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DESIGN ASPECTS OF HYDROLOGICAL NETWORKS

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CONTENTS

ANNEXES

1 INTRODUCTION

J.W. van der Made *

Network design is a subject which is of essential importance for hydrology. The system of hydrological gauging stations provides the information, necessary for all other hydrological activities.

In early times hydrological measurements were carried out already. The most famous example is the Roda Gauge at the river Nile in Egypt, from which observations are known since 641 (Hurst et al.,1965).
In the 17th century water stage measurements were carried out in Amsterdam for the ocean going vessels. At the river Rhine water stages have been observed since 1770. Rainfall measurements also started in many European countries in the 17th and 18th centuries.

In the beginning it only concerned separate gauging stations. Gradually one became more interested into the coherence of the phenomena examined and the relation between the data, measured at several stations. This lead to the concept of the hydrological network. The problem how to set up such a network became one of the main questions of the hydrological world.

The Commission of Hydrology of WMO, already in the beginning of its existence, was faced with this matter. At its first session in 1960 it established a Working Group, which produced a paragraph on network design for the Guide to Hydrological Practices.

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The 2nd session of the CHy did not establish a working group, but recommended to hold a symposium, which took place in Quebec, Canada in 1965. On the basis of this symposium a panel of experts was established within the framework of the International Hydrological Decade (1965... 1974). This panel recommended WMO to assign a rapporteur with the compilation of a Casebook on Hydrological Network Design Practices.

At its 3rd session the CHy (1968) assigned the late W.B. Langbein (USA) to act as rapporteur in this field. The above Casebook was published in 1972 (WMO, 1972). At the 4th session (1972) the rapporteur was reassigned in order to complete and update this casebook.

At the 5th session (1976) of CHy, rapporteurs were assigned in the fields of Network evaluation (M.E. Moss, USA), Network design under special conditions (I.F. Karasev, USSR) and on Environmental Monitoring (R. Brémond, France). This led to the report "Concepts and Techniques in Hydrological Network Design" (Moss, 1982).

At the 6th session of CHy (1980) the need was felt to examine the mutual aspects of the various approaches and objectives and to take socio-economic aspects into account, which lead to the assignment of the present rapporteur, as a member of the CHy Working Group on Data Collection, Processing and Transmission Systems.
The terms of reference of the rapporteur, concerning these subjects were (WMO, 1981b):

(b) To study the conjunctive design of networks, particularly the relationship between water quantity and quality networks, also using material prepared during the previous intersessional period;

(c) To finalize the report on social and economic aspects of hydrological data collection, using the available draft material prepared during the past intersessional period.

Conjunctive design concerns taking into account several aspects. This can be related to different points of view. It can concern the design of an integrated network with which several elements are measured, such as precipitation and runoff, or groundwater and surface water levels.

Secondly it can serve several objectives, such as forecasting and water resources inventory. Thirdly it can be related to simultaneous measurements of water quality and water quantity. All these aspects will be discussed in the present report.

In the the meantime also in Regional Association VI of WMO (Europe) the need was felt to study problems, concerned with hydrological networks. At its 2nd session (1973) the Working Group for Hydrology of RA-VI decided to establish a subgroup with the task to prepare a report on "Special Requirements of Hydrological Networks for Water Management Purposes".

In the intersessional period of that Working Group the members of this subgroup drafted some material. It was available at the third session (1977) of the Working Group. There it was decided that this material had to be combined and if possible, completed with newly available material.
A first draft of the report was submitted to the 4th session of the Working Group (1980), which recommended to expand the report on groundwater and hydrometeorological aspects. This led to a 1982 edition of the report concerned.

At its 1982-meeting the CHy Working Group on Data Collection, Processing and Transmission Systems decided to use the RA-VI report as a base for a report on conjunctive design of networks, which should also include a chapter on social and economic aspects.

In the compilation of this report the rapporteur was greatly assisted by a number of experts from his country (Netherlands). The experts drafted some of the chapters of the present report.

Chapter 2 includes a general discussion on the design of hydrological networks and the planning procedure. Chapter 3 gives a discussion about the variability of the phenomena considered, which is the real ground for continued measurements and thus for the existence of networks.

Chapter 4 deals with the statistical aspects, related to measurements and its application to network design. In Chapter 5 the social and economical aspects are touched in view of the importance of the produced data for the community. Then networks for the main elements of the hydrological cycle are described: precipitation and evaporation (Chapter 6) surface water (Chapter 7) and groundwater (Chapter 8). The chapters on surface water and groundwater are divided into subchapters concerning data on water quantity (levels and discharges) and water quality.

In Chapter 9 the coherence of the different networks is discussed in view of the various objectives for which networks are set up. This chapter includes a discussion of conjunctive design, in particular whether this is desirable or not.
In Chapter 10 a general review is given.

Two annexes are added to the report. Annex I includes a list of variables and characteristics to be measured for various water management purposes; Annex II gives the results of a questionnaire, which was issued by WMO to investigate the methods and approaches in different countries.

2 GENERAL CONSIDERATIONS ON HYDROLOGICAL NETWORKS

T. Schilperoort*

2.1 Introduction

Watermanagement and waterplanning are becoming more and more important during the last decades. This results from an increasing intensity of use of water resources and an increasing concern of the environment on one hand, and from limitations in budgets on the other hand.
Both watermanagement and planning require suitable hydrometeorological data.
Therefore, monitoring networks providing these data are indispensable.

The three major uses for hydrometeorological data are for planning, management and research. Planning usually requires extensive data with a "long" time base, to determine the natural variability of the phenomena. Management, on the other hand, may require less data, but what it does require may be near real time for daily management or for future forecasting. To cope with the objectives of waterplanning and management, the hydrometeorological data usually are obtained from rather broad routine monitoring networks which have a very long life time.
Generally, research requires intensive data of higher precision than for other uses. Such data may be needed to deepen the insight in and improve the (quantitative) understanding of certain processes.

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Moreover, data may be required for the development, calibration and verification of models, ranging from simple empirical relationships between some hydrological variables to complex numerical models. For these objectives, the data usually are obtained from very specific monitoring surveys. Once enough data are gathered, the monitoring can be stopped. Hence, these surveys have generally a rather short lifetime.

Because of the growing interest for watermanagement and waterplanning, the subject of monitoring networks for both quantitative and qualitative data becomes more and more in focus. The resulting strong increase in the monitoring effort, however, has been attended by restrictions of financial means the availability of reliable and dedicated readers, and changing views with respect to monitoring objectives. As a consequence, there is a growing need for practically feasible techniques for the design and optimization of monitoring networks.
In general, the basic problem to be solved is to establish that network, which provides its user(s) with sufficient information against minimal costs. Obviously, what is sufficient depends on the monitoring objectives as defined by the user(s). Therefore, a general approach is needed to design and optimize monitoring networks, which explicitly takes into account the important part of the objectives in the optimization process.

Within the framework of this approach, the following aspects should be considered:

a) the design and optimization of the network layout, including the the choice of
   - sampling variables (what is to be measured)
   - sampling locations (where is to be measured)
   - sampling frequencies (how often is to be measured)
   - sampling duration (how long is to be measured)

b) the installation of measuring equipment, including
   - the choice of measuring methods
   - the design, calibration and installation of equipment
   - the choice and installation of data transmission systems

c) the implementation of a data processing system, including the choice of
   - a suitable data base structure
   - preprocessing methods
   - postprocessing methods
   - analysis and retrieval methods
   - suitable hardware configuration

d) the organization of a Measurement Service

This report mainly deals with the first aspect. As such, it provides only a minor contribution to the rapidly growing amount of the pertinent literature. However, the specific aim of this report is to help to close the gap for most part, between the rather theoretical treatment of methods in the literature and their practical implementation.

2.2 General approach towards network design

In this section, a general scheme for the design and optimization of monitoring networks is presented and discussed in some detail (Schilperoort and Groot, 1983). Some of its elements will be worked out in subsequent chapters. This scheme, which is summarized in Figure 2-1, can be regarded as the framework of which the Chapters 6 to 8 are specific elaborations.

A monitoring network should be based upon two main boundary conditions, namely the monitoring objectives and the physical aspects of the system to be monitored.

The identification of the monitoring objectives is perhaps the most important step in the design and optimization of monitoring systems, and also a very difficult one. Objectives can be stated in generalities very easily. However, a basic problem of network design is to turn these generalities into mathematical statements which can assess the trade-offs among the various components of the monitoring system.

Perhaps even more difficult is the quantification of the objectives. This quantification is necessary because otherwise an optimal design of networks is not possible. A complicating factor in this respect is the fact that various users of the network may have different objectives. In Chapter 9 the problem of integrating networks and objectives is discussed.

Identification of monitoring objectives is important because they strongly determine the scale of changes to be detected in the data; hence, they dictate the kind of information to be extracted from the data and therefore also influence the way of data analysis.

The analysis of the data, obtained from the network, is also determined by the dynamics of the measured processes. Therefore, knowledge of the physical aspects of the monitored system is indispensable. Moreover, the physical basis of the variability of the relevant processes must be known in order to enable preliminary guesses of their dominant time - and distance scales. Since these scales strongly determine the optimal sampling frequencies and densities, this knowledge is especially important in case a network has to be designed without having historical data at one's disposal. To this subject will be returned in Chapter 3.
The scales of the processes are reflected in the covariance structure of the observed data. It is no wonder therefore that almost every design technique is based somehow on the analysis and processing of covariance-functions. In Chapter 4 the relation between process scales, covariance structure and design technique will be worked out in some detail.

At this point it is important to note the difference between data and information: a high number of strongly correlated (and hence redundant) data may contain less information than a small number of uncorrelated data.

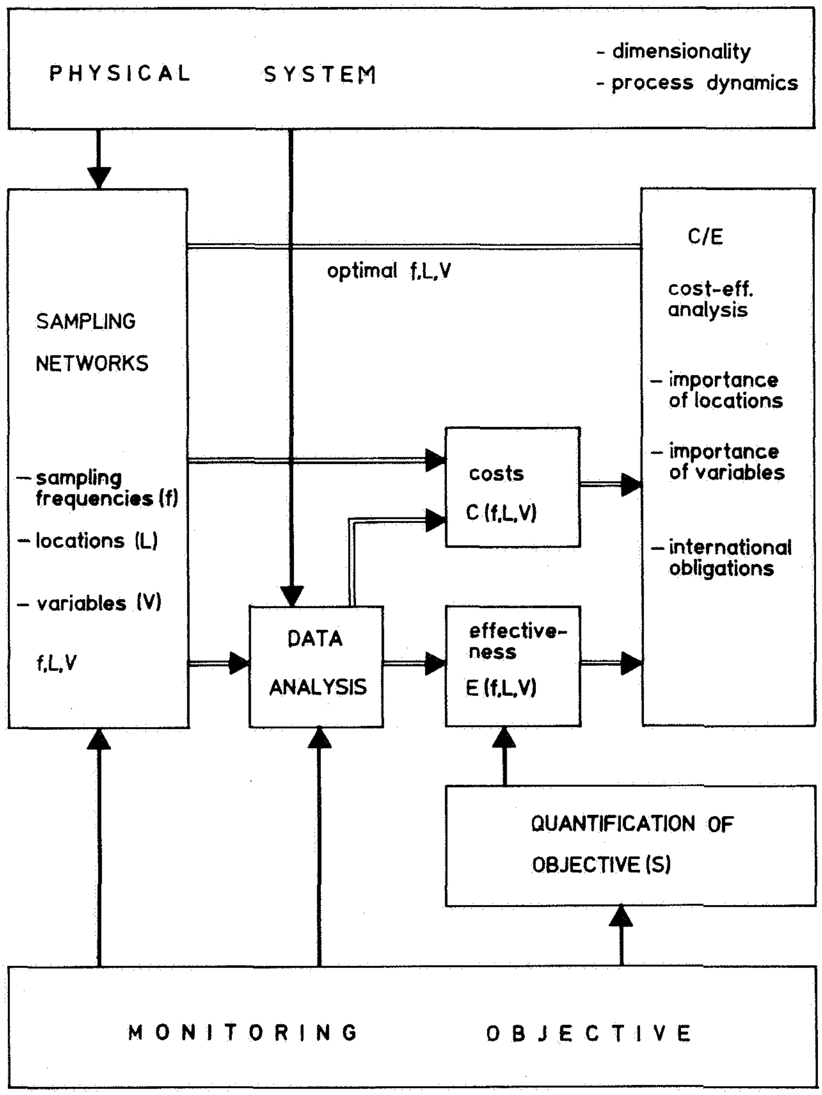

Figure 2-1 Schematic representation of the optimization process for monitoring networks. The monitoring effort is characterized by the sampling frequencies (f), sampling locations (L) and sampling variables (V)

Information, obtained from analyzing the measured data, should correspond to the information as required by the monitoring objectives. As an example, the use of a high sampling frequency enables the detection of small scale features, which may be necessary for the objective "detection of violations of standards". However, when the objective of the network only is to detect long-term trends, a high sampling frequency reveals too much detail of the processes. Hence, unwanted information is obtained at the expense of wasting money.

A central concept in the scheme of Figure 2-1 is the concept of effectiveness of the monitoring network. The level of effectiveness indicates the degree to which the information obtained from the network meets the network objectives. Therefore, the effectiveness can only be at a high level if the data collection and data analysis are optimally tuned to the objectives.
At this point, also the quality of the data, and hence the instrumental errors, come into play. Often, however, it can be assumed that a possible loss of effectiveness due to instrumentation errors is small as compared to a loss of effectiveness due to an insufficient data collection or an inadequate data analysis.
A treatment of instrumental aspects in relation to monitoring systems can be found in Herschy (1978).

To enable an optimal design of a monitoring network, a quantitative measure, E, which quantifies the effectiveness level, is required. Which measure is adequate depends on the monitoring objectives. Often, this measure can be related to statistical concepts like the interpolation error, trend detectability, detectability of standard violations, etc. Having defined an adequate effectiveness measure, this measure E will have to be related to the variables to be designed, like sampling frequencies (f), sampling locations (L) and sampling variables (V). In general, this will yield a functional relationship $E = E(f, L, V)$ by which the performance of a network can be evaluated for various combinations of f, L and V.
As an example, interpolation errors can be calculated as a function of the spatial density of a network, using some specific statistical techniques.

In Chapter 4 the problem of how to construct the functions E (f, L, V) will be discussed for various monitoring objectives. Here, it is sufficient to say, that various techniques exist by which these functions can be derived, even without using actual data from the network. This enables the evaluation of various network layouts à priori. What is needed, however, is knowledge about the spatial and temporal variability of the processes to be measured. In practice, this knowledge can be obtained from a proper processing of historical data, from physical knowledge, or from both.

The sampling frequencies (f), locations (L) and variables (V) determine not only the effectiveness E of the network, but also strongly the costs C of the network. Therefore, also these costs can be expressed as a function C = C (f, L, V).
In practice, this will be a relatively simple, although time consuming, exercise. Important aspects are the costs of:
- equipment and personnel;
- installation and maintenance;
- sample collection;
- sample analysis (e.g. chemical analysis of water quality samples);
- data storage and data processing.

