil engineering for modelling of terrain. Expressed in the FORTRAN, C and PASCAL programming languages, they are designed to be operational based upon the PC or UNIX system. Kennie has classified these packages as shown in Figure 10, introducing their summary (Petrie and Kennie, 1990).

Algorithms have been developed that can convert the contour-based information in the vector-type data to the raster-type DEM. If there is a white map with contour lines available, it is scanned for incorporation in the computer and processed by
Table 6 — Sources of Digital Terrain Model data (Petrie and Kennie, 1990)

<table>
<thead>
<tr>
<th>Source of DTM data</th>
<th>Method used</th>
<th>DTM accuracy</th>
<th>Areal coverage</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground survey</td>
<td>Total or semi-total station</td>
<td>Very high</td>
<td>Limited to specific sites</td>
<td>Small area site planning and design</td>
</tr>
<tr>
<td>Photogrammetric measurements</td>
<td>Stereo plotting machines (with or</td>
<td>(i) High (if from spot heights)</td>
<td>Large area projects especially</td>
<td>(i) Large engineering projects: dams,</td>
</tr>
<tr>
<td></td>
<td>without correlators)</td>
<td>(ii) Lower (if from contours)</td>
<td>in rough terrain</td>
<td>reservoirs, roads, open cast mines</td>
</tr>
<tr>
<td>Cartographic (existing</td>
<td>(i) Manual digitizing</td>
<td>Low — derived from contours on</td>
<td>Nationwide at small scales</td>
<td>Aircraft simulators, landscape</td>
</tr>
<tr>
<td>topographic maps)</td>
<td>(ii) Semi-automatic line following</td>
<td>medium- and small-scale topographic maps</td>
<td></td>
<td>visualization, landform representation,</td>
</tr>
<tr>
<td></td>
<td>(iii) Fully automatic raster scanning</td>
<td></td>
<td></td>
<td>military battlefield simulation</td>
</tr>
</tbody>
</table>

4.2.3 Hydrological modelling of river-basin terrain

There are many instances of hydrological modelling of terrain using DTM. Some of the recent results are published in Hydrological Processes, Vol. 5, No. 1, pp. 1–26 (1991). They are published again by Beven and Moore (1993). In the latter publication, Moore et al. (1991) reviewed the current status of Digital Terrain Modelling. They discussed the three DEM mentioned above (square-grid, TIN and contour-based), together with an outline of many hydrological and terrain models in the river basin, and quality of elevation data in America and Australia, etc. The square-grid type DEM is advantageous in that it is easily obtainable and can be connected easily with the remote sensing data, and is suitable for processing the combination with GIS on the computer. The contour line type DEM is advantageous in solving the equations as related to the complicated two- or three-dimensional flows or transportation, but it poses some difficulties because it requires a lot of storage capacity of data. Furthermore, a number of scientists have studied the runoff model based on TIN (DeVantier and Feldman, 1993). Moore et al. (1991) have pointed out the necessity to compare flow models among these three DEM.

