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LONG-RANGE WATER-SUPPLY FORECASTING

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FOREWORD

At its fifth session in 1976, the WMO Commission for Hydrology (CHy) appointed a Rapporteur on Long-range Water-supply Forecasting, Dr. M. Dyhr-Nielsen (Denmark), as a member of its Working Group on Hydrological Forecasting. The terms of reference of the rapporteur included the preparation of a paper on current methods of long-range water-supply forecasting (two to four months) and the collection of information on the feasibility of combining conceptual deterministic models and statistical data simulation for such forecasts.

The present report is the result of the information collected and literature reviewed by Dr. Dyhr-Nielsen in which he was assisted by Mr. Langfey Hannesdottir, graduate student at the Technical University of Denmark and by a Nordic supporting group.

Reviewed by the CHy Working Group on Hydrological Forecasting, the report was subsequently approved for publication by the sixth session of CHy in 1980.

It is with great pleasure that I express the gratitude of WMO to Dr. Dyhr-Nielsen and to all those who assisted him for the time and effort they have devoted to the preparation of this report. It is hoped that it will prove useful to hydrological forecasting services and to individuals involved in long-range water-supply forecasting.

A Wiin Nielsen

A.C. Wiin-Nielsen
Secretary-General

SUMMARY

This report on current methods of forecasting water supply over periods ranging from two to four months also reviews the feasibility of combining conceptual deterministic models and statistical data simulation for such forecasts. The term "water supply" is used with its meaning of runoff volumes over a defined period such as weekly, monthly or seasonal flows. The techniques described apply not only to water-supply projects but also to irrigation and hydroelectric power projects. Some are equally well-suited to long-range forecasts of floods or low flows and such applications are briefly discussed.

Section 1 reviews three methods of long-range water-supply forecasting, namely: regression methods, conceptual models and time series. Section 2 discusses the operational use of forecasting methods, based on the replies to the questionnaire on long-range water-supply forecasting which was sent in 1977 to the members of the WMO Commission for Hydrology (CHy). A comparison of the three methods, including data and computational requirements and accuracy, is given in section 3.

The report concludes that the potential of conceptual models for long-range water-supply forecasting is large and, if the accuracy of long-range weather forecasts continues to improve, it will be conceptual models which will adapt most efficiently.

RESUME

Le présent rapport sur les méthodes actuelles de prévision de l'approvisionnement en eau, valables pour des périodes de deux à quatre mois, traite également des possibilités d'utiliser, pour ce type de prévision, des combinaisons de modèles conceptuels déterministes et de simulation de données statistiques. Le terme "approvisionnement en eau" (water supply) est utilisé ici dans le sens de volume d'écoulement pendant des durées ou des périodes déterminées : semaine, mois ou saison. Les techniques décrites ne s'appliquent pas seulement à des projets d'approvisionnement en eau, mais aussi à des projets d'irrigation ou d'installations hydroélectriques. Certaines de ces méthodes - brièvement traitées ici - peuvent également être utilisées pour la prévision à longue échéance des crues et des étiages.

La section 1 traite de trois méthodes de prévision à longue échéance de l'approvisionnement en eau, respectivement fondées sur les équations de régression, les modèles conceptuels et les séries chronologiques. La section 2 traite du problème de l'utilisation opérationnelle des méthodes de prévision fondées sur les réponses données aux questionnaires relatifs aux prévisions à longue échéance de l'approvisionnement en eau, envoyés en 1977 aux membres de la Commission d'hydrologie de l'OMM. La section 3 contient une comparaison de ces trois méthodes, notamment en ce qui concerne les données, les exigences en matière de calcul et l'exactitude.

En conclusion, le rapport met en évidence les grandes possibilités qu'offrent les modèles conceptuels pour la prévision à longue échéance de l'approvisionnement en eau, tout en insistant sur le fait que, si l'amélioration de l'exactitude des prévisions météorologiques à longue échéance se poursuit, les modèles conceptuels s'adapteront d'une manière d'autant plus fidèle.

РЕЗЮМЕ

В настоящем отчете о современных методах прогнозирования объема стока воды на сроки от двух до четырех месяцев также рассматривается возможность комплексного использования концептуальных детерминистических моделей и модельных статистических данных для таких прогнозов. Термин **"Water supply"** используется в своем значении объема стока воды в течение определенного периода времени (недели, месяца или сезона). Описываемые методы касаются не только проектов по водоснабжению, но и проектов по орошению и производству гидроэнергии. Некоторые из этих методов в равной мере пригодны для выпуска долгосрочных прогнозах о наводнениях или низком стоке и такое применение кратко описывается в настоящем отчете.

В разделе 1 рассматриваются три метода долгосрочного прогнозирования объема стока, а именно: методы с использованием уравнений регрессии, концептуальные модели и временные ряды. В разделе 2 обсуждается вопрос об оперативном использовании прогностических методов, основанных на результатах опроса по поводу долгосрочного прогнозирования объема стока, который был проведен в 1977 г. среди членов Комиссии ВМО по гидрологии (КГи). В разделе 3 содержится сравнение трех методов, включая требования к данным и расчетам и точность.

В отчете делается вывод о больших возможностях концептуальных моделей для долгосрочных прогнозов объема стока и о том, что в случае повышения точности долгосрочных прогнозов погоды наиболее эффективно будут использоваться концептуальные модели.

RESUMEN

En el presente informe sobre métodos actuales de predicción del abastecimiento de agua, durante períodos que se extienden de dos a cuatro meses, se examina también la viabilidad de combinar modelos deterministas conceptuales y simulaciones estadísticas de datos para este tipo de predicción. La expresión "abastecimiento de agua" se utiliza en su significado de volúmenes de escorrentía durante un período determinado, tal como flujos semanales, mensuales o estacionales. Las técnicas descritas no sólo se aplican a los proyectos de abastecimiento de agua sino también a proyectos de irrigación y de energía hidroeléctrica. Algunas de estas técnicas pueden también utilizarse para las predicciones a largo plazo de las crecidas o del estiaje y este tipo de aplicaciones se tratan brevemente.