Once the relationships E = E (f, L, V) and C (f, L, V) are found, the optimal network can be found, in principle, by weighting E against C in a cost-effectiveness analysis. Such an analysis should, amongst others, take into account the relative importance of the sampling locations and variables. Generally, low monitoring effort corresponds to low measurement costs, and to a low effectiveness level. To find the optimal effort, the costs associated with a possible deficiency of effectiveness (e.g. consequences of wrong decisions based on insufficient information) should be calculated in principle.
However, since such an analysis is not only very difficult, but also very subjective, it is almost always avoided in practice. Instead of minimizing the total monitoring costs, the effectiveness level itself is often used as a surrogate measure for the network performance, for which a minimum value is specified a priori.

Examples are the often arbitrary specifications of interpolation accuracy, trend detectability etc. Since in general these minimal values are based on subjective and/or political considerations, the real optimal network might not be achieved. To this issue will be returned in Chapter 5.

Summarizing the above, six main steps can be distinguished in the process of designing a monitoring network:

(i) The monitoring objectives should be identified, and quantified. Also, an adequate measure of the monitoring effectiveness has to be defined, which is tuned to the objectives;

(ii) The physical aspects of the system should be studied in order to identify the relevant process dynamics and the corresponding time- and distance scales;

(iii) The way, the data should be analyzed, has to be chosen. This strongly depends on the physical aspects and the monitoring objectives;

(iv) The effectiveness of the information, E, obtained by analyzing the data from the network, should be determined. For this purpose, a relationship has to be found between the effectiveness E and the variables f, L and V;

(v) The costs of the monitoring program should be calculated, resulting in the relation $C = C\ (f, L, V)$;

(vi) A cost-effectiveness analysis should be made, yielding optimal values for sampling frequencies, locations and variables.

The crucial step in the outlined procedure is the fourth one. In the literature, methods to find relationships between some effectiveness measure and network layout get more and more attention. In Chapter 4 these methods will be discussed in some detail.

From Figure 2.1, it can be seen that the design and optimization of monitoring networks is an iterative process: the optimal (future) network is based on the information gained from the present one. This requires an initial network to start with. This can be an existing network in case of optimization.

When, however, new monitoring activities have to be started, the initial network design can only be based on physical insight in the relevant processes (correlation-structures!), and already existing data from other sources.
After a certain period of network operation, the network can be evaluated and adjusted, based on the information obtained. Several iteration steps may be required before the network approaches its optimal shape. This implies that, in practice, a real optimization is only possible for long lasting routine monitoring networks, as normally used for management and planning purposes. However, the usually rather limited duration of research related monitoring, often organized in temporary measurement programmes, does not permit such an iterative optimization.

The different time-scales and objectives of management, planning and research related monitoring often lead to the concept of more network levels, like a basic network and an additional network. Additional networks may provide information, which can be used to optimize the basic network (Langbein, 1954).
In this connection, it is important to note that in the USSR base stations and specific stations are distinguished (Karasev, 1968).

At the end of this section, it is important to realize that, in practice, the design and optimization of monitoring systems is often restricted by conditions, reaching far beyond the scope of the network, which are based on legislation and/or international commitments. This may yield fixed sampling locations, variables and frequencies, which cannot be changed, even if it is desirable from a monitoring point of view. In that case, the fixed part of the monitoring system should be the starting-point for the optimization of the remaining part. For example, in case of surface water monitoring networks, fixed locations might exist, for instance at inflows of important tributaries, at border crossings of rivers etc. (see further Sections 3.4.3 and 7.1).

3 THE PHYSICAL BASIS OF VARIABILITY

S. van der Schaaf*

3.1 Introduction

Hydrological systems are physical systems that are three-dimensional in space and one-dimensional in time.

Although this is an important feature, it does not provide a reason for establishing extensive hydrological monitoring networks with observation frequencies and spatial distribution of observation points for several physical quantities.

The one and only reason for the existence of such networks is the variability of the quantities in hydrological systems in these four dimensions.

Without variability, one measurement of each physical quantity of interest, related to the system, would be sufficient to obtain an adequate description of that system. The concept of variability will not be dealt with in detail in this section; for this moment it is sufficient to note that, for example, the variability in space and/or time of physical quantities can be described in terms of autocorrelation and distance in space or time: the higher the variability of a quantity, the more rapidly the autocorrelation coefficient decreases with increasing distance in space or time.

Variability is dealt with in a more fundamental way in the next chapter.

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Much of the variability of hydrological quantities can be traced back to physical causes. The variability of a quantity may be different in different directions or in time. Because variability is the reason for the existence of hydrological observations networks, variability should also be taken into account in the design phase of a network in order to approach an optimum design from the beginning.

In order to obtain the highest possible amount of information from installed observation points, the highest density of points should be on those places where and in those directions in which the highest variability occurs, assumed that other factors, that influence the density, like spatial correlation, socio-economic interest into the information and costs per station do not differ very much.
Two examples:

1. A series of simultaneous groundwater level measurements at different points along a groundwater contour line gives little or no more information than a single measurement. More information would have been obtained from the same number of points if the series had been made in a direction perpendicular to the contours, which is much more likely to be the direction of highest variability.

2. A series of daily observations over 50 years from one precipitation measuring station out of a number of 50 well correlated stations in a particular area gives more information about the rainfall regime in that area than 50 one year series of the same year from the 50 stations.

When designing or redesigning a hydrological observation network it is therefore necessary to have as much knowledge available as possible on the physical properties of and the processes in the system involved.

Hydrological systems have in common that they transform one or more inputs into one or more outputs.

Inputs may be precipitation in any possible form, other inflows (such as groundwater recharge from rivers) and energy (Fig. 3-1).

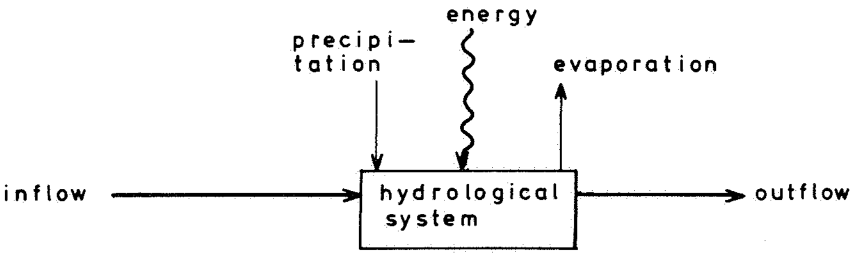

Figure 3-1 Inputs and outputs of a hydrological system

The part of the energy that is of importance in hydrologic processes is - at least in most areas - mainly dissipated via evaporation, which is one of the outputs. Another part, especially in areas with snowfall and forming of ice during the cold season, a considerable portion of the incoming energy may cause ice or snow melt. Other outputs are streamflow, surface and subsurface runoff and all other outflows of liquid water. We shall call them outflows.
The outflows differ from the inflows in their distribution of intensities in time and space.

3.2 Variability in time of inflows and outflows

The differences in time-variability between inflows and outflows deserve some special attention. They are mainly caused by the storage properties for water of the hydrological system and - as far as evaporation is concerned - by the energy input and the energy storage properties. The variability in time of outflows is therefore generally lower than that of inflows. This is because storage implies integration in time and integration in time means suppression of short-term changes.

There is a certain proportionality between the rate of outflow and the amount of water stored in the system, which suggests the presence of a flow resistance between inflow and outflow locations. Although such a system cannot be described fully in a simple scheme, we will use an approximation by the electric circuit of Figure 3-2.

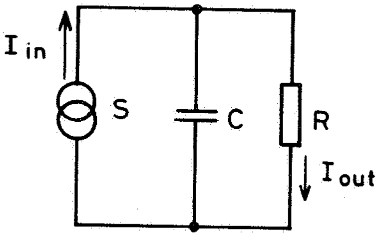

Figure 3-2 Electric approximation (simplified) of inflow and outflow of a hydrological system

The capacitor C represents the storage, the resistor R the flow resistance from point of inflow to point of outflow. The inflow consists of a sinusoidal signal with amplitude I_{in} and period T, supplied by the current source S.

The circuit of Fig. 3-2 is a simplified lumped circuit approximation with point inflow of a hydrological system with integrated storage and resistance and areal inflow. Fig. 3-2 is meant to demonstrate the effect of storage and flow resistance rather than to give an adequate description of what happens to water in a hydrological system.

By applying simple network theory, the ratio of inflow and outflow amplitude I_{out}/I_{in} (amplitude transfer ratio) can be found for any input frequency component as

$$I_{out}/I_{in} = (1 + \omega^2R^2C^2)^{-\frac{1}{2}} \tag{3.1}$$

in which ω is 2π times frequency or $\omega = 2\pi/T$, T being the time of one full period. The product RC has the dimension T and is often called the time constant of the system.

From (3.1) it can be seen that

- for ω^{-1}=RC the amplitude transfer ratio is $1/\sqrt{2}$.
- for $\omega^{-1}<$ RC the amplitude transfer ratio is approximately proportional to ωRC.
- for $\omega^{-1} >$ RC, the amplitude transfer ratio approaches 1, which means negligible amplitude reduction of output with respect to input.

A graphical representation (Bode plot) of the amplitude transfer function of Eq. (3.1) is given in Fig. 3-3.

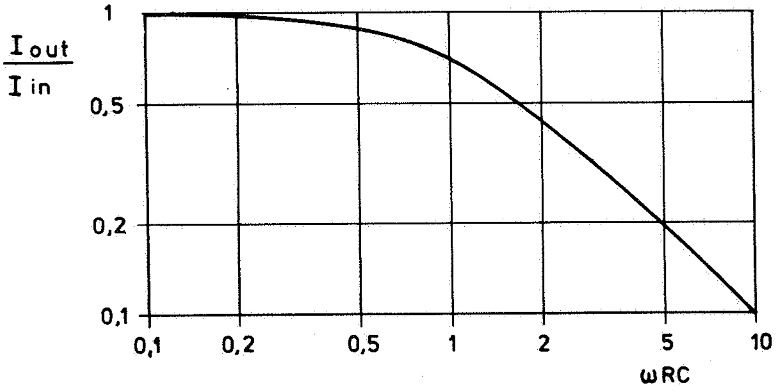

Figure 3-3 Bode plot of amplitude transfer ratio versus dimensionless frequency ωRC of the circuit of Fig. 3-2

Although it must be emphasized that this approach is very schematic, a real hydrological system can be approximated by a number of such circuits in a series/parallel system, together with some non-linear elements, caused by processes as seepage via surfaces of groundwater level dependent extension, shallow phreatic aquifers with groundwater level dependent transmissivity, etc.
Although non-linearities in a system cause generation of harmonics, they generally do not disturb the behaviour of hydrological systems to such an extent that the kind of process as shown by (3.1) is affected in a considerable way.

The general behaviour of hydrological systems in this respect is indeed characterized by a small or even negligible reduction of slow input components, such as seasonal fluctuations and a considerable reduction of fast input components such as daily fluctuations.
For variability in time, this means that indeed the variability in outflows has a tendency to be smaller than that in inflows.

3.3 Variables and characteristics

Hydrological quantities that are variable in time are called hydrological variables or hydrological variates. Examples of hydrological variables are:

- groundwater piezometric level
- surface water stage
- discharge
- water quality
- evapo(transpi)ration
- precipitation
- soil moisture content

Quantities that are supposed to be time invariant are called hydrological characteristics. Examples are:

- soil physical characteristics, such as moisture retention properties;
- land topography;
- transmissivity of an aquifer;

- hydraulic resistance of confining layers;
- storage properties and extension of aquifers;
- drainage pattern.

Hydrological variables are inflows, outflows and quantities related to stored amounts of water.
Hydrological characteristics determine the transformation of input to outflow.

However, there may be time variant factors, not being hydrological variables that influence the transform process, such as:
- seasonal variations in vegetation cover;
- energy input that causes ice and snow melt;
- seasonal variation in depth of the unsaturated zone.

Such factors cause non-linearities in the transform process of input to outflow.

Furthermore, hydrological characteristics may not be as time invariant as they seem.
Firstly, the earth's crust is a dynamic system. Erosional, sedimentological and other processes have acted probably as long as this planet exists and their action still continues, though often very slowly under natural conditions.
There may also be more sudden changes than those, that are generally induced by such processes. If they occur, they are often caused by human activities. Some examples are:
- rapid soil degradation as a result of man-induced erosion;
- leaching and accumulation of salts in or near irrigated areas;
- improvement of land drainage in agricultural areas;
- improvement of artificial drainage;
- creation of reservoir lakes;
- closure and diversion of rivers and tidal streams.

Such changes may - and eventually will - lead to changes in hydrological networks, because they affect the variability of outflows in time and sometimes in space.

Like hydrological variables, hydrological characteristics normally have a variability in space. Aquifers do not extend infinitely and their transmissivity may vary from place to place; the same is true for confining layers and their vertical resistance; rivers take up or release water from or into aquifers and they have tributaries; slopes have a top, a bottom and a finite extension, etc.
All these variabilities affect the transform process in the hydrological system and they should be taken into account when an observation network is designed.

3.4 Consequences for network design

It is strongly recommended that before designing and installing measuring sites and equipment, an inventory be made of available information on hydrological characteristics, with special attention to places and/or areas where changes in characteristics occur or are likely to occur.

They may be:
- morphological features, such as:
  - transitions from lowlands to uplands;
  - lakes with inflows and outflows;
  - natural drainage patterns.
- geological features (partly related to morphology) such as:
  - location of faults, folds, etc.;
  - sedimentological history of geological formations;
  - aquifer type (carbonate rock, sand, confined, phreatic).

Useful information sources may be soil and geological survey reports and maps, aerial photographs and even ordnance survey maps, particularly if they show good contour lines. This information should be supported by field measurements, which, if carried out properly, need be done only once per location if variability in time is really negligible.

They include:
- an additional geologic survey if insufficient information is available;
- measurement of aquifer properties including transmissivity, vertical resistance of (semi)confining layers and their lateral extensions.

Most of such measurements should be done where transitions are likely, in particular in areas where transitions cannot be found easily by distinct morphological features. Several kinds of methods may be used such as geoelectric measurements, deep drillings, pumping tests, etc. Installation of measuring sites and equipment for measuring and monitoring hydrological variables should be based on such an inventory.

In the next and last part of this chapter the use of physical information for location and density of recording sites and for determining recording frequency will be discussed briefly with respect to the measurement of some hydrological variables, which are:
- precipitation and evaporation;
- groundwater level;
- stage and discharge of rivers, sediment transport.

The section on groundwater is discussed more in extenso, since it concerns, in a way, the system, that transforms the input variability (of precipitation and evaporation) into the output variability (of discharge).

3.4.1 Precipitation and evaporation

For convenience it is assumed silently that evaporation includes evapotranspiration.
From a systems point of view, precipitation and evaporation are similar quantities that differ in sign only.

Physically they are different because they are not caused by the same factors at the same time and at the same place, which is of influence on their variability in both time and space.
Precipitation has a variability in time; intensities may vary considerably within time spells as short as one minute. Longer term variabilities may be fluctuations in intensities from night to day, especially occurring in tropical areas, and seasonal fluctuations.
Evaporation shows strong differences in intensity between day and night as well as seasonal fluctuations. It also depends on the availability of water.
As a rule, the short term variability of evaporation can be considered as being smaller than that of precipitation. However, for reasons pointed out below, this does not necessarily lead to a registration frequency for precipitation that is much higher than the registration frequency for evaporation.

Evaporation intensity depends - apart from the availability of water and energy - on local surface conditions, such as smoothness or vegetation cover; it also differs between urban and rural or natural areas. It may vary at very short distances. For example, a tree will produce an evaporation rate per surface unit that is considerably higher than that of a grass covered surface in its shade.