It has been popular since the 1980s to extract the networks of river channels automatically from DEM for analysis of basin terrain (Marks, 1983; Marks et al., 1984; O’Callaghan and Marks, 1984; Band, 1986; Takasao et al., 1989; Tarboton et al., 1989, 1991; Yoshiyama, 1990; Takara et al., 1991; Eash, 1994). Jensen (1991) made a comparison of the degrees of accuracy of analysing river channel networks using DEM of variable spatial resolutions (including even the DEM of Mars). These are mainly based on grid-based Digital Elevation Models. Tachikawa et al. (1994) have expressed river basin terrain more accurately by using not only the raster-type data, but also the vector-type data (TIN) in combination. Costa-Cabral and Burges (1994) developed an algorithm called DEMON, which can trace the flow over hillslopes using the grid-based DEM. This is an algorithm which is capable of contributing to improve a defect (O’Callaghan and Marks, 1984) in tracing the flow according to the grid-based DEM and concurrently provides an advantage of tracing the contour-based flow.
<table>
<thead>
<tr>
<th>Type of terrain coverage</th>
<th>Associated with</th>
<th>Sampling</th>
<th>Automated</th>
<th>Break lines</th>
<th>Height measurement by</th>
<th>Speed</th>
<th>Height measurement mode</th>
<th>DTM accuracy</th>
<th>Terrain representation</th>
<th>System cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>I A</td>
<td>Comprehensive high-density</td>
<td>Orthophoto production</td>
<td>Grid</td>
<td>Yes (X, Y, Z)</td>
<td>No</td>
<td>Correlator (e.g. GPM-2)</td>
<td>Very high</td>
<td>Static</td>
<td>Medium</td>
<td>Very good</td>
</tr>
<tr>
<td>B Parallel profiles (automatic)</td>
<td>Orthophoto production</td>
<td>Grid</td>
<td>Yes (X, Y, Z)</td>
<td>No</td>
<td>Correlator (e.g. Planimat + EC5)</td>
<td>High</td>
<td>Dynamic</td>
<td>Medium to low</td>
<td>Fair</td>
<td>Very high</td>
</tr>
<tr>
<td>C Parallel profiles (semi-automatic)</td>
<td>Orthophoto production</td>
<td>Grid</td>
<td>Yes (X, Y only)</td>
<td>No</td>
<td>Operator (e.g. Topocart/ Orthophoto)</td>
<td>Medium</td>
<td>Dynamic</td>
<td>Medium to low</td>
<td>Fair</td>
<td>Medium</td>
</tr>
<tr>
<td>D Regular grid (automated)</td>
<td>DTM collection</td>
<td>Grid</td>
<td>Yes (X, Y, Z)</td>
<td>No</td>
<td>Correlator (e.g. Kern DSR + VLL)</td>
<td>High</td>
<td>Static</td>
<td>High</td>
<td>Good</td>
<td>High</td>
</tr>
<tr>
<td>E Regular grid (semi-automated)</td>
<td>DTM collection</td>
<td>Grid + PS</td>
<td>Yes (X, Y only)</td>
<td>Yes</td>
<td>Operator (e.g. analytical plotter)</td>
<td>Medium</td>
<td>Static</td>
<td>High</td>
<td>Good</td>
<td>High</td>
</tr>
<tr>
<td>F Regular grid (manual)</td>
<td>DTM collection</td>
<td>Grid + PS</td>
<td>No</td>
<td>Yes</td>
<td>Operator (e.g. analogue or analytic plotting)</td>
<td>Low</td>
<td>Static</td>
<td>High</td>
<td>Good</td>
<td>Low</td>
</tr>
<tr>
<td>G Random, but specific locations</td>
<td>DTM collection</td>
<td>Selective</td>
<td>No</td>
<td>Yes</td>
<td>Operator (analogue or analytic plotting)</td>
<td>Low</td>
<td>Static</td>
<td>Very high</td>
<td>Very good</td>
<td>Low</td>
</tr>
<tr>
<td>H Contouring</td>
<td>Topo (line mapping)</td>
<td>Equal Z values</td>
<td>No</td>
<td>Yes</td>
<td>Operator (analogue or analytic plotting)</td>
<td>Low</td>
<td>Dynamic</td>
<td>Low DTM by interpolation</td>
<td>Very good</td>
<td>Low</td>
</tr>
</tbody>
</table>
4.3 Areal modelling of hydrological characteristics

4.3.1 Handling of remote sensing data on Geographical Information Systems

Apart from topographical conditions on the terrain as discussed in the foregoing section, various spatial hydrological conditions within the river basin can be taken into account for GIS. For instance, there are natural features related to soil properties and geology, land use and vegetation. In addition, there are social factors such as census and business statistics. This geographic information is being prepared as numerical geographic information in a number of countries, which lends itself to various analyses when superseded by the GIS.

However, there are many cases where some of this geographic information is inappropriate, since these vary from hour to hour. In such cases, remote sensing data prove to be useful.

Remote sensing data are the image data of spatial information with a wide coverage and are generally processed by the GIS. It can be said, therefore, that the studies in remote sensing generally use the GIS in a broad sense. The raster-type GIS is most appropriate for image processing of remote sensing data.