En la Sección 1 se examinan tres métodos de predicción del abastecimiento de agua a largo plazo, a saber: métodos de regresión, modelos conceptuales y series cronológicas. La Sección 2 trata de la utilización operativa de los métodos de predicción, basándose en las respuestas al cuestionario sobre predicción del abastecimiento de agua a largo plazo que se envió en 1977 a los miembros de la Comisión de Hidrología (CHi) de la OMM. En la Sección 3 se describe una comparación de los tres métodos, incluidos los datos, los requisitos en materia de cálculo y la precisión.

El informe llega a la conclusión de que existe una gran posibilidad de utilizar modelos conceptuales para la predicción del abastecimiento de agua a largo plazo y deduce que si la precisión de las predicciones meteorológicas a largo plazo continúa mejorando los modelos conceptuales se adaptarán de una forma más eficaz.

LONG-RANGE WATER-SUPPLY FORECASTING

1. METHODS FOR LONG-RANGE WATER-SUPPLY FORECASTING

1.1 Introduction

Forecasting future flows depends basically upon two factors:

(a) The state and water storage of the basin;

(b) Future meteorological events.

In principle, the first factor may be measured, whereas the second factor relies upon meteorological forecasts. Reliable long-range meteorological forecasts are not available at present, and this may be the reason why most efforts have been concentrated on forecasting methods to describe and apply information on the state of the basin. In areas where snowmelt or groundwater dominate, such methods yield satisfactory results. A typical example is the use of snow accumulation indices and regression analysis.

However, where precipitation during the forecast period significantly affects runoff, due consideration of this factor is necessary and conceptual catchment models have proved promising in such cases.

Recently, forecasting techniques developed in stochastic control theory have been applied to hydrological time series. Such methods have not yet been applied operationally, but might, in certain situations, be a valid alternative to regression methods or conceptual models.

1.2 Regression methods

The oldest, and by far the most widely used technique for long-range forecasting, is the use of regression methods. Although forecast relationships may still be developed by the graphical plotting of data, subjective weighting of variables, etc., the widespread availability of computer programs for multiple regression and similar data analysis has outdated these methods.

It should be stressed that, although the development of the forecast relationships is made most efficiently by computer, the daily use of such parameters in forecasting may still be effected most conveniently by manual calculations, the use of diagrams, etc.

1.2.1 Basic concepts

The forecasting model is developed by finding a regression relation between the variable that is to be forecast and a group of independent variables. The relation for time, t, may be written as:

$$Q_{t+l} = f(I_{i,t}), \quad t = 1,2\text{-}n, \quad i = 1,2\text{-}m,$$

where Q_{t+l} is the forecast runoff at time t+l for a forecast with lead time l. $I_{i,t}$ are independent variables describing the state of the basin at time t. In some cases, the independent variables include forecasts of precipitation during the lead time l.

The value Q_t may also be included in the independent variables.

In most cases, the forecast relation is a linear combination of the independent variables $I_{i,t}$, obtained empirically by multiple regression analysis on at least 10-20 data sets. The accuracy of the relation is often given by the correlation coefficient. However, a better measure of the reliability of the forecasts is the standard estimated error, which is readily available from computer programs. Confidence limits for the forecasts are an even better measure, and these values are also easily available.

The selection of the independent variables is most critical for the usefulness of the method, but is often limited by the lack of long data series (more than 10 years). The choice of variables depends on the basin. In mountainous basins where there is heavy snowfall, an index of the snow equivalent before spring runoff is the most important. In basins where groundwater and runoff from lakes are significant, indices for the state of the groundwater and lake reservoirs are important.

Regression methods are mostly used for snow-fed basins, where indices for snow cover and/or winter precipitation are of primary importance. Other data may include soil moisture, temperature, wind and solar radiation to account for secondary effects such as runoff losses. A list of significant independent variables is given in Table I.

TABLE I

Independent variables

Variable	Principal source	Used as	Relation to		Significance	
			Runoff	Peak		
						%
Snow water equivalent	SCS	PI	Positive	Positive	Very high	60-90
Streamflow (antecedent)	USGS	PI	Positive	Positive	Moderate	5-15
Base flow	USGS	PI	Positive	Positive	Moderate	5-15
Soil moisture	SCS	LI	Positive	Positive	Moderate	5-10
Precipitation						
Autumn	NOAA & SCS	PI	Positive	Positive	Moderate	5-20
Winter	NOAA & SCS	PI	Positive	Positive	Moderate-high	30-60
Spring	NOAA & SCS	PI	Positive	Positive	Moderate-high	10-25
Temperature	NOAA	LI	Negative	Positive	Moderate-high	10-25
Wind	NOAA	LI	Negative	Negative	Moderate	5-20
Radiation	NOAA	LI	Negative	Negative	Moderate	5-15
Relative humidity	NOAA	LI	Positive	Positive	Moderate	5-10

Note: This table is a summary of the relative significance of variables. The significance percentages indicate in broad terms what percentage of the variability accounted for by a multiple regression equation is attributable to a particular variable (from reference 1).

Spring precipitation may be included in the development of the forecast relationship, as it is not uncommon for this variable to be the second most significant index. In operational use, where spring precipitation is unknown, its mean value and selected quantiles (i.e. 25 per cent and 75 per cent) may be used to give forecasts of various probabilities.

If a large amount of data is available, a selection of the most significant variables may be found by the use of stepwise multiple regression. In such cases it is important to avoid the inclusion of highly correlated variables, for example the results of snow surveys. Principal component analysis may be used to obtain independent combinations of the variables.

1.2.2 Data requirements

As mentioned above, the data requirements depend on the nature of the basin:

For snow fed rivers in the western U.S.A., the Soil Conservation Service of the Department of Agriculture uses a selection of the variables given in Table I (1). The most important forecasting variable is snow water equivalent, determined from snow surveys. In arid areas, soil-moisture data are important in accounting for runoff losses and may be indexed by introducing autumn precipitation as an independent variable. If base flow and spring precipitation are significant, they are included in the forecast relationship.