However, such very detailed effects are not often of interest and it is almost never feasible to establish a network for monitoring them.
For practical purposes, particularly in flat regions, the spatial variability of evaporation can generally be considered as being lower than that of precipitation, which implies that in most cases more gauging sites are needed for measuring precipitation than for evaporation.
In mountainous regions the spatial variability of both increases, as may be expected on physical grounds.
However, the designer of a hydrological network will have to rely rather heavily on statistics as physical features of the hydrological system alone will usually provide an insufficient basis for the design of the precipitation/evaporation part of a network. The reason is simply that the main physical factors that determine the variability of precipitation are not part of the hydrological system.

Variability in time does not have as much implication for the measuring frequency of precipitation and evaporation as for a number of other hydrological variables. The reason is that both precipitation and evaporation measurements usually are carried out as integrating measurements (sums) over a certain period of time.
This means that the influence of short term fluctuations is averaged over the measuring time interval. Thus high frequency components are suppressed by the same kind of process as by which they are suppressed in the hydrological system (see Fig. 3-3).

The observation frequency can therefore be adjusted to be in agreement with the frequency response of the system and thus with the frequency spectrum of the outflows and storage variables such as groundwater levels. In practice, the observation frequency should be at least equal to or - preferably - 2 to 5 times as high as the observation frequency for storage and outflow variables.

3.4.2 Groundwater levels

The variability of groundwater levels in both space and time depends much more on hydrological characteristics than precipitation and evaporation. There is a certain difference in behaviour between phreatic and confined aquifers. There are also interactions between them. Phreatic aquifers may have a shallow or a deep unsaturated zone, which influences their behaviour.

Groundwater levels in phreatic aquifers with a shallow unsaturated zone:

Variability in time and space often is the largest in phreatic aquifers where the earth surface cuts locally into the phreatic level at times, thus in fact draining the aquifer. Such systems are often artificial: actually all artificially drained areas have such a phreatic system. In such areas the product of storage coefficient and drainage resistance, approximately equivalent to the time constant RC in Equation (3.1), is low because of the low drainage resistance.

If phreatic levels are near the surface and evaporation is not very high, the pF-value in the remaining unsaturated zone will be low and because of this, many smaller pores will be filled with water. As a result, the effective storage coefficient will have a much lower value than with a lower groundwater table. This also contributes to very fast groundwater level reactions on rainfall. The variability of groundwater levels in the horizontal plane in such aquifers may be considerable partly because a few decimeters of difference in distance between water table and surface may create considerable differences in groundwater level reactions and partly because they are drained locally.

To adequately describe the behaviour of the groundwater level in such aquifers, daily observations in a relatively dense network may not even be sufficient for a full description as the variability of levels within one day may be considerable. However, such a high observation frequency will not be feasible in many cases. A reasonable solution may be to have automatic recording equipment installed on a limited number of places spread over the area, together with a number of other sites that are observed less frequently.

Groundwater levels in confined aquifers:

Confined aquifers underlying phreatic aquifers will have a much lower spatial variability in head, because their low storage coefficient causes a rapid horizontal propagation of local fluctuations, which in fact means that many local effects are averaged over a large area.
The same low storage coefficient, however, may cause a considerable propagation of short term fluctuations from the phreatic aquifer into the confined one.

In fact, there are two storage coefficients: one for the aquitard and one for the confined aquifer itself.
The flow through the aquitard - which is assumed vertical - is governed by the following equation (Bredehoeft and Pinder, 1970):

$$\frac{\partial^2 h}{\partial z^2} = \frac{S_s}{K} \cdot \frac{\partial h}{\partial t} \qquad (3.2)$$

where

h	head	L
K	vertical permeability of the aquitard	LT^{-1}
S_s	specific storage (storage per length unit)	L^{-1}
t	time	T
z	vertical axis variable (cartesian)	L

Equation (3.2) is essentially a one-dimensional diffusion equation. An approximate solution for such a system can be obtained if the storage is thought of as concentrated in the middle of the aquitard, connected to the overlying aquifer by one half of the vertical hydraulic resistance of the aquitard and to the underlying confined aquifer by the other half. The electric circuit equivalent (Karplus, 1958) is given in Fig. 3-4. Addition of the storage in the confined aquifer yields the circuit of Fig. 3-5.

Although this is not an exact representation of the hydrological system because the circuit has lumped storage whereas the hydrological system has distributed storage, the result is sufficient for the semi-quantitative approach of this chapter.

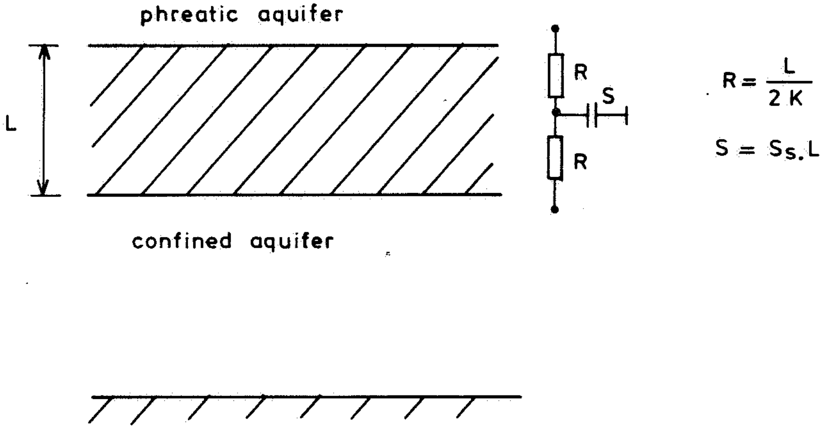

Figure 3-4 Lumped circuit approximation for vertical flow through an aquitard

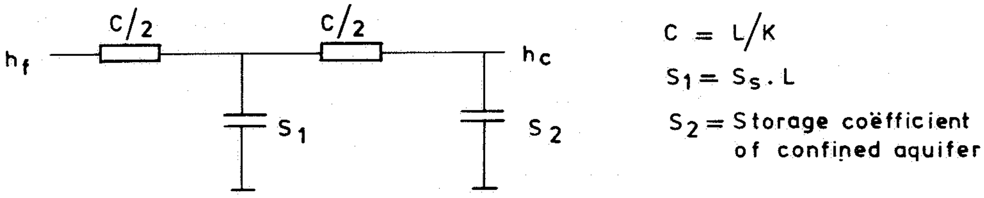

Figure 3-5 Circuit of Figure 3-4 completed with storage in the confined aquifer

Application of network theory yields the following amplitude transfer function for an arbitrary frequency component of the fluctuation of the head in the phreatic aquifer:

$$\frac{h_c}{h_f} = \{ (\tfrac{1}{4}\omega^2 c^2 S_1 S_2 + 1)^2 + \tfrac{1}{4}\omega^2 c^2 S_1^2 + \omega^2 c^2 S_2^2 \}^{-\frac{1}{2}}$$

where

ω	2π times frequency	T^{-1}
c	hydraulic resistance ($c=L/K$)	T
h_c	head amplitude in the confined aquifer	L
h	head amplitude in the phreatic aquifer	L
S_1	storage coefficient of the aquitard ($S_1=S_s.L$)	-
S_2	storage coefficient of the confined aquifer	-

If the two storage coefficients S_1 and S_2 are of the same order of magnitude, the Bode plot of Equation (3.3) is similar to curve 1 in Fig. 3-6.

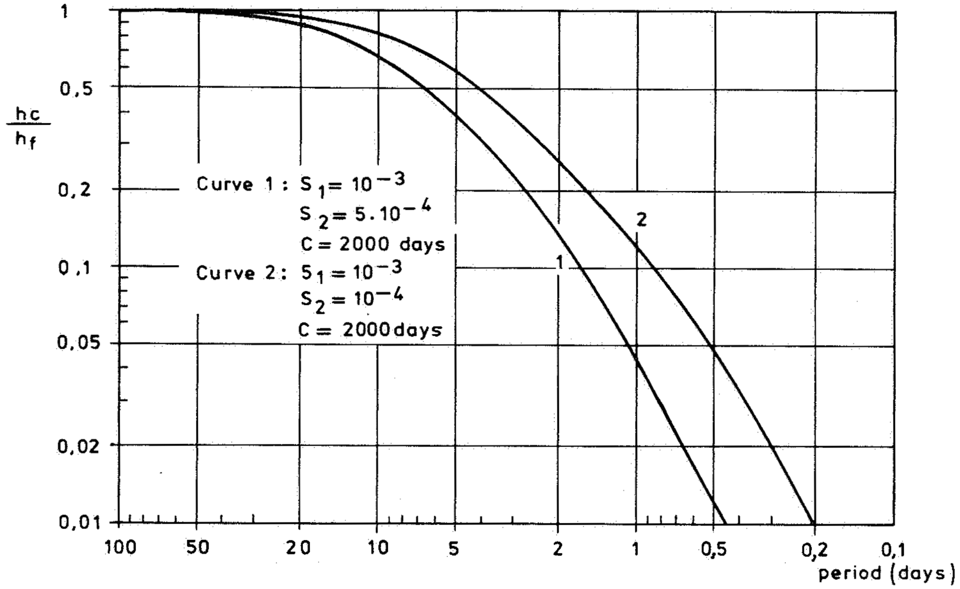

Figure 3-6 Amplitude transfer ratio h_c/h_f versus period length for equal time constants S_2L/K and $S_1L/(2K)$ (curve 1) and time constants differing by a factor 5 (curve 2); according to Eq. (3.3)

If they are of different order of magnitude, a curve of the shape of curve 2 in Fig. 3-6 is obtained. The behaviour of the system is practically determined by the time constant of either S_2L/K or $S_1L/(2K)$.

In such an aquitard/aquifer system with, say, S = 0.0005 and C = 2000 days, the value of the time constant is between 0.5 and 1 day, which means that the amplitude of a frequency component with a 3 to 6-day period is suppressed by a factor of less than 1.5.
All this implies that the number of observation points for a confined aquifer can be much lower than for the overlying phreatic aquifer, but that one should be very careful, when considering a lower observation frequency for the confined aquifer than for the overlying phreatic aquifer.
]

Groundwater levels in phreatic aquifers with a deep unsaturated zone:

Much slower reactions to precipitation inputs are shown by phreatic aquifers with a deep unsaturated zone. Storage and vertical flow resistance in the unsaturated zone effectively suppress the effects of fast fluctuations, leaving only the slower term fluctuations (e.g. time periods of a month to perhaps a year, depending on the depth of the unsaturated zone) relatively unaffected.
If insignificant irregularities occur in such an aquifer, the levels will show very gradual changes in horizontal directions. In such aquifers the variability in both space and time is low, allowing for an observation network of low density and a low observation frequency.
An underlying confined aquifer may - perhaps somewhat surprisingly - show higher variabilities in time if it has a lateral contact with a water body that has faster fluctuations. A low storage coefficient and a high transmissivity in the confined aquifer may cause a rapid lateral propagation of such changes over a large distance if the vertical resistance of the confining layer is high.

The two situations with respect to phreatic aquifers described here are extremes and many situations will be somewhere in between the two. However, many other factors may influence variability of groundwater levels in time and space.
Some examples are:

- horizontal anisotropy in folded areas. Such kind of anisotropies may also occur in formerly glaciated areas (push moraines);
- along tectonic faults, large differences may occur between levels on both sides of the fault;
- groundwater levels in coastal areas may be influenced by tides;
- human influences such as artificial drainage, irrigation, groundwater pumping stations, etc. influence groundwater levels in both space and time;
- groundwater level fluctuations may be reduced in the presence of lakes;
- barometric effects may occur, particularly in confined aquifers;

- snow melt may cause a rapid and considerable rise in groundwater level;
- evaporation may cause diurnal groundwater level fluctuations (Meyboom, 1964).

3.4.3 Stage and discharge of rivers, sediment transport

The variability of the surface water, i.e. the river stage and discharge, is a function of the variability of the input (precipitation and evaporation), which is transformed by the characteristics of the catchment.

Relatively slow changes in discharge occur in rivers with a high base flow component, that may originate from storage of and outflow resistance to groundwater, the presence of storage in large lakes in the river course, snow and glacier melt in warm periods, etc.

More rapid changes occur in rivers that mainly transport water from low storage catchments that transmit rapid changes in inflow (e.g. short periods of precipitation), such as areas with shallow soils (or no soil at all) on hard rock. Undrained bogs and mires also release water rather rapidly, wheras drained peat areas generally show increased storage properties (Ivanov, 1981).

The storage properties and outflow resistance of feeding reservoirs may be influenced by human action: artificial drainage causes a distinct increase in short term outflow by lowering outflow resistance and a drop in base flow - for which it actually is installed - but may also cause some increase in storage capability. Erosion causes a decrease in both storage capability and outflow resistance.

Creation of reservoirs causes an increase in both.

As a consequence, the desirable measuring frequency for river stage and related quantities depends highly on the conditions in the catchment and along the course of each tributary and one should be aware of the possibility of changes in those conditions.

Gauging sites in rivers or other open water areas should anyway be located on places where changes are obvious, such as (WMO, 1972):

- at inflows of important tributaries;
- at branching points of rivers (e.g. in deltas);
- at the inflow of a river into the sea, a lake or a reservoir;
- at the outflow of a river from a lake or a reservoir;
- upstream and downstream of weirs and sluices;
- where a narrow and confined streambed enters a wider valley;
- where a stream flows from a wide into a narrow valley.

If considerable changes in discharge appear to occur between measuring sites, e.g. because of release or uptake of water into or from an aquifer along the river course, it may be useful to install one or more additional sites between such places.

River stages can be recorded manually or by automatic equipment. Whether a combination, or one of the two methods is used, depends on:

- the variability in time of the stage;
- a trade-off between cost and required accuracy of the recording of the fluctuation pattern (see also Chapter 5).

In free flowing rivers a relation exists between river stage and discharge. Such a relation may change slowly as a result of changing conditions in the river bed. However, such changes normally are slow enough to justify computing discharge from stage data. Discharge measurements serve the purpose of:

- defining the relation between stage and discharge;
- detecting possible changes in the relation between stage and discharge.

The frequency of such measurements is thus determined by the slowly changing properties of the river, rather than by the more rapidly changing discharge.

The fluctuation speed of discharge depends on geohydrological and other characteristics of the catchment areas that discharge via the river involved and on the climatic conditions in those areas.

Sites for measuring sediment transport should preferably be combined with stage measuring sites, since sediment transport depends on discharge. Sediment transport may also show more or less strong seasonal influences.

4 STATISTICAL ASPECTS

T. Schilperoort*

4.1 Scales, variability and correlation structure

In 1924 Nyquist proved that, using a sufficiently close discrete point sampling, it is possible to recover the original continuous sample from the discrete observations. His statement implies that using sampling intervals which are at least two times smaller than the smallest time or distance scales in the process, no information loss will occur due to sampling. However, such small intervals are not feasible in practical systems. First of all because of enormous costs associated with very dense networks, and secondly because many objectives do not demand a very detailed reconstruction of the continuous processes.

The essential problem in finding an optimal sampling density is the determination of the time and distance scales which are pertinent to the monitoring objectives, and their effect on the effectiveness of a sampling programme.

Time and distance scales of the considered processes are the result of variations in boundary conditions of the hydrological system, and of variations in the physical characteristics of the system itself. These physically determined scales will be called the intrinsic scales of the process. These scales are reflected in the correlation structure of the observations of that process.