Tatetsu (1990) has stated that the advantages of consolidated processing of the remote sensing data and the geographic data are as follows:

(a) The accuracy in classification is higher with the use of geographic data than with the use of only the remote sensing data in classifying soil cover and vegetation;

(b) Use of the remote sensing data makes it possible to use the latest data on soil cover, vegetation, temperature on the land surface, etc. for analysis;

(c) It is possible to produce image maps with the remote sensing image for a background.

He has also mentioned the following problems:

(a) In cases where the degree of resolution or positional accuracy varies greatly between the remote sensing data and the geographic data, it is difficult to use these in a consolidated manner;

(b) A large volume of the remote sensing data sometimes presents difficulty to input into a GIS database.

The raster-type GIS is more suitable for processing the image data such as the remote sensing data, whereas the vector-type GIS is better for analysing terrain and networks. However, conversion of the data from the raster-type to the vector-type, which often allows image positions to be easily oriented, is made possible by superposing the remote sensing image on the network map of roads and rivers.

As satellite remote sensing data, Landsat of the USA (spatial resolution of 30 m) and SPOT of France (spatial resolution of 20 m in multi-spectrum mode, 10 m in panchromatic mode) have been popularly used, but there are sensors with a higher spatial resolution ability scheduled for release in the near future. For instance, the AVNIR on the ADEOS of Japan had a spatial resolution ability of 16 m in the multi-spectrum mode and 8 m in the panchromatic mode. These optical sensors are passive sensors and are subject to such restrictions as interception in visibility due to clouds and darkness. On the other hand, ERS-1 (European Remote Sensing Satellite) and JERS-1 (Japanese Earth Resources Satellite, Fuyo) equipped with a cloud-free, darkness-free synthetic aperture radar have been launched and studies have just begun to utilize the data of such active sensors.

As regards the use of remote sensing and the GIS, reference should be made to Star and Estes (1990) and Malher (1992). An expert meeting was held by the American Society of Civil Engineers (ASCE) to discuss applications of remote sensing and the GIS to civil engineering. Eight reports dealing with the applications of the GIS to water resources are included in the proceedings (Stafford, 1991).

4.3.2 Application of Geographical Information System to runoff analysis/forecast and water resources planning and management

A study has begun to consolidate various topographical data and hydrological areal data to analyse or forecast a runoff to contribute to the planning and management of water resources in the river basin. Herein, an attempt is made only to list the reports which have dealt with the above-mentioned subject (Aschwanden et al., 1993; Djioke and Maidment, 1992; Drayton et al., 1992; Liu et al., 1989; Romanowicz et al., 1993; Schumann, 1993; Smith, 1993; Vieux, 1992; Zhang and Montgomery, 1994).

However, no mention has been made of the names of a large number of reports submitted to workshops related to the application of GIS to hydrology and water resources (69 reports of Kovar and Nachtnebel (1993), 63 reports of Harlin and Lanfear (1993)) in addition to 11 reports published in the special issue on GIS (Vol. 119, No. 2) of the Journal of Water Resources Planning and Management by ASCE (1993).

4.3.3 Other instances

The analysis of land cover, evapotranspiration, vegetation and so on provides basic information on runoff analysis. It is important to prepare these databases step by step for each river basin. The GIS can be utilized to structure the database, while the database structure is used by GIS in a consolidated manner, thus making it possible to analyse various sorts of issues under variable conditions including runoffs, water resources, hydrological environments and disaster prevention.

As regards disaster prevention, Laru et al. (1991) have developed a remote sensing and geographic information analysis system (RSGIS) on a minicomputer which excels in graphic processing for evaluating the spread of a forest fire and recovery of vegetation or judging the locations of danger caused by landslides.

Since the latter half of the 1980s, an information distribution system which may be referred to as a real-time GIS has been developed (Kunayashi et al., 1987) and is used today for disaster prevention by many river administrators of local governments.

Generally speaking, GIS is often used in processing the latest spatial information, but there is some doubt as to whether old spatial information should be processed by GIS. Takara and Watanabe (1992) have attempted to revise the river drawings of about 200 years ago with geometric correction to restore the river courses to that of those days and estimate their flowing ability. The attempt has not been thoroughly completed yet, but this type of approach has, at least, been under consideration to see if there is any clue to estimating paleohydrology and paleoclimate.