The U.S. National Weather Service makes forecasts based on winter precipitation measurements instead of snow surveys. The data collection is simplified in this case and if the forecasts are updated as proposed by Tangborn *et al.* (2), results tend to be as accurate as forecasts based on snow surveys.

A procedure for combining snow-survey data and winter precipitation for improved forecasts has been given by Schermerhorn and Barton (3).

Forecasting procedures in Europe have been summarized by Liebscher (4), but he found few examples of long-range forecasting, such as that which describes forecasts for the Rhine river (5). The independent variables include discharge at the forecast station, discharge at large lakes, lake volumes, water equivalent of snow cover, air temperature, precipitation, storage capacity of reservoirs and reconstructed natural runoff.

In France, multiple regression on monthly rainfall and temperature is used to forecast runoff volumes and subsequent evaluation of low water flows (6).

In Finland, spring inflow to Lake Oulujärvi is forecast by a regression equation containing lake level, snow water equivalent, autumn precipitation and the sum of positive winter temperatures (7).

For Norwegian rivers, forecast relationships have been based on winter precipitation and runoff with reasonable success (8).

Forecasts of average quarterly discharge (in monthly increments) of inflow to the Kiev, Kanev and Kremending reservoir in the U.S.S.R. were based on water storage in the basin and water storage in the channel at the end of the preceding quarter (9).

Forecasts of the total flow of water to large lakes of the Ladoga basin in the U.S.S.R. a year in advance have been based on a relationship between anomalies of flow and atmospheric circulation and on the development of the latter processes (10).

As noted above, many different variables may be used in forecast relationships. However, snow data are by far the most important, as successful regression relations are usually only found for rivers with large snow runoff in the spring. Unfortunately, snow measurements are difficult to obtain manually and, therefore, recent developments have attempted to automate this type of data collection. Developments in radio communications and micro-computers have made it possible to use meteor bursts to facilitate telecommunications over large distances (11).

The usefulness of satellite data has also been investigated, and promising results have been obtained with spring flow forecasts for the Indus River, based on satellite observations (12). The potential of satellite data for snow-cover estimation has been treated in detail (13). Such techniques seem promising, particularly in areas with scarce data, but it will take time before sufficiently long data series are available to warrant the use of empirical regression methods.

1.2.3 Updating

Naturally, the regression relation should be updated as more data become available, in order to improve the reliability of the forecasts. However, the annual forecast itself may be updated when more information on, for instance, spring precipitation is available. If data are processed by computer, it does not require much extra effort to obtain monthly forecast relationships. The March forecast will not include April precipitation but the April forecast will, and will, therefore, be more accurate. An example of the development of updated forecasts is shown in Figure 1 (8).

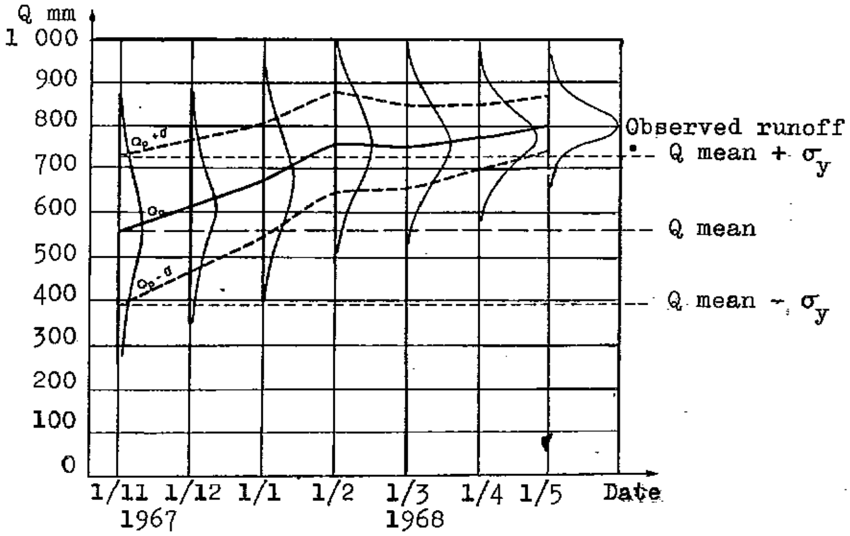


Figure 1 - Forecast development of runoff

By considering the runoff in a "test month" before the forecast is made, it is possible to update the snow water equivalent in the basin and improve forecasting accuracy considerably (2).

1.3 Conceptual models

The regression models use simple, empirical relationships between future runoff and the variables which influence this runoff. Conceptual models introduce a relationship between runoff and forecasting variables which is more physically based. A distinction may be made between the conceptual models which describe only a part of the hydrological cycle and those which cover the complete cycle. Models of the first kind, such as snowmelt models, are the most common, particularly in the U.S.S.R. The use of complete hydrological models for long-range forecasting is relatively new but seems to offer a promising approach to the problem.

1.3.1 Snowmelt models

A detailed description of the structure and data requirements of snowmelt models is given in (14). A distinction is made between snowmelt from lowland and that from mountain basins.

The relationships for snow ablation in snowmelt runoff models are based on rather simple temperature-index methods. However, more physically based methods which consider the total heat budget of the snow cover do not show any better accuracy as the data available for operational use are mostly of a poor quality.

For a model operating on snowmelt and spring runoff only, initial values such as soil moisture and groundwater storage are estimated by index methods. Base flow, groundwater levels, autumn precipitation and depth of frozen ground, etc., indicate the magnitude of losses that will occur during the snowmelt period.

Snowmelt models for flat land should account for the difference in melt dynamics between open and forested areas. In mountain regions, the change of temperature with altitude must be carefully modelled, particularly in view of the lack of data usually characteristic of higher altitudes.