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This correlation structure includes all possible spatial and temporal auto- and cross correlation functions of the process.
A correlation function $\rho_{xy}(\tau)$ gives the correlation between two variables x and y as a function of their time or distance spacing τ. Therefore, it gives information about the distance and time scales over which a process is coherently related in itself or to other processes. The larger these scales, the larger the distances in space or time over which observations will be correlated to each other.

Besides these scales, also the intrinsic variability of the processes at a fixed location or moment has strong implications on network design. This variability is reflected in the variance, σ^2, of the observations of the processes.

The variances and the correlation structure determine together the covariance structure of the data. As an example, two spatial covariance functions $\gamma_x(\tau)$ are sketched in Figure 4-1. Since $\gamma_x(\tau)=\sigma^2\rho_x(\tau)$ the first one characterizes a highly irregular process with strong variations over short distances, whereas the second one corresponds to a very smoothly behaving process.

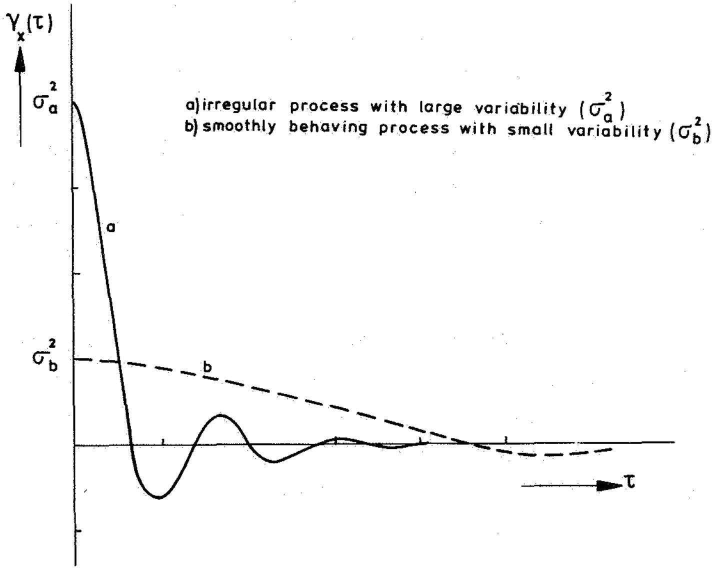

Figure 4-1 Example of a covariance function

The scales and variability of a process determine the amount of information, contained in one observation, and also its redundancy. As is well known, the amount of information decreases with increasing variability, σ. Moreover, this information becomes more redundant with increasing ratios, Γ/Δ , between the dominant scales, Γ , and the sampling interval, Δ. Hence, σ and Γ/Δ are two important parameters in network design.

A third parameter, which may be crucial, is the ratio, T/Γ ,between the measurement duration, T, (or area) and Γ . This is especially true when mean values, or related properties like trends, have to be estimated.

It can be stated that for almost all monitoring objectives, which are usually defined for watermanagement and planning, the effectiveness of a network depends somehow on the three parameters σ, Γ/Δ and T/Γ. This will be illustrated in the next two sections, one of which is related to the design of a sampling interval in time, and the other to a sampling interval in space.

4.2 Sampling frequency

In this section, an example is presented which illustrates the relationship between the variables σ_x^2, Γ/Δ and T/Γ on one hand, and, on the other hand, the sampling frequency of a network for which the main objective is the estimation of mean values.

For other objectives, quite different approaches may be needed. However, the general statements remain valid.

Suppose a sampling frequency has to be chosen, which enables the calculation of a mean value of some hydrological variable x at a certain location with some prescribed accuracy. Moreover, let us assume that the variance σ_x^2 and the correlation function $\rho_x(\tau)$ of the considered process are known (to this assumption will be returned later).

Let us first consider the situation of monitoring without making any instrumental or observation error.

Discrete sampling, with a sampling interval Δ, will yield $N(\Delta,T)$ sample values $x(t_k)$ at times $t_k = k\Delta$, $k = 1 \ldots N$, with $N(\Delta,T) = T/\Delta$ and T the measurement period.

Based on these samples, a mean value can be calculated according to

$$m_x = \frac{1}{N(\Delta,T)} \sum_{k=1}^{N(\Delta,T)} x(k\Delta) \qquad (4.1)$$

Regarding the objective, an appropriate measure of effectiveness E might be the reciprocal standard deviation in m_x. It can be shown then that

$$E(\Delta,T) = \frac{1}{\sigma_m(\Delta,T)} = \frac{1}{\sigma_x} \sqrt{N^*(\Delta,T)} \qquad (4.2)$$

Here $N^*(\Delta,T)$ denotes the <u>effective number of independent observations</u> in an autocorrelated time series with autocorrelation function $\rho_x(\tau)$. This N^*, which depends on both the sampling interval Δ and the measurement duration T, is given by (Bayley and Hammersley, 1946):

$$N^*(\Delta,T) = N(\Delta,T)\left\{ 1 + 2 \sum_{i=1}^{N(\Delta,T)} \left(1 - \frac{i}{N(\Delta,T)}\right)\rho_x(i\Delta) \right\}^{-1}$$

$$N(\Delta,T) = T/\Delta \qquad (4.3)$$

In case of uncorrelated data, $\rho_x(i\Delta) = 0$ for $i \neq 0$, Equation (4.3) simply becomes $N^* = N$. This implies that each observation is effectively independent from the others, and contains the maximum amount of independent information. This situation can only occur when the sampling interval is larger than the dominant time scale Γ, i.e. when $\Gamma/\Delta \ll 1$. With correlated data, N^* might deviate considerably from the real number of observations N. Usually, N^* will be smaller than N, because correlated data contain, to a certain extent, redundant information. This is illustrated in Figure 4-2, in which N^* is given as a function of N, assuming an exponential correlation function $\rho_x(\tau)$ given by

$$\rho_x(\tau) = \exp\,(-\tau/\Gamma')$$

This implies

$$\rho_x(i\Delta) = (\rho_1^m)^i \tag{4.4}$$

with

$$\rho_1 = \exp(-\Delta_1/\Gamma')$$

in which ρ_1 denotes the correlation coefficient between two observations with a unit time lag Δ_1, and $\Delta = m.\Delta_1$.

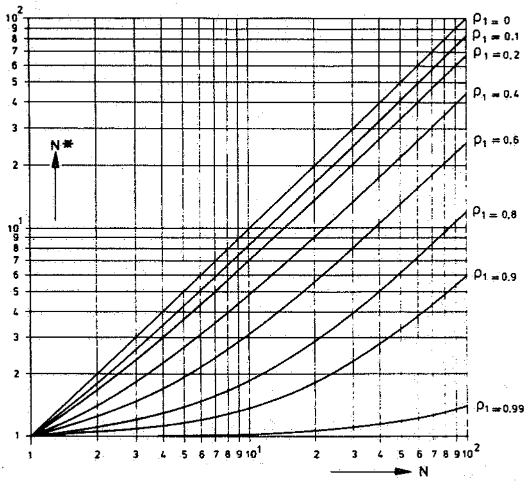

Figure 4-2 Relation between N* and N for various correlation coefficients (exponential correlation model)

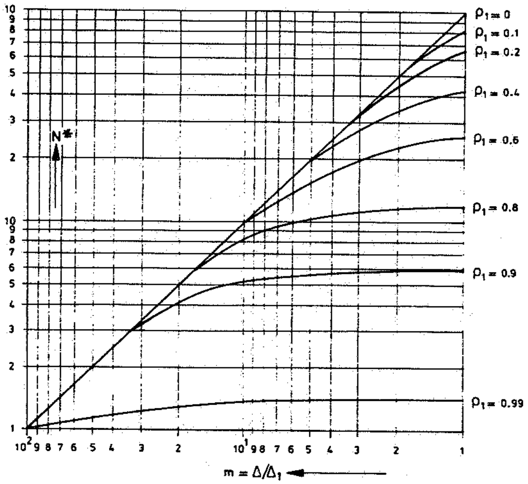

Figure 4-3 Relation between N^* and m for various correlation coefficients and $T=100\Delta_1$ (exponential correlation model)

The expression between the braces in Equation (4.3) is comparable to the integral scale as used in turbulence to characterize the large scale eddies. Indeed, $N^*(\Delta)$ has an upper bound N^*_{max}, which is determined by the ratio, T/Γ, of the measurement duration, T, and the dominant time scale, Γ . This upper bound is independent of the sampling interval, Δ , as can be argued rather easily. For fixed T, a reduction in Δ will result in an increase of the number of observations, N,but also in a stronger correlation between them. The corresponding effects on N^* will tend to compensate each other. This is illustrated in Figure 4-3, which gives N^* as a function of Δ/Δ_1 for $T = 100\Delta_1$. These lines can be constructed easily from Figure 4-2, giving $N^*(N)$. Take for example $\rho_1 = 0.9$. Then for $\Delta = \Delta_1$, (hence $m = 1$) we have 100 observations with a serial correlation of $\rho_1 = 0.9$, yielding $N^* = 5.8$. When $\Delta = 2\Delta_1$, we have 50 observations with a serial correlation of $\rho_1^2 = 0.81$, which results in $N^* = 5.7$, etc. These curves clearly show the saturating behaviour of $N^*(\Delta)$ for decreasing Δ , which indicates that the reduction of Δ below some critical value Δ_c only results in a marginal increase in N^*, and hence in a waste of effort. Since this value Δ_c becomes larger for processes with larger time scales (large ρ_1), the sampling frequency for those processes often can be reduced without loss of effectiveness.

It must be realized, however, that the upper bound N^*_{max} decreases with increasing ρ_1. The corresponding upper bound E_{max} of the effectiveness might even become less than the minimal value as required by the objectives. Again, it should be stressed that this E_{max} cannot be increased by raising the sampling frequency. What is needed then is an increase in T, hence an extension of the measurements over a longer period. When this is not possible, a solution might be to weaken the objectives, and to be content with a lower accuracy. However, such a reconsideration of the objectives should be the last thing to do.

A way to improve the effectiveness without changing T is to incorporate physical knowledge in the data analyses as much as possible instead of processing the raw data directly. To this subject will be returned later.

4.3 Sampling locations

What has been said about scales and variability in relation to the sampling frequency also applies to the spatial design of networks. This will be illustrated here by a simple example.

Suppose that the objectives of a one dimensional spatial network (e.g. gauging stations along a river) are defined in such a way, that the monitoring effectiveness can be quantified by the interpolation error with which the state between the sampling stations can be determined. Hence, a relation between this error and the sampling distance Δ is needed.

Let us consider a very simple case, viz. the interpolation between two observation points, located at positions $x_0 = 0$ and $x_N = \Delta = N\Delta_1$ along the x-axis, with Δ_1 a unit distance. What is the accuracy of the interpolated value at location $x_\Theta = \Theta\Delta_1$?

Suppose we use a linear interpolation scheme, e.g.:

$$\hat{y}_\Theta = \alpha_0 y_0 + \alpha_N y_N \tag{4.5}$$

where y_0 denotes the observed value at location x_0, etc.

Moreover, assume that no instrumental or observation errors are made and that the observed process y is stationary with mean value μ, variance σ^2 and correlation function $\rho(y_i, y_j) = \rho_{ij}$.

Then, the mean square error (mse) in the estimate $\hat{y}_\Theta$ is given by

$$\begin{aligned} \text{mse}\,(\hat{y}_\Theta) &= E(\hat{y}_\Theta - y_\Theta)^2 \\ &= \{1 + \alpha_0^2 + \alpha_N^2 - 2\alpha_0\rho_{0\Theta} - 2\alpha_N\rho_{N\Theta} + 2\alpha_0\alpha_N\rho_{0N}\}\sigma^2 + \mu^2(\alpha_0 + \alpha_N - 1)^2 \end{aligned} \tag{4.6}$$

The last term of this equation is the bias term. This term disappears if $\alpha_0 + \alpha_N = 1$. Minimizing Equation (4.6) under this restriction yields the optimal weights $\tilde{\alpha}_0$ and $\tilde{\alpha}_N$:

$$\begin{aligned} \tilde{\alpha}_0 &= \tfrac{1}{2} + \frac{2\rho_{0\Theta} - \rho_{N\Theta}}{2(1 - \rho_{0N})} \\ \tilde{\alpha}_N &= \tfrac{1}{2} - \frac{\rho_{0\Theta} - \rho_{N\Theta}}{2(1 - \rho_{0N})} \end{aligned} \tag{4.7}$$

The mean square error of the corresponding optimal estimate $\tilde{y}_\Theta=\alpha_0 y_0 + \alpha_N y_N$ equals

$$\tilde{mse} = \tfrac{1}{2}\sigma^2\{3 + \rho_{ON} - 2\rho_{0\Theta} - 2\rho_{N\Theta} - \frac{(\rho_{0\Theta} - \rho_{N\Theta})^2}{1 - \rho_{ON}}\} \tag{4.8}$$

Note that the optimal weights and the mean square error only depend on the values of the correlation coefficients ρ_{ij}, and not on actual observations of y.

Let us now consider some special cases.

i Distance scale $\Gamma \ll \Delta_1$

Then $\rho_{ON} = \rho_{0\Theta} = \rho_{N\Theta} = 0$, which results in

$\tilde{\alpha}_0 = \tilde{\alpha}_N = 0.5$ (equal weighting) and $\tilde{mse} = 1\tfrac{1}{2}\sigma^2$.

ii. Distance scale $\Gamma \gg N\Delta_1$

Then $\rho_{ON} = \rho_{0\Theta} = \rho_{N\Theta} = 1$, which results in

$\tilde{\alpha}_0 = \frac{N - \Theta}{N}$; $\tilde{\alpha}_N = \frac{\Theta}{N}$ (linear weighting) and $\tilde{mse} = 0$.

iii. Interpolation point half-way the observation points

Then $\rho_{0\Theta} = \rho_{N\Theta}$, which results in

$$\tilde{\alpha}_0 = \tilde{\alpha}_N = 0.5 \text{ and} \tag{4.9}$$

$$\tilde{mse} = \tfrac{1}{2}\sigma^2\{3 + \rho_{ON} - 4\rho_{0\Theta}\}.$$

iv. Interpolation at the observation points

When $\Theta = 0$ then $\rho_{0\Theta} = 1$ and $\rho_{\Theta N} = \rho_{0N}$, which results in

$\tilde{\alpha}_0 = 1$, $\tilde{\alpha}_N = 0$ and $\tilde{mse} = 0$.

When $\Theta = N$, then $\rho_{0\Theta} = \rho_{0N}$ and $\rho_{\Theta N} = 1$, which results in

$\tilde{\alpha}_0 = 0$, $\tilde{\alpha}_N = 1$ and $\tilde{mse} = 0$.

v. Exponential correlation function

Then $\rho(x,y) = \exp\{-|x-y|/\Gamma'\}$. Hence, when $|x - y| = k.\Delta_1$ then

$$\rho(k\Delta_1) = \rho_1^{\,k} \tag{4.10}$$

with
$$\rho_1 = e^{-\Delta_1/\Gamma'}$$

This implies $\rho_{0\Theta} = \rho_1^{\,\Theta}$, $\rho_{0N} = \rho_1^{\,N}$ and $\rho_{\Theta N} = \rho_1^{\,N-\Theta}$, which results in:

$$\begin{aligned} \tilde{\alpha}_0 &= \tfrac{1}{2}\left\{1 + \frac{\rho_1^{\,\Theta} - \rho_1^{\,N-\Theta}}{1 - \rho_1^{\,N}}\right\} \\ \tilde{\alpha}_N &= \tfrac{1}{2}\left\{1 - \frac{\rho_1^{\,\Theta} - \rho_1^{\,N-\Theta}}{1 - \rho_1^{\,N}}\right\} \end{aligned} \tag{4.11}$$

These (exponential) weights are sketched in Figure 4-4 as a function of Θ for various values of ρ_1.