GIS has an extremely great role to play in those issues on global environments and climatic changes. In the field of environmental analyses and management, an international symposium was held in Japan in 1991 to discuss environmental changes and GIS (INSEG '91, 1991). Moriguchi (1991) is now developing all types of environmental information systems ranging from local districts to a worldwide scale and Fukushima et al. (1990) tried to structure a support system for the management of the closed water body. Naiman (1992) has introduced several examples of application of GIS to landscaping of ecological systems in forests.
REFERENCES


Kovar, K. and H.P. Nachtenbol (Eds.), 1993: Application of GIS in hydrology and water resources management. IAHS Publication No. 211, 693 pp.


CHAPTER 5
FUTURE PERSPECTIVES

5.1 Issues of areal modelling in the future

5.1.1 Constraints of areal model

While lumped hydrological models have been adequate for addressing the practical hydrological problems, the recent management needs have stimulated the development of new modelling approaches that explicitly take into account the spatial distribution of catchment properties. High resolution spatial and temporal data are now available to analyse hydrological phenomena in river basins through the distributed models such as SHE and IHDM, which are, in principle, compatible with the data structure of GIS and applicable to the remote sensing data. However, these distributed models have not been to work with remote sensing data and more efforts will be necessary to be taken to apply distributed parameters or variables observed by remote sensing.

As already mentioned in Chapter 2, distributed models have several characteristics. According to Beven (1985), the role of distributed models is as follows:

(a) To forecast the effects of land-use change;
(b) To forecast the effects of spatially varying inputs and outputs;
(c) To forecast the movement of pollutants and sediments;
(d) To forecast the hydrological response of ungauged catchments where no data are available for calibration of a lumped model.

Because of these promising purposes, distributed models will be more widely applied for the operational problems in hydrology.

However, there are several constraints in the distributed models. Beven (1985) also mentioned the practical difficulties of applying distributed models. In his opinion at that time, major constraints were economic, with programming effort, computing requirements and field experiments making up the major part of the cost. Some of these difficulties have now been solved to some extent by the rapid advance of computer and remote sensing technology.

As already discussed in detail in Chapter 2, there are now several items still to be solved, such as:

(a) Improvement of the model structure, including basic equations for catchment scale;
(b) Flexible model structure.

5.1.2 Necessity of stochastic approach for natural heterogeneity

Hydrological modelling for distributed models needs appropriate data for initial and boundary conditions of catchment characteristics. Requirement of these data includes spatial and temporal variability of hydrological elements. This is one of the fundamental problems in distributed models arising from the fact that the properties of natural earth materials are highly variable in space. Jensen and Mantoglow (1993) mentioned the impossibility of collecting the amount of data required to specify the complex field heterogeneity in order to fulfil the parameter requirements of all the grid elements in a deterministic model application over a certain scale. As mentioned in Chapter 2, a stochastic interpretation may be a logical alternative approach to reduce the required parameters in distributed models.

The measurement scale is an important issue in relation to defining the appropriate parameters at the selected grid scale. In general, increasing the measurement scale will tend to decrease the variance and increase the correlation length. This interrelationship between measurement scale and effective parameters needs to be investigated. Data from remote sensing will give some criteria for this problem in the future.

5.2 Satellite remote sensing for hydrological modelling in the future

5.2.1 Main constraints of remote sensing

The data required for modelling the spatial variation of hydrological characteristics in catchments are expected to be obtained from remote sensing.

However, the main constraints on the application of remote sensing data are as follows:

(a) Repeat period of satellites;
(b) Space resolution of sensors.

It will be necessary to study how to use satellite remote sensing to hydrological modelling by overcoming these constraints. In addition, satellite remote sensing has hitherto been used for quantitative modelling through the use of qualitative information as an extension of aerial photography. But in the future, there will also be new types of remote sensing data to be used for hydrological purposes as already mentioned, since the space agencies are developing completely new space systems. As microwave observation has come to be accepted in general, quantitative physical properties are estimated directly and used for hydrological modelling. Some new techniques are under development in remote sensing. The new hydrological potential offered by this tremendous amount of new information will certainly require, in the future, more complex GIS hardware and software (Schultz, 1993).