1.3.2 Models of the complete hydrological cycle

Today, there are available a wide variety of models for the total hydrological cycle. A comparison of such models which pays particular attention to their forecasting abilities was undertaken as described in (15). (Emphasis, however, was on flood-forecasting abilities and the long-term forecasting properties were not examined.)

In principle, any hydrological model which accurately predicts flood runoff may be suitable for long-range forecasting but certain modifications may be necessary. Flood models are tested and calibrated on their ability to simulate flood peaks. If the model calibration seeks to minimize flood-peak errors, errors in monthly flows may be neglected which can, particularly in low flow situations, be very great. Therefore, models for long-range forecasting should be calibrated to minimize the error in monthly flow, even if this implies large errors in simulated floods.

The optimal structure of a long-range forecasting model may be different to that of a flood model. Accurate routeing of overland flow and streamflow is of major importance for a flood model but less critical in a runoff-volume model. On the other hand, modelling of evapotranspiration losses and soil-moisture conditions may be critical for a reliable forecast of runoff volume.

Moreover, a proper modelling of the groundwater response may be significant for long-range forecasts, whereas flood forecasts are usually insensitive to errors in the groundwater component.

When designing the structure of a forecast model, care should be taken to balance the sophistication of the model with the available data base. In particular, data bases available for operational use are limited in comparison with the research-oriented data bases which often form the basis for advanced hydrological models. In the case of long-range forecasting, the uncertainty in the input during the lead time of the forecast limits the accuracy of the forecast, no matter how accurate the hydrological model. Model accuracy, therefore, should be tuned to this inherent and unavoidable uncertainty.

An efficient long-range forecasting model may therefore be relatively simple in structure, although both runoff losses and the groundwater component should be carefully designed. In general, the use of conceptual models appears most promising in basins with a slow and damped response to precipitation input. In mountainous basins with significant snow runoff, modelling of snow conditions at a series of altitudes is important to account properly for the melting processes during spring.

When a hydrological model has been developed and calibrated to simulate accurately a known series of runoff volumes, its operational use for forecasting depends on two factors:

(a) The ability to simulate accurately the state of the basin on the day the forecast is made;

(b) Predicted information on future meteorological events to be used as input to the model.

The first factor depends on efficient updating procedures. The second factor may be used if quantitative precipitation and temperature forecasts are available. If this is not the case, forecasts can be made by statistical data simulation only.

1.3.3 Quantitative precipitation forecasts

The capability within the field of quantitative precipitation forecasts (QPFs) is still limited. Replies to a 1977 WMO questionnaire on quantitative precipitation forecasts for hydrological purposes indicate that the lead time is at most a few days for forecasts based on dynamic meteorological models. The space resolution of the forecasts is at best 10 000 km^2, which is relatively coarse for hydrological purposes. The reliability of a quantitative precipitation forecast decreases appreciably in mountainous regions. Therefore, when long-range forecasts are the point of interest, it would appear that the potential for using quantitative precipitation forecasts in conjunction with hydrological models is rather limited.

There may be some advantage in issuing statistically based forecasts months in advance, when the forecast is limited to statements concerning averages. Such forecasts might prove useful in combination with statistical data simulation.

1.3.4 Extended streamflow prediction

If quantitative precipitation and temperature forecasts are unable to provide information to the forecast model, only one possibility is left - to use a series of historical precipitation and temperature data as input with its present initial conditions (16). The result is a series of possible runoff volumes that can be analysed statistically. The procedure is illustrated in Figure 2 and the forecast is presented as a conditional probability distribution of future flows.

It is important to note that this method may easily provide information on variables other than runoff volumes; probabilities of future flood flows, low flows, duration of specific flow rates etc, are all obtained without difficulty (17). Also, the operation of water-resources projects might be included in the model and forecasts made, for instance, of reservoir levels under different operational rules.

Extended streamflow prediction has proved to be particularly useful during extreme phenomena, such as prolonged droughts, where traditional linear regression methods may lose their reliability in conditions exceeding the limits under which the relationship was developed.