The corresponding interpolation error is shown in Figure 4-5. The maximum error occurs at $\Theta = \tfrac{1}{2}N$, and equals

$$\tilde{mse}_{max} = \tfrac{1}{2}\sigma^2\{3 + \rho_1^{\,N} - 4\,\rho_1^{\,N/2}\} \tag{4.12}$$

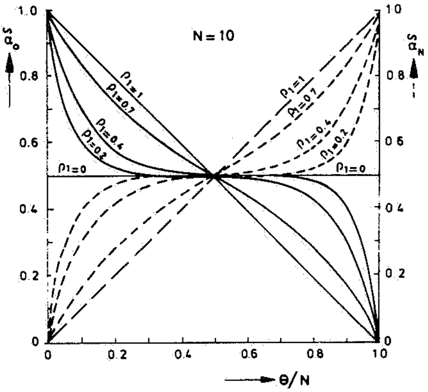

Figure 4-4 Optimal exponential weights $\tilde{\alpha}_0$ and $\tilde{\alpha}_N$ as a function of Θ/N for various values of ρ_1, and $N = 10$

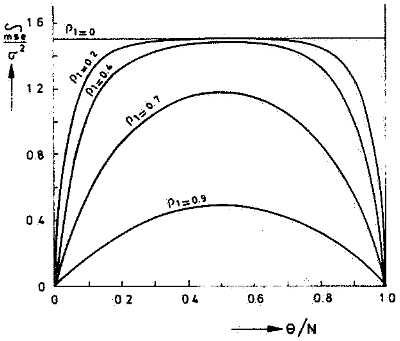

Figure 4-5 The relative mean square error as a function of Θ/N for various values ρ_1, and $N = 10$

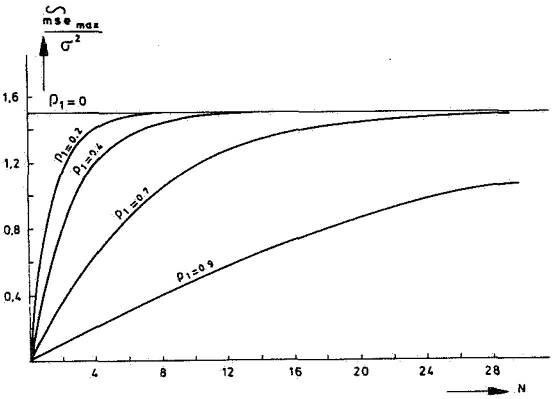

Figure 4-6 The relative maximum mean square error as a function of N for various values of ρ_1

In Figure 4-6 this error is presented as a function of N for various ρ_1.

Suppose the maximum interpolation error is not allowed to exceed some critical value. Then, Equation (4.12) can be used to calculate the corresponding maximal N (N_{max}), and hence the maximal sampling distance $\Delta_{max} = N_{max} . \Delta_1$.
The results clearly show that the larger the distance scale Γ is, the higher N can be. Hence, also in this case the ratio Γ/Δ is an important parameter in network design.

In the previous section it was shown that a large time scale resulted in a large sampling interval, but also in measurement periods, which had to be long in order to meet a certain effectiveness level. So, from a monitoring point of view, correlation had both a positive and negative effect on the monitoring effort. In this example, the negative effect is lacking. It is important to realize the reason for this. In fact, it is inherent in the objectives used in the examples. In the first case, a mean value had to be estimated. Such a mean value is a characteristic of a random process, and therefore a deterministic variable. Since only one realization of this process is observed, it has to be sufficiently long to provide the number of degrees of freedom which is sufficient for the required estimation accuracy.
In the second example, however, the question is not to estimate a characteristic of a random process, but to estimate some values in one specific realization of that process. And this estimation obviously can only improve with longer correlation scales.

The simple interpolation scheme of Equation (4.5) can be extended rather easily to interpolation schemes which make use of more than two observations, i.e.

$$\hat{y}_{\Theta} = \sum_{i=1}^{N} \alpha_i y_i \tag{4.12}$$

Again, the optimal weights $\tilde{\alpha}_i$ and the corresponding $m\tilde{s}e$ only depend on the correlation structure of y, and not on actual observations.

When the observation points x_i are distributed over a two dimensional area, the resulting equations for $\tilde{\alpha}_i$ and $m\tilde{s}e$ directly correspond to the well known kriging equations for spatial interpolation.

Finally, it is important to note that basically the same procedure can be followed in case of estimating spatial averages; only slight modifications in the governing equations for the optimal weights $\tilde{\alpha}_i$ are needed. For more details the reader is referred to the pertinent literature (e.g. Delhomme, 1978).

4.4 Instrumentation and observation errors

In the above, possible instrumentation and observation errors have not been taken into account. From a practical point of view, this is rather unrealistic. Fortunately, however, this can be done rather easily.

Instrumentation and observation errors manifest themselves in a certain extrinsic variability of the data, which is added to the intrinsic variability. Therefore, the covariance structure of the data is influenced by these errors. Usually, this influence is reflected mainly in the variance of the data, and not in their correlation scales.

Suppose the observations $y(k\Delta)$ of the process x are disturbed by independent observation errors $v(k\Delta)$, i.e.

$$y\ (k\Delta) = x\ (k\Delta) + v\ (k\Delta) \tag{4.13}$$

Then

$$\gamma_y(k\Delta) = \begin{cases} \sigma_x^2 + \sigma_v^2 & k = 0 \\ \sigma_x^2 \rho_x(k\Delta) & k \neq 0 \end{cases} \tag{4.14}$$

and

$$\rho_y(k\Delta) = \frac{\gamma_y(k\Delta)}{\sigma_x^2 + \sigma_v^2} \tag{4.15}$$

Here σ_x^2 and $\rho_x(k\Delta)$ denote the intrinsic variance and correlation function, σ_v^2 the extrinsic variance, $\rho_y(k\Delta)$ and $\gamma_y(k\Delta)$ the correlation- and covariance function of the data.

By using Expressions (4.14) and (4.15) instead of the intrinsic functions, the extrinsic variability can be incorporated in the network design.

4.5 A priori knowledge of the covariance structure

Whatever method is used in network design, knowledge about the covariance structure is a prerequisite. In the above, this knowledge has been assumed tacitly. In practice, however, it has to be obtained from historical data, from physical insight, or from both.

In case of covariance calculations from measured data, one must be aware of the extrinsic variability which may disturb the data. To estimate this variability, knowledge about instruments and measurement procedures is necessary. In case of water quality monitoring, also the effects of the chemical and biological analysis applied to the samples must be considered.

Another point of concern is the statistical error in empirical covariance functions, which is inherent in the estimation procedure. To reduce these errors to an acceptable level, often long data series are required, extending over several times the relevant correlation scales. Moreover, in case of historical data with a sampling interval Δ , the covariance functions can only be estimated for a set of discrete values of Δ , which may hamper the evaluation of the network effectiveness for all relevant sampling schemes.

To reduce this problem, a model for the covariance structure can be assumed, of which only the parameters have to be estimated. This imposes less demands on the lengths of available records, and also allows the effect of all possible variations in the sampling density to be investigated. But, also in this case the extrinsic variability of the data and the estimation errors may influence the result, although generally to a lesser extent than without model assumptions. However, the choice of the model might be rather critical, and may result in significant systematic deviations with regard to the real intrinsic structure.

Often, the covariance models used in conjunction with network design are merely black-box parametrizations or empirical models. Examples are the time series models (AR, ARMA etc.) in time domain and the variogram models in spatial domain. These models characterize the covariance structure without explaining it. As a consequence, the data are considered to be fully stochastic.

Often, however, deterministic components in the data can be observed, which can be explained on physical grounds. By making a physically based model of this deterministic part, it can be removed from the original raw data. This results in new data which, in general, will have a smaller variance and smaller correlation scales. Because the monitoring network then only has to provide information about this remaining stochastic part, the sampling density can be reduced without a reduction of effectiveness. An example of such reduction is presented in section 7.2.

By the incorporation of deterministic models in network design, sometimes a trade-off can be made between sampling density in space versus time. However, this requires models which describe the spatial and temporal behaviour of the measured processes simultaneously. When these models can be formulated in a state-space form, design techniques based on Kalman-filtering can be used. In the next section this will be worked out in some more detail.

The use of deterministic models in network design also implies their use in network operation. The information, obtained from the measured data, strongly depends on these models. Therefore, the models have to be checked regularly in order to avoid misinterpretations of the data. This requires temporary monitoring activities to provide sufficient data for model validation and a possible recalibration. Hence, the reduction of routine monitoring due to model incorporation implies an increase in temporary specific surveys.

4.6 Techniques for network design

The purpose of this section is to provide a connection between the previous general sections and the applications in Chapters 6, 7 and 8. Therefore, the principles of only a restricted number of techniques will be discussed, without going in too much detail.

The techniques to be described have one property in common: they can provide relations between some (surrogate) effectiveness measure (e.g. interpolation error, trend detectability) and the sampling effort. A cost-effectiveness analysis, however, is not included in these techniques. Hence, these techniques do not incorporate the eventual decisions that may be based on the outcome of the network. This is a serious drawback, which must be realized each time when they are used for network design.

As a consequence, there is a growing interest in techniques based on statistical decision theory. Their Bayesian statistical framework permits the inclusion of quantitative measures of decision effects in network design. These measures can be related explicitly to the uses of the data from the network. Moreover, in addition to the hard factual data sets, which are also used in the non-bayesian techniques, less direct information such as subjective feelings may be used.

The inclusion of subjective information leads to the major criticism of Bayesian statistics: the diversity of answers obtained. Because each person in general will weigh subjective information differently, the results of the analysis will vary from analyst to analyst.
Another complaint against Bayesian analysis is that it usually results in a very cumbersome if not intractable set of relations. In order to arrive at an answer it may be necessary to use large-scale computing facilities either to obtain numerical integrations of the relations or to simulate the system.

Finally, the available non-bayesian techniques are much more diverse in applicability and sophistication than the Bayesian techniques, and therefore can be chosen more in accordance with the objectives. But, in spite of these drawbacks, the development of Bayesian techniques, possibly in connection with existing non-bayesian methods, shoud be stimulated.

Design of sampling frequencies

The amount of information, contained in a sampled time series x(t) can often be related to the effective number of observations $N^*(\Delta, T)$ as introduced in Section 4.2. This N^* plays an important part in the determination of the sampling effectiveness for various objectives. In Section 4.2. it was illustrated that, in case the main objective is the estimation of mean values, the network effectveness can be related to N^* according to

$$E\ (\Delta,T) = \frac{1}{\sigma_x} \surd(N^*(\Delta,T)) \qquad (4.16)$$

Moreover, one can show (Lettenmaier, 1976) that the effectiveness of a network to detect a long-term trend with an absolute magnitude Tr over a period T is monotonically related to the quantity Q, given by

$$Q\ (\Delta,T,Tr) = \frac{Tr}{c\sigma_x}\ \sqrt{(N^*(\Delta,T))} \qquad (4.17)$$

with c a trendshape-dependent constant. Hence, Equation (4.17) provides a means to relate the monitoring effectiveness to the sampling interval Δ in case the main objective is the detection of trends. In Section 7.2 an example of the use of this equation in network design is presented.

Another objective, which may be important, especially in water quality monitoring networks, is the detection of violation of standards. An appropriate measure of the monitoring effectiveness then is

$$E(\Delta) = \frac{\text{expected number of detected violations}}{\text{expected number of violations}}$$

Often, such violations can be described by level crossings of the considered processes. In that case E(Δ) can be approximated by (Beckers et al., 1972).

$$E(\Delta) \simeq \frac{T_0}{\Delta}\ \left\{ \frac{\exp(-\Delta/T_0) - \exp(-\Delta/T_1)}{(T_0/T_1\ - 1)} \right\} \qquad (4.18)$$

with T_0 and T_1 the average non-violation and violation duration respectively. Obviously, these time scales T_0 and T_1 depend on the average process level and the level which correspond to the standard. T_0 and T_1 can be estimated from historical data, from physical insight, or can be calculated from estimated covariance functions or spectral density functions.

In case the objective of a measurement network is the reconstruction of the state of the system from noisy, discrete measurements, obtained over some period of time T, an effectiveness measure might be the mean square error of the reconstructed (or interpolated) data. To be more precise, suppose one wishes to estimate the state $x(t)$ at an arbitrary time Θ from noisy discrete measurements $y(k\Delta)$, given by:

$$y(k\Delta) = x(k\Delta) + v(k\Delta) \qquad k = 1 \ldots N \tag{4.19}$$

where $N = T/\Delta$ and $v(t)$ is a zero mean random process, describing measurement noise. Moreover, the estimate $\hat{x}(\Theta)$ is restricted to be a linear function of the available data, i.e.:

$$\hat{x}(\Theta) = \sum_{i=1}^{N} \alpha_i y(i\Delta) \tag{4.20}$$

The weights α_i must be chosen such that $\hat{x}(\Theta)$ is unbiased and optimal, which implies the minimization of the mse $E\{\hat{x}(\Theta) - x(\Theta)\}^2$ under the restriction $\Sigma\alpha_i = 1$. $(i = 1 \ldots N)$.
This minimization yields a set of equations for the optimal weights $\tilde{\alpha}_i$, which can be solved when the correlation structure of the process y is known. Hence, the resulting optimal interpolation mse, and therefore the performance of the network, can be evaluated as a function of Δ without use of actual observations from that network.

The techniques described above are suitable to optimize a measurement network for one variable in one dimension (time or one spatial direction), where the variable is assumed to be a stationary stochastic process. So, from a practical point of view, the applicability of these techniques seems to be rather limited. However, several extensions are possible.
For the simultaneous optimization of the sampling frequency for more variables, multivariate time series analysis can be used. This extension requires knowledge about all relevant auto- and cross correlations (or auto- and crossspectra). Sometimes, non-stationary time series can be dealt with by first applying differencing operations. These extensions, however, will not be treated in this report.

Design of sampling locations

For almost all objectives, as usually defined in routine monitoring, the effectiveness of a spatial network can be related somehow to the accuracy of spatial interpolation. Hence, when a sampling density has to be designed or optimized, interpolation procedures are required which provide not only interpolated values, but also the accuracy of these values.

It is no wonder therefore that both Gandin's optimum interpolation method (Gandin, 1970) and kriging get more and more attention in the literature. Both techniques are in fact two-dimensional extensions of the one-dimensional interpolation scheme in Section 4.3. Gandin's method has been originally developed for meteorological fields whereas kriging had it first application to geological data. One point in which kriging differs from Gandin's optimum interpolation technique is that use is made of the (semi) variogram $\nu_x(|h|)$ in stead of covariance functions. It gives half the variance of the difference of some variable $x(\vec{r})$ for two points in a plane, separated by a distance $|h|$, i.e.

$$\nu_x(|h|) = \tfrac{1}{2}\,\mathrm{var}\{x(\vec{r} + \vec{h}) - x(\vec{r})\} \tag{4.21}$$

When $x(\vec{r})$ is isotropic, there is a direct relation between the variogram and the covariance function

$$\gamma_{xx}(|h|) = \sigma_x^2 - \nu_x(|h|) \tag{4.22}$$

Kriging can be extended to variables which are not homogeneous by adopting the "generalized intrinsic hypothesis" (Delhomme, 1978).
In essence, this is comparable with the already mentioned differencing procedure for non-stationary time series.