5.2.2 Satellite remote sensing plan in the future

Intensive remote sensing of global environmental monitoring was scheduled to start in the latter half of the 1990s. Shown in Table 8 is a schedule of satellite launchings from 1995 through 2000. Included in the schedule is the realization of a visible and infrared radiometer (VIS/IR) and a passive or an active microwave sensor is expected to play a vital role. (For future hydrological observation plans, the materials prepared for a scientific research subsidiary application form of the Ministry of Education, Japan, "Investigation into a continental-scale hydrological and thermal energy flow by means of satellite measurements" (represented by Professor A. Sumi at Tokyo University, Weather System Centre), as well as the materials distributed at a Global Environmental Observation Committee meeting of the National Aerospace Development Agency/Remote Sensing Technological Centre have been referred to.)

Moreover, a high-frequency observation at intervals of one to three days with a wide range of observation will become a reality. However, basic researches for practical applications have not been sufficient at present, and it is of urgent necessity to develop approaches to quantitative observation of physical properties with the multiple application of these sensors.
Table 8 — Schedule for launching global observation satellites

<table>
<thead>
<tr>
<th>Year</th>
<th>Satellite</th>
<th>Country</th>
<th>Sensor: Visible infrared sounder (VIS/IR)</th>
<th>Infrared sounder (IRS)</th>
<th>Microwave radiometer (MR)</th>
<th>Microwave sounder (MS)</th>
<th>Synthetic aperture radar (SAR)</th>
<th>Precipitation radar (PR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>RADAR SAT</td>
<td>Canada</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>ERS-2</td>
<td>ESA*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td>ADEOS</td>
<td>Japan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>TRMM</td>
<td>Japan/USA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>NOAA-K-N</td>
<td>USA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>EOS AM-1</td>
<td>USA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>ENVISAT-1</td>
<td>ESA</td>
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*European Space Agency

5.2.3 Multiple remote sensing of the processes of the hydrologic cycle

With the sensors currently available taken as examples, prospects for monitoring of hydrological processes by means of multiple remote sensing will be discussed as follows.

It is possible to estimate the vertical profile of atmospheric humidity and temperature by microwave sounders such as TOVS and AMSU with NOAA and SSM/I with DMSP. The use of TOVS and AMSU, and AVHRR of NOAA in addition to VISSR of GMS makes it possible to estimate the short-wave and long-wave radiation from the sky to the ground. The surface albedo can be extracted from the AVHRR and Landsat/TM data. The land surface temperature, on the other hand, can be estimated from the data of SSM/I, AVHRR and VISSR, while precipitation can be estimated from the data extracted from SSM/I, AVHRR and VISSR. In addition, it is expected that a detailed observation of precipitation will be possible by means of TRMM/PR. Soil moisture can be estimated by synthetic aperture radar other than SSM/I and AVHRR. Furthermore, the use of SSM/I, AVHRR and SAR makes it possible to measure the snow accumulation, while snow cover only will be more effectively extracted by TM. Furthermore, the roughness can be estimated through the use of AVHRR or SAR.

The radiation flux is obtained from the short-wave/long-wave radiation and albedo by the combination with the information of remote sensing, while the surface flux such as the amount of evaporation can be estimated from the vertical profiles of atmospheric humidity and air temperature, land surface temperature, soil moisture, and roughness in addition to the wind velocity observed. This information, in addition to precipitation, soil moisture, etc., can be used to evaluate the water budget in the river basin.

The following sensors will be available in the future:

- **DPR (Dual-frequency Precipitation Radar)**: performs a highly accurate three-dimensional radar observation of precipitation with 14 and 35 GHz.
- **AMSR (Advanced Microwave Scanning Radiometer)**: observes atmospheric moisture, clouds' liquid water content and snow moisture through 14-180 GHz microwave radiometer.
- **GLI (Global Imager)**: monitors with high accuracy the oceanic colors, land vegetation, etc. through multi-band observation of visible and near-infrared sensor.
- **LIDAR (Light Detection and Ranging)**: observes with high accuracy the vertical profile of atmospheric moisture, and the accurate altitude of sea surface and ice surface by means of difference-absorption LIDAR.