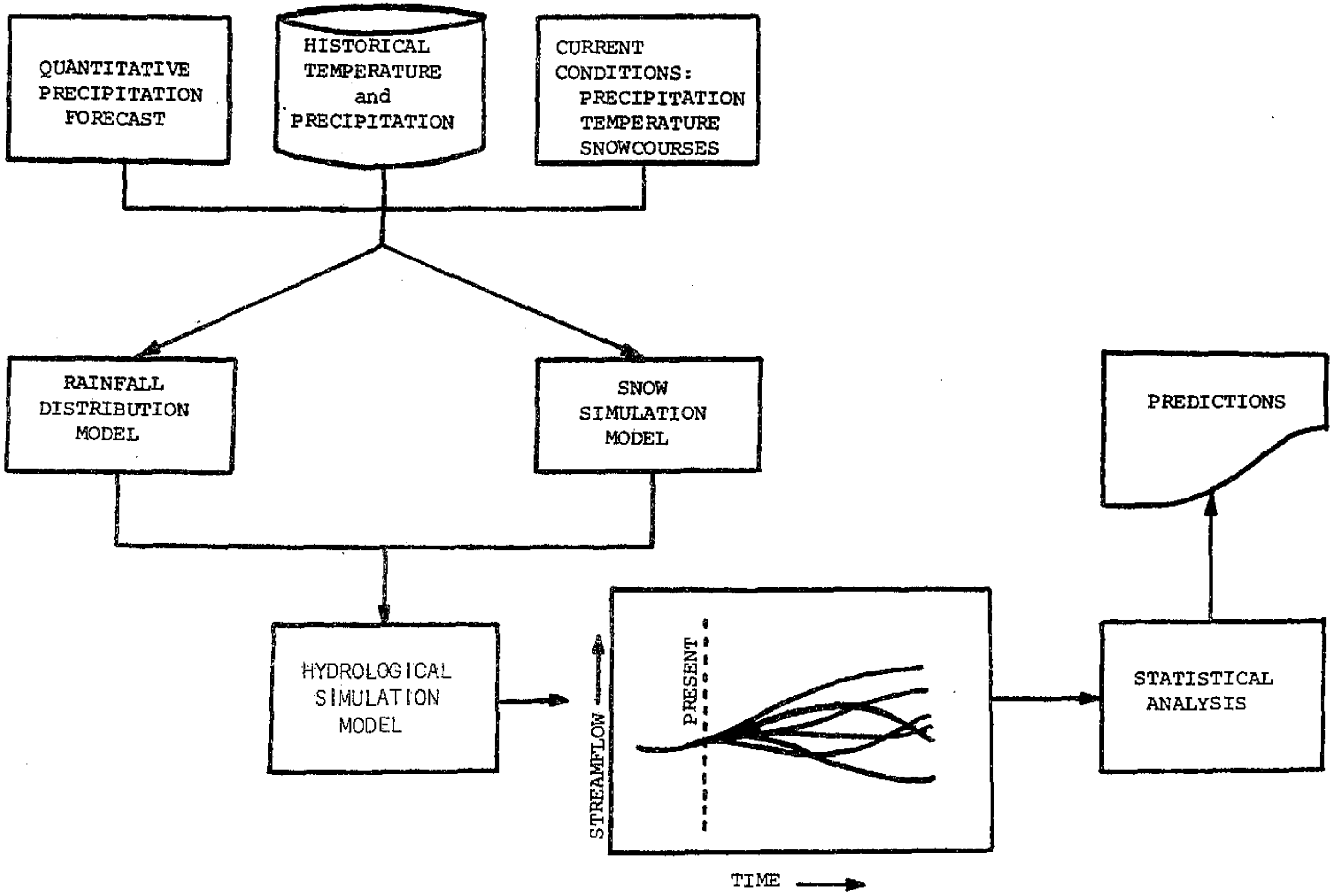


Figure 2 – Scheme of conceptual simulation model for extended streamflow predictions (from reference (17))

At present, long-range forecasts made by data simulation derived from hydrological models appear to be the most promising technique if sufficient data are available and a reasonable model can be established.

However, several problems need further study. At present, all historical series are used indiscriminately. Research is necessary to assure that future weather conditions are indeed independent of the previous weather situation.

It has been proposed to develop a stochastic model for precipitation and temperature input and to use this to generate a much larger sample (18). However, such models are very difficult to establish, and it might be just as efficient to fit a stochastic model directly to the generated flows.

1.3.5 Updating

It is important to ensure that the initial conditions of the model are correct for the day the forecast is made. Due to errors in both the model and the data, discharge simulations will not agree with the observations. This may be due also to incorrect values of the storage component of the model. To achieve agreement between simulation and observation, model parameters and variables must be updated concurrently.

A simple and straightforward procedure may be to adjust precipitation input until proper results are obtained (19). Precipitation data may be rather inaccurate, particularly when snow is falling, so a modification may be justified. An alternative would be to adjust the storage component in the model on the day of the forecast. Such a procedure for updating the content of the snow water storage is given in (20).

A promising technique for handling the updating problem with a hydrological model may be the use of Kalman filters as tested in Norway (21) and work is under way in the U.S.A. to apply Kalman filters to the National Weather Service model.

1.4 Time-series methods

1.4.1 Probability forecasting

In the classical forecasting technique, for instance in many uses of regression relations, the forecast is given as a single value without any probability of occurrence. Naturally, the forecast contains errors, but the intention is to give a single value which is as accurate as possible.

However, the uncertainties of hydrological forecasts and in particular long-range forecasts are so large that a single-value forecast is misleading. Instead, the forecast should give the conditional probability distribution of future flows.

Forecast distributions with small variance correspond to the "error-free" single-value forecasts. However, forecasts with great uncertainties may also be of considerable value in the operation of water-resource systems. The major obstacle in the proper use of such forecasts is a lack of understanding of how to apply and use probability information when formulating decisions relating to water availability and allocation. However, if the use of decision theory becomes a more common technique, the need for probability forecasts will increase significantly.

If the concept of a forecast as a conditional probability of future events is accepted, it would seem natural to consider alternatives to the cause-effect approach in forecasting techniques, such as regression methods, for example. Forecasts may then be developed which are based directly on stochastic models describing the conditional probabilities of the independent variables.

TABLE II

Summary of replies to the 1977 WMO questionnaire from countries which reported issuing long-range water-supply forecasts

	REGRESSION METHODS					CONCEPTUAL MODELS			TIME SERIES
		INDEPENDENT VARIABLES					OUTPUT		
COUNTRY	USED	SNOW	PRECIP.	TEMP.	RUNOFF	USED	FORECASTS	ESP*	USED
AUSTRALIA						X		X	X
BULGARIA	X		X		X				
CANADA	X	X	X		X				
CZECHOSLOVAKIA	X		X	X	X				
COSTA RICA	X					X			
POLAND	X					X	X		X
ROMANIA	X		X		X	X	X		
SPAIN	X		X						
SWITZERLAND	X	X			X				
SWEDEN						X		X	
THAILAND	X								
TUNISIA	X		X			X			
TURKEY	X								
UNITED KINGDOM						X		X	
U.S.A.	X	X	X	X	X	X		X	
U.S.S.R.	X	X	X	X	X	X			

*Extended streamflow prediction

1.4.2 Simulation analysis

A simple but often useful tool for probability forecasting is the use of statistical techniques in the same way as they are used in design practice. An application of simple statistical techniques used in a forecast situation may be found in reference (22), where historical series are used to evaluate probabilities of emergency action in the operation of a water-supply reservoir. The statistical analysis should take into consideration initial values, such as the storage of the reservoir, the current inflow to the reservoir, etc. By straightforward simulation of a long time series, storage probabilities dependent on present reservoir levels and inflows can be found.