Simultaneous design of sampling frequency and density

The above mentioned techniques are suitable to solve at least parts of the total optimization problem. However, some practical problems remain:

- the condition of isotropy in all dimensions seems very unlikely to be fulfilled when one considers time and space dimensions simultaneously;
- many data are required to estimate the complete correlation structure in the multivariate case;
- not every type of non-stationarity can be removed by differencing operations.

Because the multivariate correlation structure, anisotropy and non-stationarities are consequences of the underlying physical processes, these problems can (partly) be overcome by incorporating physical knowledge in the optimization process. When this knowledge can be formulated in terms of a mathematical (state space) model, techniques based on Kalmanfiltering offer good possibilities. Moreover, it is possible in principle to optimize simultaneously sampling frequencies, locations and variables. This can be explained as follows.

Information about the correlation structure is essential for the optimization of a monitoring network. This information can be obtained from observations, but can also be based on a-priori knowledge of the process dynamics.

The techniques treated above only use observation-based information, like covariance functions and variograms. A Kalmanfilter can use both sources of information, since it is based on two equations:

- the <u>state equation</u>, by which the physical knowledge is modelled;
- the <u>observation equation</u>, which indicates the way the observations are related to the state variables.

In principle, the state equation (the model) is used to predict future values of the state vector. Each time measurements are taken, these predicted values are compared with the measurements and adjusted. The degree of adjustment depends on the uncertainties of the model ("system noise") and of the observations ("measurement noise").

In this way, the best estimate of the state vector is obtained. It is important to note that also unmeasured state variables can be estimated, because they are related to the measured ones by means of the state equation.

Apart from the estimates, also their covariance matrix is calculated. This covariance matrix, which is a measure of the reliability of the estimates, strongly depends on the measurement matrix from the observation equation. Since this matrix indicates at which moments and on which locations which variables are measured, it reflects the monitoring effort.

Hence, the behaviour of the covariance matrix can be investigated for all relevant combinations of sampling frequencies, locations and variables. In the case the state equation is linear in the state variables, this even can be done without actual measurements, allowing the performance of a network to be determined a-priori for different monitoring strategies. So, when the effectiveness can be related to the covariance matrix, the total optimization problem can be solved in a very elegant way. However, in practice several problems may arise.

First, many hydrological models are non-linear in the state variables. Since then the covariance matrix becomes dependent on the actual state vector, the network performance cannot be evaluated a-priori anymore.

Second, the dimension of the state vector, being roughly proportional to the product of the number of variables and sampling locations involved, may become too large for practical use. This situation even gets worse when unknown model parameters have to be estimated simultaneously by state augmentation.

Third, the dynamics of many hydrological variables are still too poorly understood, to enable the development of a sufficiently detailed mathematical model.

In spite of these problems, the development of optimization techniques based on Kalmanfiltering should be stimulated. The dimensionality problem of the state vector may be overcome when sophisticated numerical techniques are used to solve the filtering equations (Bierman, 1977).

Also, much effort is put now in the development of mathematical models for hydrological processes. It may be expected that due to these developments the Kalmanfilter related techniques will become practical instruments to optimize complex monitoring systems.

5 SOCIAL AND ECONOMIC ASPECTS

J.W. van der Made*.

Social and economic aspects can influence the design of hydrological networks considerably. In fact most of these aspects can be reduced to the question in how far a society and its policy makers are ready to do investments and efforts in order to realize a network. This, at its turn, is related to the value that is attached to the information about the hydrological phenomena.

In this chapter these matters will be discussed just on the face of it. More intensive study would be required to arrive at definite conclusions and recommendations. However, a first approach will be undertaken here.

Although the use of water is essential for life, in low developed communities with sufficient availability of water resources there may seem no need for any numerical information. Besides, the first need may not seem the construction and establishment of a network of gauging stations or even of single stations, but rather to give priority to other matters like food production and health care. Even if detailed information about water and water resources would really be necessary, the population and its policy makers are not always fully aware of the problems and the required approach to their solutions.

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It can be stated however that a minimum level of data collection is desirable in a nation-wide basic hydrometric network, regardless of present or prospective economic development. Hydrometric data are time bound. This means that they are mainly dependent on records which can be collected only as the phenomena unfold with the passage of time. It has been estimated that at least twenty-five to fifty years of hydrometric data are desirable to give an adequate picture of conditions for design of water-resources projects. This is obviously an ideal situation, unlikely to be realized very often before development commences, however, it indicates the need for setting up at least a minimum network in undeveloped areas, well in advance of actual need for the data.

Once a development plan is under consideration, the need for the data is immediate. It is of course difficult to determine ahead of time what data will be required, and impossible to put a station on every stream in a country, hence it is necessary to plan the station network carefully to achieve the maximum return from available resources.

In developed areas, hydrometric data provide the basis for water apportionment, water licensing and surveillance of water quantity and quality to meet requirements specified by municipal, provincial, interprovincial, national or international obligations. As environmental concerns increase, there will be need for more monitoring and surveillance. The more an area is developed, the more environmental impacts occur, and the more data are needed to assess them. The need for hydrometric data therefore does not vanish just because the natural resources of an area are already being exploited. The emphasis may change and also the type of information may change, but the demand or need will steadily grow as users require more data and increasingly sophisticated real-time data to continue and expand their operations.

In this connection it should be noted that in the framework of the International Hydrological Programme attention is paid to the development of public awareness of the role of water in the human society and, consequently, in the development and promotion of operational and scientific hydrology (UNESCO, 1982).

Besides the fact, whether the establishment and management of a more or less developed network lies within the willingness of a society, the fact if a network can really be managed plays a role too. This concerns matters like the degree of population and the accessibility of the regions concerned. For instance, if somewhere gauging stations would be desirable, are people disposed to carry out the observations and to maintain and manage the stations and the equipment? In remote areas possibly only fully automatic stations might give a solution. In these cases the methods of power supply and of data acquisition and transmission to be applied are of essential importance. Can, in those cases expensive automatic stations be justified?

The accessibility of the stations' sites can be of importance too. One can imagine cases that a station is well accessible under normal conditions, but during floods, when the data are just of great importance, the whole surrounding area and the roads to the station may be impassable. Can funds be provided to secure the accessibility and functioning under such conditions by adequate provisions?

In this connection it is not astonishingly that in many mountainous regions raingauges are established in valleys but only a few in the higher zones. Such a network will not produce data representative for the region as a whole.
It is sometimes difficult to extend a network, although the need is obvious, on the other hand, and this may play a role in developed countries, it is often difficult to stop measurements at certain stations, even if these are no longer required from a hydrological point of view. Here in many cases questions of status and of habitude play a role, e.g. whether an important city is willing to give up its own measurements, even if the data can easily and accurately be derived from other, neighbouring stations. Competence questions between services and institutes can be of influence.

At borders between countries and even between administrative regions, each having their own data processing systems, separate stations may remain, even if this is hydrologically not required. If problems of water management and allocation exist such facts can hardly be avoided. In such cases political solutions should be pursued at first.

Besides the above mentioned aspects the question can be posed whether the information produced by a network has such a value to society that the costs of construction, maintenance, management and data processing are justified. This is particularly pressing during periods of economic stagnation or retrenchment. Aware of the economic implications of their activity, a number of hydrologists have attempted during the last decades to ascertain the benefits obtainable from hydrological data and to compare them to their costs and thus assess if collection of hydrological data is economically efficient. The difficulties of such assessment have been formidable for two reasons: the complexity of a theoretical framework for assessing the total benefits and costs because of the special stochastic characteristics of the hydrological data, and the practical difficulties related to the lack of information on the incremental benefits from water resource projects resulting from incremental hydrological data. These difficulties are clearly reflected in the literature on the subject (WMO, 1982).

In order to judge the value of the data, produced by the network and its stations, it is important to review the information content in relation to objectives for which these data will be used. These might concern information in relation to water-resource development, inventory (water resources assessment), planning and design, operation and monitoring, and forecasting. Hydrological data used for forecasting and operation are more amenable to cost-benefit analysis than those used for other purposes (Day, 1973). As a whole however it is still a difficult problem to assess the real value of the data for society, although many attemps have been made (Dawdy, 1979).

A lack of information about the quantities and the quality of the water can lead to wrong measures, thus to economic losses. These losses, due

to lack of information compared with the ideal situation whereby all possible information is available, will be called the "information loss".
The information loss can be decreased by an extension of the network, which at its turn will increase the costs. If the network is built up in such a way, that the total of information loss and the network costs (construction, maintenance, operation, data processing etc.) is minimal, the economically optimum solution is found.

Besides it is of importance to examine in how far the network costs can be reduced without affecting the data production, thus aiming at a highest efficiency of the network (Moss, 1982).

Since it is often difficult or even impossible to assess the benefits in quantitative terms, one will often go along other lines.

Examples of alternatives are:
1. to build the most efficient network within budgetary limits.
2. to design the network in such a way that the errors of interpolated data, will be always smaller than a fixed criterion.

Both are surrogate approaches. The first is simply to apply, but does not take into account the errors of estimate, thus in fact the extent of information loss. Improving the efficiency (more information at equal costs) will reduce the information loss but not the network costs, which are fixed by the budget.

In the second approach the errors of estimate are fixed, thus with it the information loss. Improving of the efficiency will reduce the network costs, but not the information loss. In practice it is difficult to assess a criterion as a design value for the standard error. Inquiries of data users will only in special cases lead to a satisfactory answer. It is recommended that the designer of the network makes up his mind before he poses such a question and that he makes a concrete proposal about the design error of estimate to the data users.

A graphical demonstration of the various relations can be given on the hand of Fig. 5-1, consisting of 4 quadrants. Quadrant I shows the physical relation between the network density and the maximum standard error of estimate that will be obtained somewhere in the gauged area. This is more or less a boundary condition. Quadrant II gives the relation between standard error of estimate and the information loss, which is assumed to be linear (Ingledow, 1970). This relation depends for instance on the importance of a certain information. Very important information can show a relation 1, less important information a relation 2.

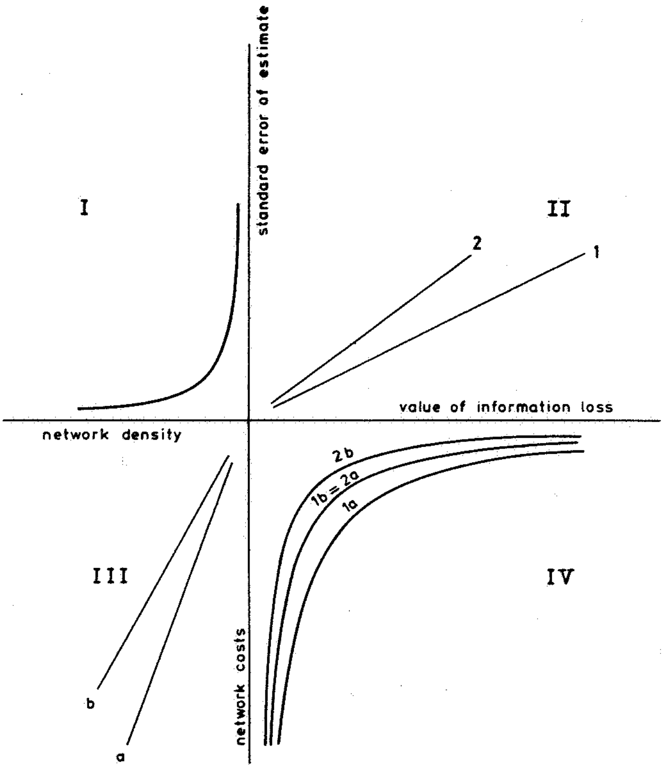

Figure 5-1 A relation between network density and standard error of estimate, transformed into possible relations between network costs and information loss

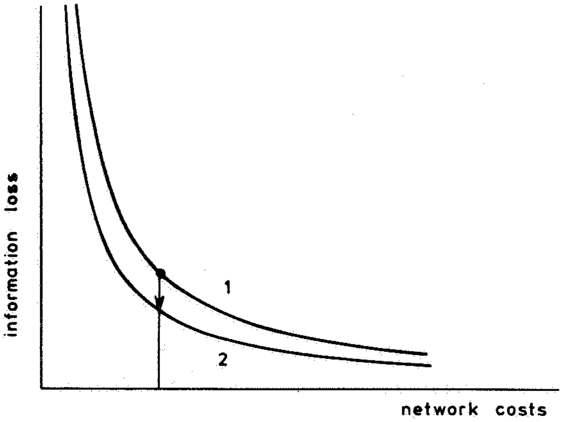

Figure 5-2 The budget approach

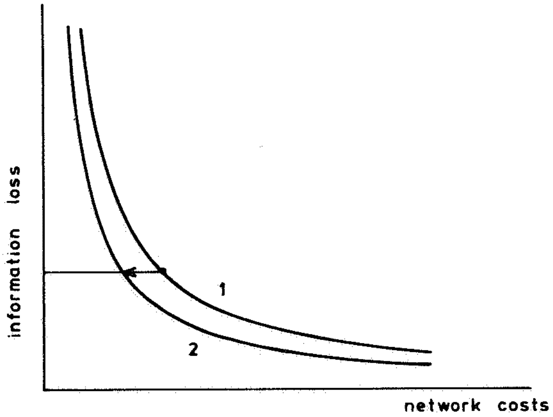

Figure 5-3 The information loss approach

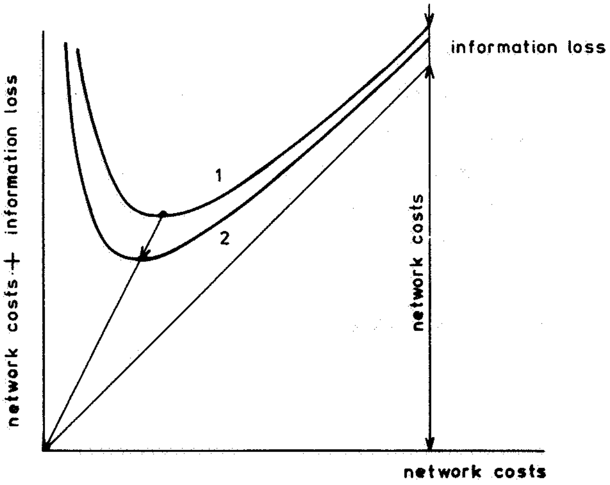

Figure 5-4 The total costs approach

In quadrant III is shown the relation between the network density and the costs of the network in the broadest sense. A high cost level will produce a relation a, a lower cost level a relation b.

On the basis of the existing relations in the quadrants II and III a relation between the value of the information loss and the network costs can be derived, the result of which is shown in quadrant IV for combinations of the cases of the quadrants II and III. Curve 2-a, for instance, implies a lower information loss at equal costs than curve 1-a. Or: curve 2-a attains equal information loss against lower costs than curve 1-a.

Now consider the relations, given in quadrant IV separately, in view of the approaches discussed above.

Fig. 5-2 shows the "budget approach". Two curves are given: curve 2 corresponds with a more productive network system than curve 1, i.e. curve 2 implies less information loss at equal network costs.