- **MSSAR (Multi-frequency and Multi-polarisation SAR)**: measures the soil moisture and snow moisture using multi-frequency (L, C and X bands) and dual-polarization (HH/VV) synthetic aperture radar.

These are still at the conceptual stage, but with advancements in technology and development in science associated with remote sensing, it is expected that they will make a steady step forward towards materialization.

5.3 Perspectives related to Geographical Information Systems

5.3.1 Role of Geographical Information Systems in hydrological modelling

Without any doubt, the role of GIS in hydrological planning and management will increase. But this process has to be accompanied by adequate improvement in both database systems (time-series data) and simulation models. Kaden (1993) says that user-friendliness, open interfaces and portability are important features facilitating successful applications. GIS application and its future are discussed in detail in Chapter 4.

Hydrologically-oriented GIS should be able to store, manipulate and display geomorphological data related to the basin landscape domain resulting in an appropriate set of operational tools oriented to solve hydrological problems: databases are the fundamental skeleton over which information analysis can be performed.

Water resource system simulations provide estimates of what might take place, over space and time. In the future, the simulated output will be visualized by multi-media which links with GIS. This is pointed out by Loucks (1993) briefly. Perhaps the most challenging research will be in the integration of video with simulation output.

5.3.2 Preparation of data for Geographical Information Systems

Nakamura and Shimizu (1991) have commented that the following points are future problems to be solved for the GIS:

(a) Formulation of a standard format for data of the Digital Terrain Model;
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(b) Contents of the database of the Digital Terrain Model and expression of accuracy;
(c) Real-time data acquisition;
(d) Development of three-dimensional mapping of digital terrain;
(e) Consolidation of application systems with GIS;
(f) Introduction of artificial intelligence and expert system.
A few comments on these issues are as follows.
Preparation of the database will be the key issue on GIS. GIS will be of no use without data. In addition, if the format of the data is not uniform or compatible, extra processing will be required even with the aid of GIS. As the necessary items for a GIS standard format, Sakauchi et al. (1992) mentioned these six points: user interface, network, software environment, information retrieval, visualization and data. Among these, they have reviewed the developments of standardizing the data formats in Japan and the USA, in particular, pointing out a shift from the standardization of data exchange formats to the standardization of data management.

Shibasaki (1991) studied the factors contributing to the errors in the Digital Terrain Model used in GIS and analysed the influence of the errors in the Digital Terrain Model upon the results of analyses. This type of study is very important to GIS, since several maps with errors differing in nature are superposed. GIS is not good for everything, but the accuracy of its result depends upon the data used and the quality of the analysing method adopted.

5.3.3 New trend to Geoscientific Information System — four-dimensional Geographical Information System

Recently, a term "Geoscientific Information Systems" has come to be used (Turner, 1992). Geoscientific data will not be sufficient if only the land surface and the sea surface are dealt with two-dimensionally. It will necessitate three-dimensional data and their analysing methods including the atmosphere, subsurface and underwater. In order to handle environmental changes or climatic changes on a global scale, a new dimension in terms of time will have to be introduced. That is to say there will have to be a shift from a three-dimensional GIS to a four-dimensional GIS. This will make it necessary to develop a high-speed computer, capable of processing GIS data of such a high dimension.

5.3.4 Updating of data

Langran (1992) has dealt with GIS and its relations with time. With GIS, the degree of space resolution often brings a problem but the degree of resolution in terms of time is also important to planning and management. For instance, in urban areas where changes are abrupt, updating annually the land use data is desirable. It is said that it now takes about four years in Japan for the data obtained in aerial photography to be completed as a file. Thus, the time required in preparing a database often proves to be unsuitable for meeting the purposes of hydrological analyses.

In addition, this problem is more serious with GIS designed for disaster prevention which calls for a real-time response. From the time the data are obtained, quick and accurate processing of the data for analysis, indication and judgment is required. Under such circumstances, artificial intelligence as well as the expert system approach will have a great role to play in the future as incorporated in the GIS.

REFERENCES

Beven, K.J. 1985: Distributed models, Hydrological Forecasting, Chapter 13, M.G. Anderson and T.P. Burt (Eds.), John Wiley & Sons Ltd.