1.4.3 Forecasting with ARIMA models

Box and Jenkins (23) have developed stochastic time-series methods which are useful for forecasting purposes. Applications for hydrological data can be found in (24) and (25).

If streamflow itself is a valid measure of the state of the basin, univariate ARIMA models of monthly flow may give reasonable results from one to four months in advance. Such cases may be found in catchments with a highly damped response to precipitation inputs and with insignificant snowmelt runoff.

Multivariate ARIMA models may be used, if precipitation has to be included in the forecast relationship. If snow runoff is significant, ARIMA-models are not feasible (21), because the snowmelt process is poorly accounted for.

2. OPERATIONAL USE OF FORECASTING METHODS

2.1 WMO questionnaire

A questionnaire on long-range water-supply forecasting was sent in 1977 to the members of the WMO Commission for Hydrology (CHy) in order to collect information on the subject. The questionnaire is reproduced in the annex to this report. Replies to the questionnaire were received from 45 countries and from among these, sixteen countries stated they issued long-range water supply forecasts. Thirteen of these replies in the affirmative came from countries in Europe, the U.S.A., Canada, the U.S.S.R. and Australia. One was received from Central America, and one from both Africa and Asia. It is thus evident that operational long-range forecasts are rarely used in the developing countries. A summary of the affirmative replies is given in Table II. It is evident that the classical regression methods are the most common, that conceptual models are also relatively frequent, but that the use of time-series methods is very restricted.

2.2 Regression methods

Thirteen countries reported using regression methods for their forecasts. Precipitation and discharge data are the most commonly used independent variables, probably because they are the most readily available. Only Canada, Switzerland, the U.S.A. and the U.S.S.R. reported applying snow data in the forecast relationships. In Switzerland, lake levels are used as independent variables and in Poland, barometric pressure is used in some cases.

In the U.S.A., precipitation and snowfall accumulation of known probability as determined by analysis of past records are utilized in the preparation of probability runoff forecasts. The forecasts include an evaluation of the standard error of the prediction model. The forecasts are presented at three levels of probability as follows:

(a) Most probable - That runoff which is expected to occur if precipitation subsequent to the date of forecast is median;

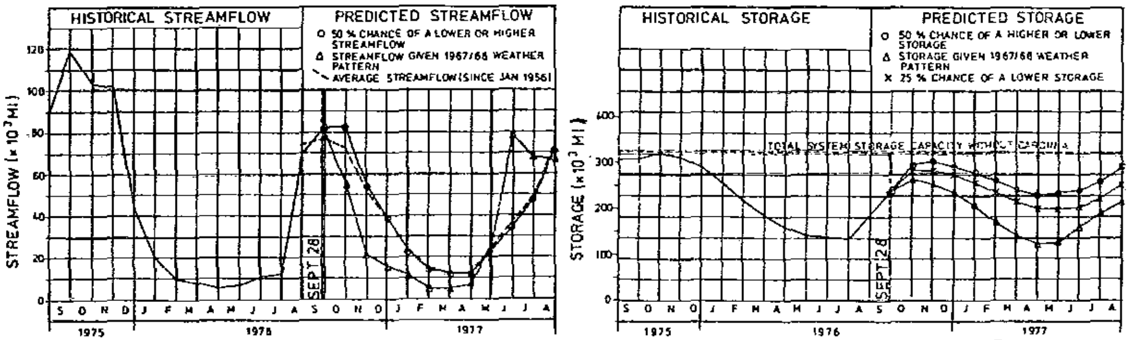
(b) Reasonable maximum - That runoff which is expected to occur if precipitation subsequent to the date of forecast is equal to the amount which is exceeded on average once in ten years;

(c) Reasonable minimum - That runoff which is expected to occur if precipitation subsequent to the date of forecast is equal to the amount which is exceeded on average nine out of ten years.

2.3 Conceptual models

Nine countries gave affirmative replies to the question of using conceptual models. Detailed information on the use of models of the complete hydrological cycle was received from Australia, Sweden, the United Kingdom and the U.S.A.

In Australia, a simple hydrological model, called the Soil Dryness Index Model, has been used on an operational basis for Melbourne's water-supply system (26). Simulation of storage levels and water use is included in the model. Probabilistic forecasts are issued according to previous catchment and current storage levels by running the model with a sequence of historical rainfall and temperature inputs. In particular, critical weather patterns may be shown specifically (see Figure 3).



PREDICTED STREAMFLOW
TOTAL FOR ALL WATER SUPPLY CATCHMENTS

PREDICTED WATER STORAGE

Figure 3 - Presentation of forecast for Melbourne's water-supply system. (after reference (26))

In the United Kingdom, a similar approach was used by the Thames Water Authority (27) during the drought of the water year 1976/77, where simulation of groundwater storage was included in the model. In Sweden, a simple rainfall-runoff model, named the HBV model, has been used for extended streamflow prediction in rivers involved in hydroelectric power production (28). Besides forecasting runoff volumes, probability forecasts of peak flows have been made, results of which are presented in Figure 4. A vertical line represents each occasion at which a forecast of the peak flow of the remaining flood season was issued. The five levels represent maximum, 25 per cent, median, 75 per cent and minimum peak flow of 13 simulations; the observed hydrograph is also shown.