Fig. 5-3 shows the "information approach". Improved productivity leads to lower network costs at equal information loss.

Fig. 5-4 finally shows the minimum total costs. This introduces a 3rd approach, the "total costs approach". Improving of the productivity gives profits for the network costs as well as for the information loss. From this point of view the minimum total costs approach would lead to the optimum solution. However all necessary data for such an approach have to be available. Since this is only seldom the case one has to work with assumptions, which will surely be determinental to the final result.

Another point is, that the total costs curves at their minimum may have a rather flat shape, i.e. the total costs are varying only little with the network costs. This means that reduction of the network costs in that area implies an equal increase of information loss. Since network costs are more clearly defined than information loss a tendency can be expected towards low network costs, until at last the information loss becomes too high. In fact the "information loss" approach of Fig. 5-2 is being applied then.

Apparently the above approaches are closely related. Since in fact the network budget will be more or less be adjusted to the needs the question is whether the results will differ importantly. Anyhow it is recommended to examine all possibilities when designing a network.

In order to judge the various approaches adequately, the relation between information loss, expressed in financial terms, and the (standard) error of estimate or a detection probability should be determined. However, the value of information can not always be given in financial terms. For many aspects only a sensitive value can be given. It depends strongly on the opinion of the policy makers and the general public what value is assigned to things like loss of lives, loss of historical and cultural treasures, but also to the importance of hydrological science, and consequently of water resources management to the community. In this respect no general directives can be given.

The possibility to produce financial equivalents of the errors of estimate decreases with the timespan within which the data are required. In this order the following objectives can be given:
- hydrological forecasting (incl. navigation);
- operation of water management objects;
- water balance compilation etc.;
- study of long term trends;
- insight into the hydrological processes.

However, already for hydrological forecasts a closing financial balance can hardly be made. There are cases however, for which a reasonable calculation could be set up. An example of this concerns flood forecasting in Canada (Reynolds, 1982).

Also for navigation, beneficial values might possibly be concretized. Here the quantity of freight, that could be transported might give some information, as was shown by a tentative study of the river Rhine navigation. A decrease of the standard error of estimate of the forecast will correspond with an increase of the allowable draught. It was indicated that an increase of draught of 10 cm corresponds with a ships' capacity gain of 3% to 4%. Depending on the prices and the traffic intensity this can easily be converted into an amount of money.

Concerning the information needed for the operation of water management objectives the economic value of the data is even more difficult to determine.
But here also in some cases attemps have been made. Here is referred, for instance, to the hydrometric network, designed for the operation of the Iskar reservoir in Bulgaria (Georgiev, 1974).
In this case three different network densities were examined, each with three different levels of automization and equipment. The sum of annual costs and information loss was calculated for all 9 alternatives, finally showing what alternative was to be preferred.

Also other examples are described in the literature (Attanasi et al., 1977; Fontaine et al., 1983; Ward et al., 1973).

Continuing the list of objectives one arrives in the field of water balance compilation, water resources inventories, data for design of water projects etc. Here a complete total cost assessment can hardly be done, so that one has to take resort to a surrogate criteria, such as a fixed standard error of estimate. As was shown earlier this can lead to an acceptable solution.

To conclude it can be stated that hydrologic data have an important value for the society but that it is difficult, or even impossible to concretize it in financial terms. So for network design an approach, based on real data, can only be applied in a few, as a rule simple cases. Further research in this field is required. An evaluation of the present state of the art was the item of a WMO workshop to which can be referred in this context (WMO, 1982).

6 NETWORKS FOR PRECIPITATION AND EVAPORATION

T.A. Buishand*

Most meteorological institutes maintain an extensive network of daily read storage gages. For precipitation amounts over periods of time shorter than a day, use is made of registrations of continuously recording gages. The network density of these instruments is generally much lower than that of daily read gages, and, even today, short-interval precipitation data are not readily available in many areas of the world.

The commonly accepted types of instruments are subject to appreciable underregistration of the real precipitation amounts (3-30 percent or sometimes even more). This instrumental problem is not considered in this report although it can be an important aspect of network design. For a comprehensive review of the subject the reader is referred to Sevruk (1982).

In countries or regions with snowfall, measurements of snowcover are generally also included in the meteorological network. Observations of snow depth are made at a large number of sites whereas snowdensity is measured at selected stations (because of its smaller spatial variation). Snow courses may be undertaken to obtain additional information about the water equivalent of the snowpack and satellite data may be used to determine the areal extent of the snowcover.

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Direct measurements of actual evaporation are still difficult to carry out, this in contrast with those of precipitation. Usually one must rely on indirect, semi-empirical methods in which data of existing meteorological networks are used as an input, in particular global radiation, wind speed, air temperature and humidity. As an alternative observations of a special network of evaporation pans can be used as a starting point in calculations of actual evaporation.

The objectives of the users of the data from the above networks are very different. It may be useful at this stage to discriminate the following groups of applications:

a. hydrological forecasting,
b. casestudies of extreme precipitation events that have caused floods or other damage,
c. water management,
d. water balance compilations,
e. planning and design of water projects,
f. studies of long-term changes of climate.

A measure of the forecast error has to be introduced to evaluate the use of meteorological data in hydrological forecasting. This application is discussed in Chapter 9.
For casestudies of extreme precipitation events it is important that precipitation amounts can be interpolated with sufficient accuracy. Also for watermanagement purposes the effectiveness of a network has sometimes been related to an interpolation error. However, as soon as areal averages of point observations are used in watermanagement and water balance compilations the accuracy of this average value should be considered. Quite a few other criteria have to be used in design and planning of water projects. Here it is important to know how much data are needed to estimate a 10-year or a 100-year return value with a given accuracy. For studies of long-term climatic changes it is necessary to examine detection probabilities of certain types of trends. In the sequel a number of helpful comments will be given about these concepts.

6.1 Errors of interpolation

The accuracy of spatial interpolation has often been used to test the performance of rain gage networks. An example of the relation between the root mean square error (rmse) of interpolation and the network density is given in Fig. 6-1. The error refers to the estimation of the rainfall amounts in points of a 1 km square grid over the area of the Wessex Water Authority (WWA), UK by a rather advanced optimum interpolation procedure.
The solid line in Fig. 6-1 presents the situation of the existing network and arbitrarily reduced networks. By reducing the existing network, no attemps were made to obtain a more regular distribution of the gages over the area. This is in contrast with the rationalized networks where special attention was paid to the locations of the stations.
Further, in these rationalized networks preference was given to stations with a good raingage site and with high quality records. From the figure it is seen that such rationalized networks have a smaller average rmse of interpolation than largely unplanned networks of the same size.

An important point that Fig. 6-1 shows, is a rather slow decrease of the average rmse with the number of gages in the area. For instance, for the rationalized network of 133 gages (∿ 1 per 75 km^2, a common density of many national networks in Europe) the average rmse is 1.4 mm. Extending the network to 220 gages leads to an average rmse of about 1.25 mm. So doubling the number of gages leads only to a reduction of 10% in the average rmse.

In Fig. 6-1 only days were considered on which the average rainfall amount of 12 widely spread gages in the WWA-region exceeded a threshold of 1 mm. The magnitude of the rmse of interpolation strongly depends on the height of this threshold. For daily rainfall totals in the Netherlands the publication of Kruizinga and Yperlaan (1977) indicates that the rmse increases linearly with the square root of the average value at surrounding points. In network design it is therefore generally not sufficient to quantify an admissable rmse of interpolation only. One usually also has to specify a threshold or another condition on the rainfall events.

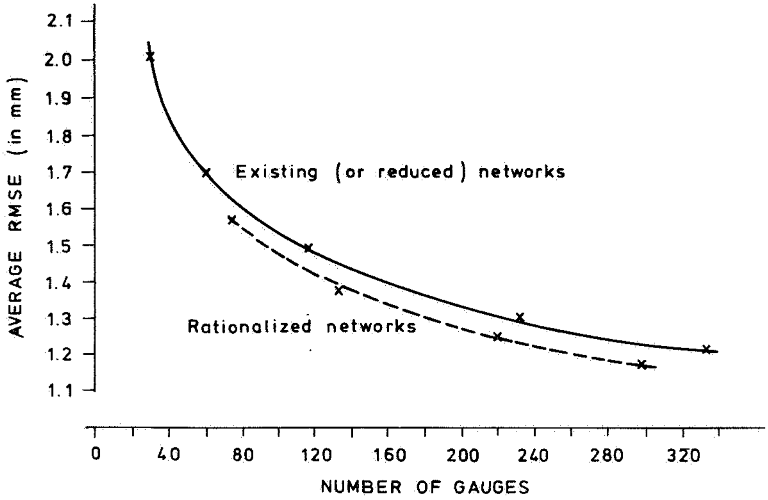

Figure 6-1 Average root mean square error of interpolation over the area of the Wessex Water Authority, UK (9900 km^2) for days with wide spread rainfall of over 1 mm.
Taken from O'Connell et al. (1978, 1979)

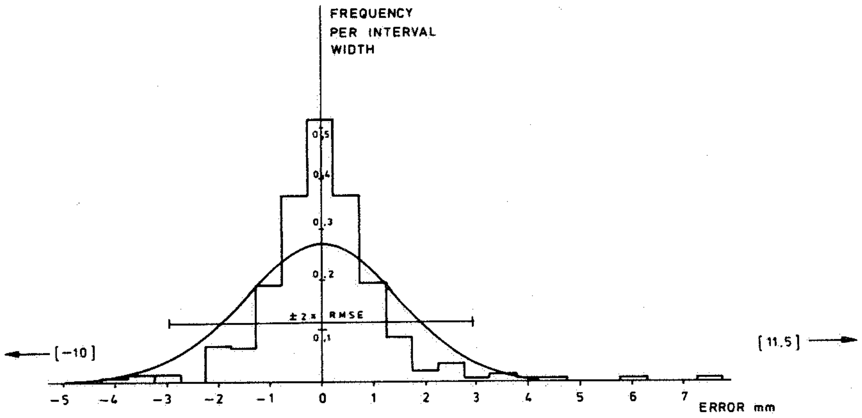

Figure 6-2 Histogram of estimation errors from optimal linear interpolation of daily rainfall on days with widespread rainfall of over 1 mm, with fitted normal distribution. Sample rmse = 1.47 mm. Taken from O'Connell et al. (1978)

It should be realized further that interpolation errors of daily rainfall amounts are often not normally distributed. Fig. 6-2 shows a histogram of the interpolation errors for a raingage site in the WWA-region. Although the distribution of the errors is symmetric, it is not normal. From the figure it is seen that the distribution has a higher peak and longer tails than the normal distribution. Values of more than 5 times the rmse have even occurred. Therefore, the magnitude of the rmse should be interpreted with some care. In this particular example about 95% of the errors are within the 2 rmse bound, despite the fact that their distribution is non-normal.

6.2 The accuracy of areal averages

In many hydrological applications one is interested in the average value of precipitation over an area. In those cases a useful measure to evaluate the network layout is:

$$F = \text{var}\ (\hat{P}_A - P_A) \qquad (6.1)$$

where P_A stands for the true average value and $\hat{P}_A$ is an estimate from point observations. The symbol A is used to denote the particular area as well as its areal extent.

For any network configuration the value of F can be derived from the covariance-structure of the precipitation field (Section 4.3). This requires usually numerical integration. For regular networks, however, a simple approximation formule for F can be derived (Kagan, 1965; Gushchina et al. 1967; WMO, 1972, III-1.2) Examples of the use of F in raingauge network design are given by Bras and Rodríguez-Iturbe (1976b), Lenton and Rodríguez-Iturbe (1977), Jones et al. (1979) and Bastin et al. (1984).

To obtain a given degree of accuracy in areal averages, generally a much less dense network is required than to obtain the same degree of accuracy for point interpolation. Moreover, the error in the areal average is much more sensitive to changes in network density than an error of point interpolation. This will be demonstated here with Kagan's formula.

Assume that we have N stations, evenly distributed over a homogeneous and isotropic area A. Then a natural estimate P_A is the arithmetic average of the N point observations:

$$\hat{P}_A = \bar{P} = \frac{1}{N} \sum_{i=1}^{N} P_i \tag{6.2}$$

Further it is assumed that the following relation exists between interstation correlation and distance:

$$\rho(d) = \rho_0 e^{-d/\Gamma'} \qquad , \; d > 0 \tag{6.3}$$

where $\rho(d)$ denotes the correlation coefficient of the measured precipitation amounts for two stations at a distance d; ρ_0 and Γ' are two unknown parameters which usually have to be estimated from data. The fact that $\rho(d)$ differs from 1 for very small interstation distances is ascribed to observation errors (Section 4.4), but one can also think of microscale variations. Under these assumptions the following approximation can be derived for the error variance F:

$$F \approx \frac{\sigma_P^2}{N} \{(1 - \rho_0) + \frac{0.23}{\Gamma'} \rho_0 \sqrt{A/N}\} \tag{6.4}$$

where σ_P is the standard deviation of the point observations P_i.
Fig. 6-3 gives a plot of $\sqrt{F}$ against the reciprocal of network density for monthly rainfall amounts in the Netherlands (σ_P = 30 mm, ρ_0 = 0.98, Γ' = 350 km). From the figure it is seen, that as the area over which the average rainfall is required increases, F decreases if the network density remains fixed (for fixed A/N the quantity F is proportional to 1/A). Further the figure shows that F is rather sensitive to network density. Doubling the number of gages in a given area A gives about a 35% reduction in the value of $\sqrt{F}$. This is much larger than the percentage reduction in the rmse of interpolation.

The value of F depends strongly on the quantity $1-\rho_0$, especially for dense networks (small A/N). Since the estimate of this quantity is usually rather poor, Eq. (6.4) only gives a rough idea about the magnitude of F. Further, the validity of the correlation function (6.3) is questionable for small d. Therefore, Eq. (6.4) can not be used for arbitrarily small interstation distances (small A/N). On the other hand,from a practical point of view, it is usually sufficient to have a rough idea about F and how it can be influenced by changes in the network layout.

Kagan's formula holds for regular networks. The error variance F will be larger when the stations are unevenly distributed over the area, even if an optimal estimate of P_A is used instead of the arithmetic mean $\bar{P}$ (Gandin, 1970). Just like the rmse of interpolation, the value of F usually increases with event magnitude (Huff, 1970; Bastin et al., 1984). Therefore, also for this quantity, it can be worthwile to consider only areal averages of rainfall events that satisfy some condition.

6.3 Planning and design of water projects

It is obvious that more data result in better rainfall-frequency-duration relationships. The standard error of a 10-year return value is usually between 3 and 15% if a rainfall record is available with a length greater than 50 years. This is generally judged as being good enough for planning and design.

For large return periods (>100 years) use has to be made of regional estimates based on data from several correlated sites.

It is difficult to quantify the uncertainty of these estimates and therefore no recommendations can be given yet for the amount of data needed when large return periods are of interest.