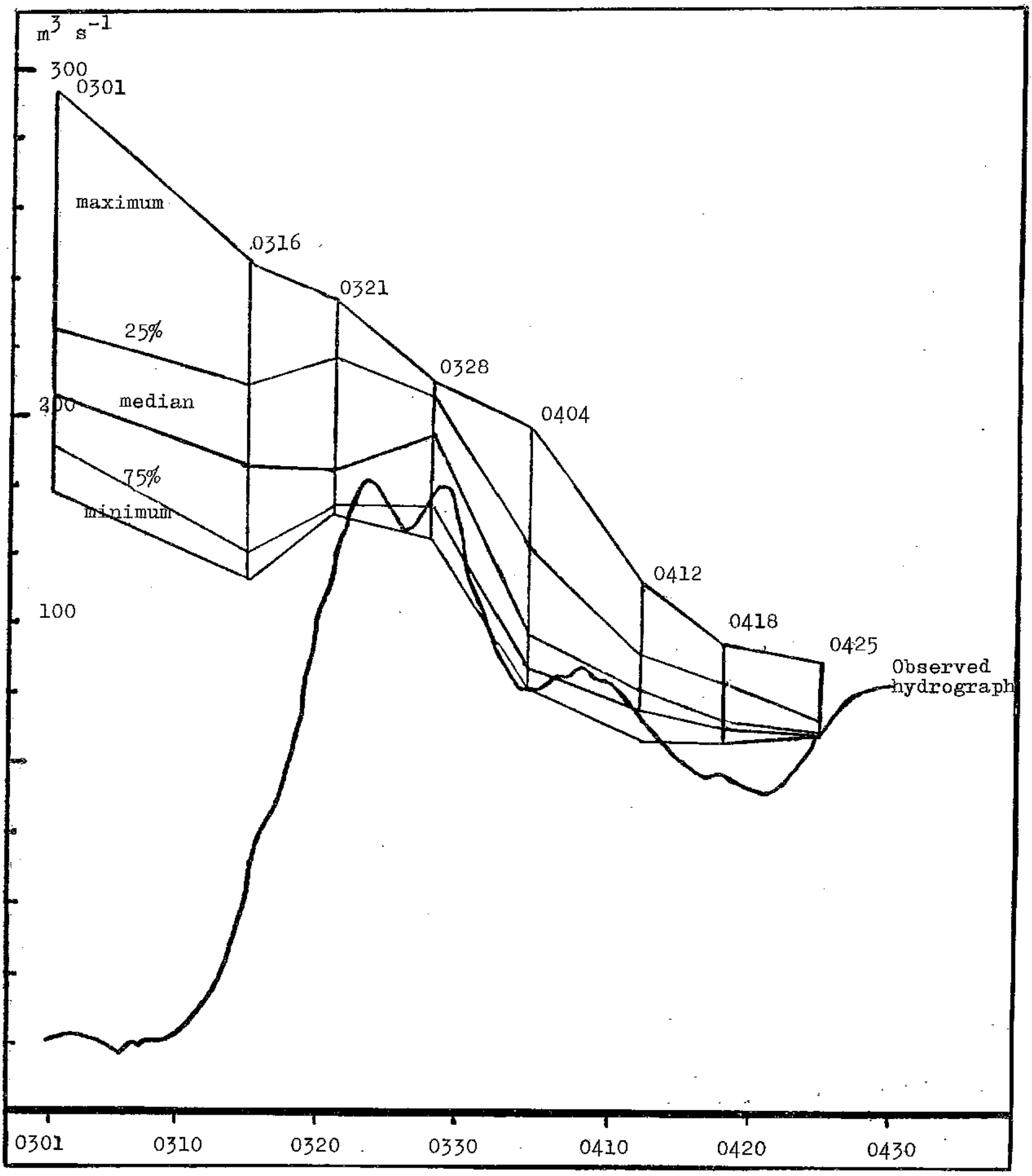


Figure 4 - Forecast of peak flows in Blankostrom based on 13 simulations

In the U.S.A., extended streamflow prediction was applied during the California drought of 1976 and 1977 (17). The results were presented as reasonable maximum, most probable, and reasonable minimum of the 1977 runoff, as indicated in section 2.2 of this report. An example of the inflow forecasts to two reservoirs is given in Figure 5.

2.4 Time-series methods

It would seem that time-series methods have found very limited operational use. Simulation analysis was used during a drought in the Occoquan reservoir in Virginia, U.S.A. (22) and a similar technique has been applied in Australia to the

Canberra water-supply system (29). No operational applications of the methods of Box and Jenkins (see section 1.4.3) have been found.

3. COMPARISON OF METHODS

3.1 Data requirements

If a regression method is used for forecasting, a series of precipitation and discharge data over at least 10 to 15 years is the minimum requirement. Further, if no snow data are available in regions where snowmelt runoff is important, then precipitation stations must be representative of the parts of the catchment where snow accumulates.

Snow-survey data are used extensively in regression methods. Such data are expensive to obtain but recent developments in data-collection systems, such as satellite observations (13) and meteor-burst communication systems (11), have improved the availability of snow data. It has been found that sometimes only a limited amount of the available snow-survey data are actually used in the forecast relationships. Therefore, close co-operation between the data-collection service and the forecasting service is essential.

It has been shown that, in some cases, forecasts based on precipitation alone may be more accurate than forecasts based on the more expensively obtained snow-survey data (2). However, a combination of precipitation and snow-survey data is probably the most promising approach (3).

The conceptual models used for operational forecasting are all of a relatively simple structure, i.e. they need only precipitation and temperature data as input. Snow-cover storage is simulated in the model so snow data are not needed, but some work has been carried out in applying snow-survey data for updating purposes (20). For calibration of the model, an historic series of discharge, precipitation and temperature data must be available although, in general, the length of the calibration series may be shorter than that required for regression methods, e.g. 5 to 10 years. This is a significant advantage in areas where data are scarce.

The time-series methods need discharge data only, if univariate methods can be used but calibration of the time-series model can only be made if a long data series is available (i.e. 10 to 15 years).

3.2 Operational use of forecast methods

For all three methods, the most practical means of establishing the forecast relationships is a computer. A multitude of graphical methods are available for making a regression relation but with the widespread availability of standard programs for regression analysis, computer computations are preferable. However, in the operational use of the forecast relations, regression and time-series methods are usually sufficiently straightforward to be applied by manual computations, the various charts and graphs having been generated previously by computer. On the other hand, conceptual models have to be used by computer if they are to be feasible, although the simple structure of many models means that a mini-computer may be sufficient.

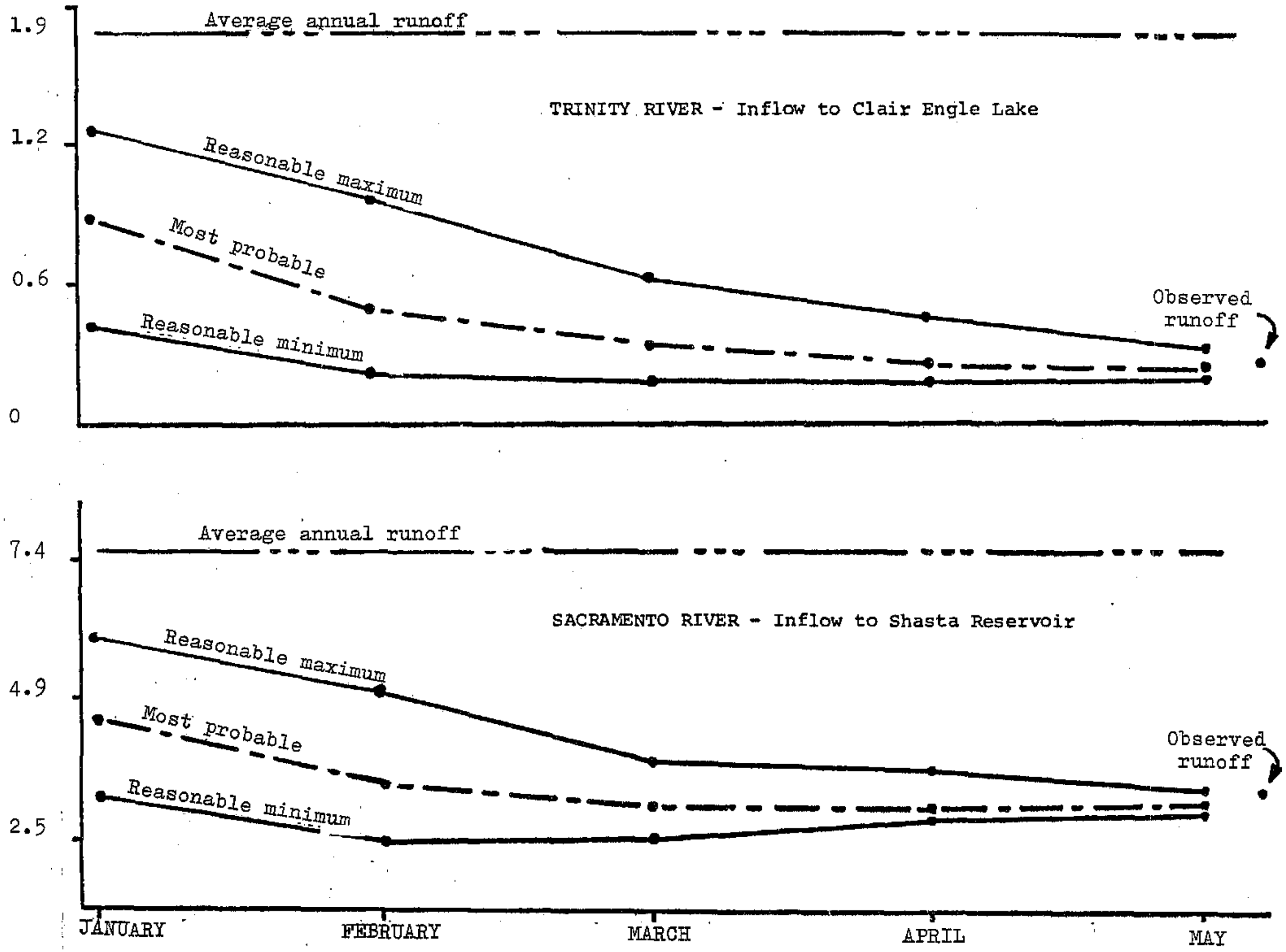


Figure 5 - Forecast of 1977 runoff in cubic kilometres

3.3 Accuracy of forecasts

Generally speaking, the introduction of the more sophisticated conceptual models have not improved greatly the accuracy of long-range water supply forecasts, compared with forecasts made by the classical regression methods. From this point of view, the two methods give rather similar results at present. It is probable, however, that future developments in conceptual modelling, particularly with respect to updating procedures, will improve the accuracy of model forecasts. Such improvements seem unlikely with regression methods which, after many years of refinement, have reached the limit for further significant improvement.

Very limited experience of time-series methods is available, but their accuracy cannot be expected to be better than that of the regression methods.

3.4 Usefulness of forecast methods

Regression and time-series methods are most suited to forecasts of runoff volumes. With conceptual models, probability forecasts of the time distribution of the runoff are readily available, including peak and low flows, etc. Furthermore, forecasts of secondary information from the models, such as snow-cover depletion, soil-moisture conditions and groundwater levels, may be useful. Conceptual models may also incorporate water-resource structures, such as reservoirs and withdrawal for consumption and thereby yield forecasts of the state of a water-resources system.

The potential of conceptual models is therefore large and it is the conclusion of this report that, if the accuracy of long-range weather forecasts continues to improve, it will be conceptual models which will adapt most efficiently.

ANNEX

Questionnaire on long-range water-supply forecasting

Member of WMO: ____________________

Are long-range water-supply forecasts issued operationally in your country;

YES ☐ NO ☐

Comments: ____________________

If YES, answer the following, providing references or publications where possible.

(a) Name(s) and address(es) of Service(s) preparing and issuing the forecasts:

(b) The basic methods used for forecasting are:

	YES	NO
Regression on time	☐	☐
Regression on other variable (describe below)	☐	☐

	YES	NO
Stochastic time-series analysis	☐	☐
Conceptual models	☐	☐
Growth curve, e.g. (describe below)	☐	☐

	YES	NO
Other (describe below)......................	☐	☐

(c) Are meteorological forecasts used in the long-range water-supply forecasts?

	YES	NO
QPF (quantitative precipitation)	☐	☐
Air temperature	☐	☐
Other (describe below)	☐	☐

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