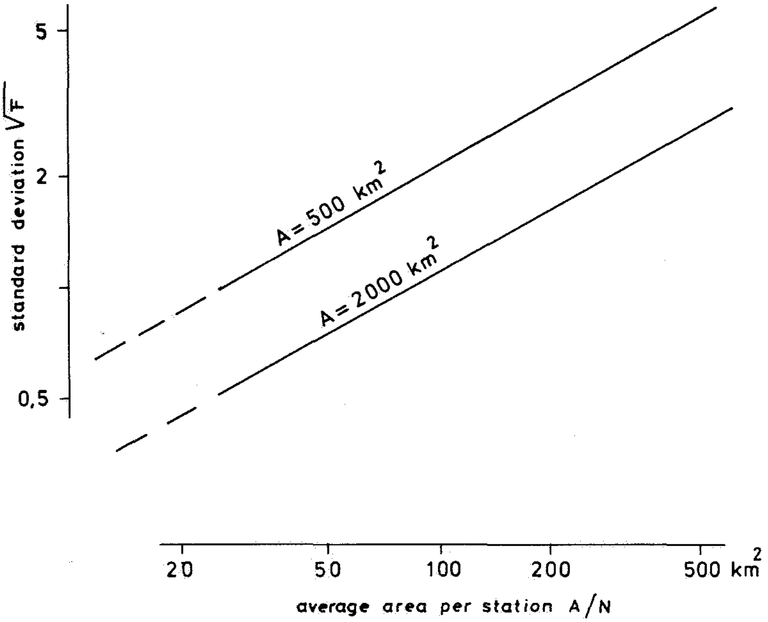

Figure 6-3 Standard deviation $\sqrt{F}$ of the estimate of the average monthly rainfall amount over an area of A km^2 from a regular raingage network with N gages for the Netherlands

The accuracy of design values is an important objective in regions with no or sparse data. Especially for short durations there is still a deficiency of precipitation data in many parts of the world. In such situations it may be possible, however, to obtain some information from adjacent countries or from generalized rainfall-frequency-duration relationships (Bell, 1969). Such information does not only provide the order of design values but it gives also a rough idea of the accuracy of estimates which can be used in planning additional measurements.

6.4 Studies of long-term changes of climate

For reference stations providing data for studies of long-term climatic changes a high standard is required with respect to the measurement site and the quality of observations. Up to now little attention has been paid to quantitative methods to determine the optimal density of such stations. Here this topic will be illustrated with an example.

In studies of climatic changes over a large region, it is advantageous to consider a sequence of regional averages instead of a record from a single site. An important question is: how many stations are required in the regional average?

For the variance of the average of N stations over a region A we can write (Rodríguez-Iturbe and Mejía, 1974):

$$\text{var}\ \bar{P} = F_2(N)\sigma_P^2 \qquad (6.5)$$

where σ_P^2 is the variance of point observations and $F_2(N)$ is a variance reduction factor. This factor is comparable with the quantity 1/N* in Section 4.2.

For annual rainfall amounts of randomly distributed stations in the Central Venezuela region Portuguesa (30,000 km^2) Rodríguez-Iturbe and Mejía found the following values for $F_2(N)$:

N = 1	$F_2(N)$ = 1
= 10	= 0.37
= 100	= 0.31

So the variance of the average annual precipitation amount of 10 stations is 0.37 σ_P^2 and this reduced variance gives a gain in power for testing for a systematic change in mean precipitation. For instance, the detection probability of a systematic linear change in the mean of 10% over a 100-year period is about 40% for rainfall data of a single record in this region (level of significance = 0.05); using the average of 10 stations gives a detection probability of about 80% for such a trend.

Going from 10 to 100 stations does not result in a considerable variance reduction due to increasing dependence between adjacent stations with growing network density. Hence, for the detection of long-term trends over a large area usually a low density of reference stations is sufficient.

6.5 Further remarks

In the previous comments the emphasis was on precipitation networks. Little has been published yet about optimal densities of networks for snowcover data and for evaporation data.

Chemerenko (1975) discusses the rationalization of the network for data on the water equivalent of snow in the USSR, using the accuracy of areal averages as a measure for network performance. Attention is paid to the effect of network density and the size of the area on $\sqrt{F}$. Further, the optimal location of new stations, given a number of existing stations, is also considered. The combination of a sparse network of snow density measurements with additional measurements of snow depths at a large number of sites is not examined in Chemerenko's paper.

Research on evaporation has mainly been devoted to the estimation of actual evaporation by semi-empirical methods or by physical experiments, but not on the optimal densities of stations providing information on this element. The determination of areal evaporation is often considered to be a purely physical problem. Yet, for water balance compilations, for instance, it would be worthwhile to examine the magnitude of interpolation errors or the errors in estimating an areal average for evaporation data, and to compare this with the same quantity for the precipitation amounts.

A problem in designing or redesigning a network for evaporation data can be that networks of such elements as temperature, global radiation, etc. must be considered, which have not been primarily designed for hydrological applications.

Most literature about rainfall network design is on network density and on station configuration. Much less attention has been paid to sampling frequency.

For the use of meteorological data in hydrological models the sampling frequency has to be adjusted to the frequency response of the system (Section 3.4.1). Network density and sampling frequency have quite different cost effects. The cost function C regularly increases with the number of gages, but it jumps at the time-interval of 1 day because for shorter durations more expensive recording gages (or radar) are required.

7 NETWORKS FOR SURFACE WATER

Networks for surface water data concern all water bodies where the water, in liquid form, shows an open level which is in direct contact with the atmosphere. Such water bodies are:

- rivers;
- lakes and reservoirs;
- deltas and estuaries;
- seas and coastal waters.

7.1 Networks for surface water quantity

J.W. van der Made.*

In rivers the quantity of water carried off is of primary importance, i.e. the discharge, as a rule expressed in m^3/s. Besides, if the main purpose is focussed on water balance aspects, the discharge data will be converted into runoff data expressed in mean depth over the drainage basin, e.g. in mm/year.
If the scope is mainly directed to flood warning or to navigation, one is more interested in the water levels as such. Since the water surface profile shows more variations along the river than the discharges, the network for water levels should be more dense than the discharge network. However, as in most cases the discharges are derived from rating curves, the discharge network can easily be integrated in the water level network.

In lakes and reservoirs, deltas and estuaries, seas and coastal waters one is mainly interested in water levels as such.

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In reservoirs the level data are used to calculate the water volume in the reservoir. For all these kinds of water bodies flood warning is one of the most important scopes, together with navigation purposes. Although the river flow is important too, in particular in the river reaches in deltas and estuaries, this phenomenon as a rule will not be measured directly, since it is subject to the water level in the water receiving body (sea, lake) and will often show alternating flow directions. In case of tidal movements the river outflow can be only a minor part of the total flow. Unless direct measurement techniques are used, such as ultrasonic measurements, the flow has to be derived by complicated calculations, based on the flow and continuity equations.

In Table 7.1 the variable to be measured (level or discharge) is indicated for the different water bodies on the one hand and for a number of uses on the other hand. Distinction is made into immediate operational uses (water management, flood warning, navigation) and uses for water policy (water balances, long term changes). The different requirements may lead to different networks. However, for reasons of efficiency it might be expedient to combine these to one network. For network planning procedures it is recommended to start with separate designs and afterwards to integrate these into one single network.

Table 7.1 Uses of surface water networks

	operational use			**water policy use**	
	water management	**flood warning**	**navigation**	**water balances**	**planning, included long term changes**
Rivers	**1/d**	**1/d**	**1/v**	**d**	**1/d**
Lakes and reservoirs	**1/d ***	**1**	**1**	**1**	**1**
Delta's and estuaries	**1/d ***	**1**	**1/v**	**1/d ***	**1**
Seas and sea coasts	**-**	**1**	**1**	**-**	**1**

1 = levels
d = discharges; v = velocities
d * = discharges, not derived by rating curves

7.1.1 Water level networks

Regarding the steps in the design process, as discribed in section 2.2 one should first determine the objectives. These differ from site to site. At specific sites data should be acquired anyhow, e.g. at:
- inflow of important tributaries;
- branching points of rivers (e.g. in deltas);
- at inflows of a river into the sea, a lake or a reservoir;
- upstream and downstream of weirs and sluices.

Also political and organizational aspects may require measurement stations, e.g. at:
- international border crossings;
- important cities, harbours, navigation locks, intake points, etc.

Whether along intermediate reaches more observing stations are needed depends on the requirement of accuracy of the values to be estimated from the gauging stations. At navigable rivers for instance, stations should be located such that the transition from water levels at sites to the values of depth at shallows is possible; also the acquisition of operational information about ice phenomena should be taken into account.

The transfer of data from gauged to non gauged sites, can be done by interpolation or by hydraulical computations.
Here one arrives at the second step in Section 2.2, the investigation of the physical system. The need for knowledge is obvious if hydraulical computations have to be used. However, also for the application of an adequate interpolation technique some knowledge of the physical system is desirable, since this strongly influences the correlation structure. In tidal waters, for instance, the correlation structure is related to the system of harmonic components and the velocity of propagation of the tidal waves. Also in non-tidal rivers the motion of the waters influences the correlation structure. Insight in the channel network structure can lead to a better understanding of the behaviour of the correlation as a function of distance and time.

The third and fourth step in Section 2.2 require the examination of the relation between distance (or reversely, density) and standard error of estimate. This can be carried out on the hand of existing data and of physical considerations.

Like for all hydrological networks, here the rule also holds that for any site it should be possible to determine the phenomena concerned with sufficient accuracy. This standard error should not exceed a certain limit value, which depends on the requirements made by the user. It might be tried to determine this value by a cost benefit analysis as described in Chapter 5.

However, since in many cases it is impossible to express the standard error of estimate in financial terms, one often resorts to what is called a surrogate criterion. This is also a limit value, not to be exceeded by the standard error of estimate. As a rule the assessment is more or less arbitrarily, based on different considerations. Sometimes this limit is assessed at a value equal to the standard error of measurement at the gauging stations. This choice can be justified by the fact that a network, designed on that base, will produce data which are affected with about equal standard errors, either of measurement or of estimate, along the reach or over the area considered. From this point of view this is indeed an efficient solution if the same accuracy is required everywhere. If certain sites require a greater accuracy the network design should be focussed on such requirements.

Although the WMO Technical Regulations require an accuracy of 1 cm, and in special cases even 3 mm, in practice the standard error of measurement appears to amount to some centimeters, say 1 to 3 cm, depending on the conditions of the gauging station, its location and the hydraulic conditions in the adjacent area (Van der Made, 1982).

For the calculation of the water levels at interstation sites the following methods might be considered:

- pure mathematical interpolation (e.g. linear, higher power curves, spline functions);
- interpolation, based on statistical considerations (e.g. optimum interpolation, kriging);
- physical models (e.g. hydraulical computations based on the St. Venant equations).

All those kinds of calculation models might be combined with an adaptive mechanism, e.g. a Kalman filter, in order to find the best results. In most cases these techniques are still in an experimental phase.

Whatever method is used, it is necessary to check the results with the reality. Therefore it is recommended to carry out measurements at some intermediate sites for comparison with the interpolation results. The relations which are used in the interpolation methods can change in course of time. A second, additional network, besides the main network can serve this scope.

This leads to the concept of two network systems along the same water body, i.e. a main network of stations of high quality and reliability and an additional network of stations, as a matter of fact also of good quality, but for which the requirements are lower. For the latter category a limited number of interruptions might be accepted.

Further arguments, besides the regularly check of the used relations, for an additional network are to supply information in case of:

- fall out of a main network station;
- extreme conditions, for which the used relations are not fully adequate.

As a general guideline the main and additional networks might be planned in such a way that an additional station is located somewhere halfway between two main stations.

The above concept was used for the design of the hydrometric network of the major rivers, the tidal streams, the coastal zones and the main lakes in the Netherlands.

A network intended for reservoir operation must ensure the determination of the mean water level, computation of actual water balances of the reservoir, collection of information about ice phenomena, waves and other regime elements necessary for the operation of hydro-electric power plants, water intake structures, navigation, fish industry, recreation, etc.
As an example is discussed the water level network in the tidal estuary of the Western Scheldt in the Netherlands (Fig. 7-1).

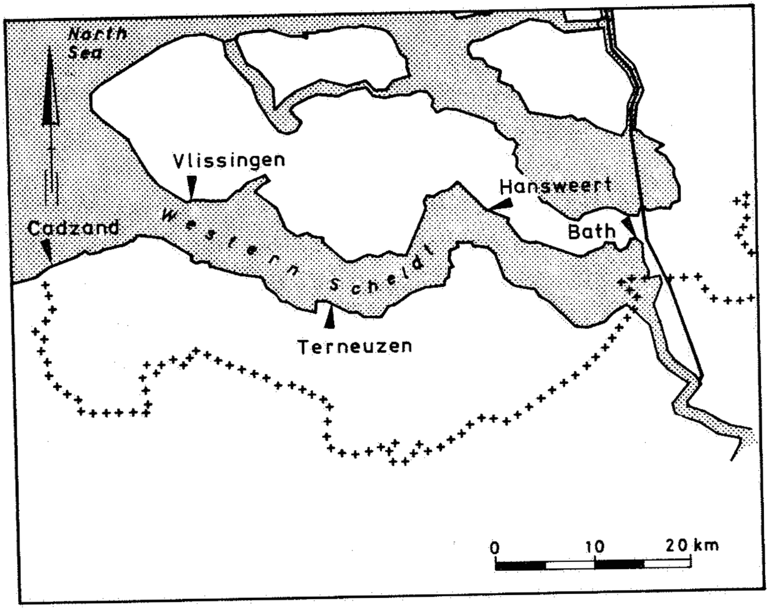

Figure 7-1 Water level gauging stations in the Western Scheldt tidal estuary

The standard error of the difference y between a measured level at an intermediate site between a series of main network stations and the value, calculated for that site, using the data of the main stations, can be derived according to:

$$\sigma_{\Delta y}^{2} = \frac{|R\ \text{all stations}|}{|R\ \text{main stations}|}\,\sigma_{y}^{2} \qquad (7.1)$$

where:

σ_y^2 = the variance of the water level at the intermediate site

$|R\ \text{main stations}|$ = the determinant of the correlation matrix between the water levels at the main stations

$|R\ \text{all stations}|$ = the determinant of the correlation matrix between the water levels at all stations, i.e. at the main stations and at the intermediate site

If there are n input data of the main stations, the determinant of the denominator is of the order n, that of the numerator of order (n+1).

In the example considered the data of the station Terneuzen were derived for 2 cases:

- from the couple Vlissingen-Hansweert (42 km);
- from the couple Cadzand-Bath (78.4 km).

Besides simultaneous data at the three stations also use was made of data, occurring a time interval Δt earlier at the seaward station, and of those, occurring Δt later at the landward station. Thus, of the two main stations, two data each were used, in total 4 input data. In this case the denominator determinant was of order 4, the numerator determinant of order 5.

The spatial, auto- and cross correlation coefficients, figuring in the correlation matrices were derived from a relation, including the harmonic tidal components, the propagation velocity of the tidal wave and a noise term, decreasing with time and distance.

The behaviour of the standard error $\sigma_{\Delta y}$ as a function of the time interval Δt and the location of the main stations is shown in Fig. 7-2. Here the influence of the tidal motion is shown. The standard error shows a local maximum at a distance, where the propagation time between the two main stations is equal to the time interval Δt but it shows a minimum if the propagation time is twice Δt.

Since the design criterium of $\sigma_{\Delta y}$ was assessed at 3.5 cm a time interval of 0,5 h would be preferable. In that case a maximum distance between the stations of around 50 km could be accepted. For larger time intervals this result could not be obtained, whereas shorter time intervals would not lead to an improvement.

Finally the five stations, shown in Fig. 7-1 were included in the network, partially as main stations, partially as additional stations.

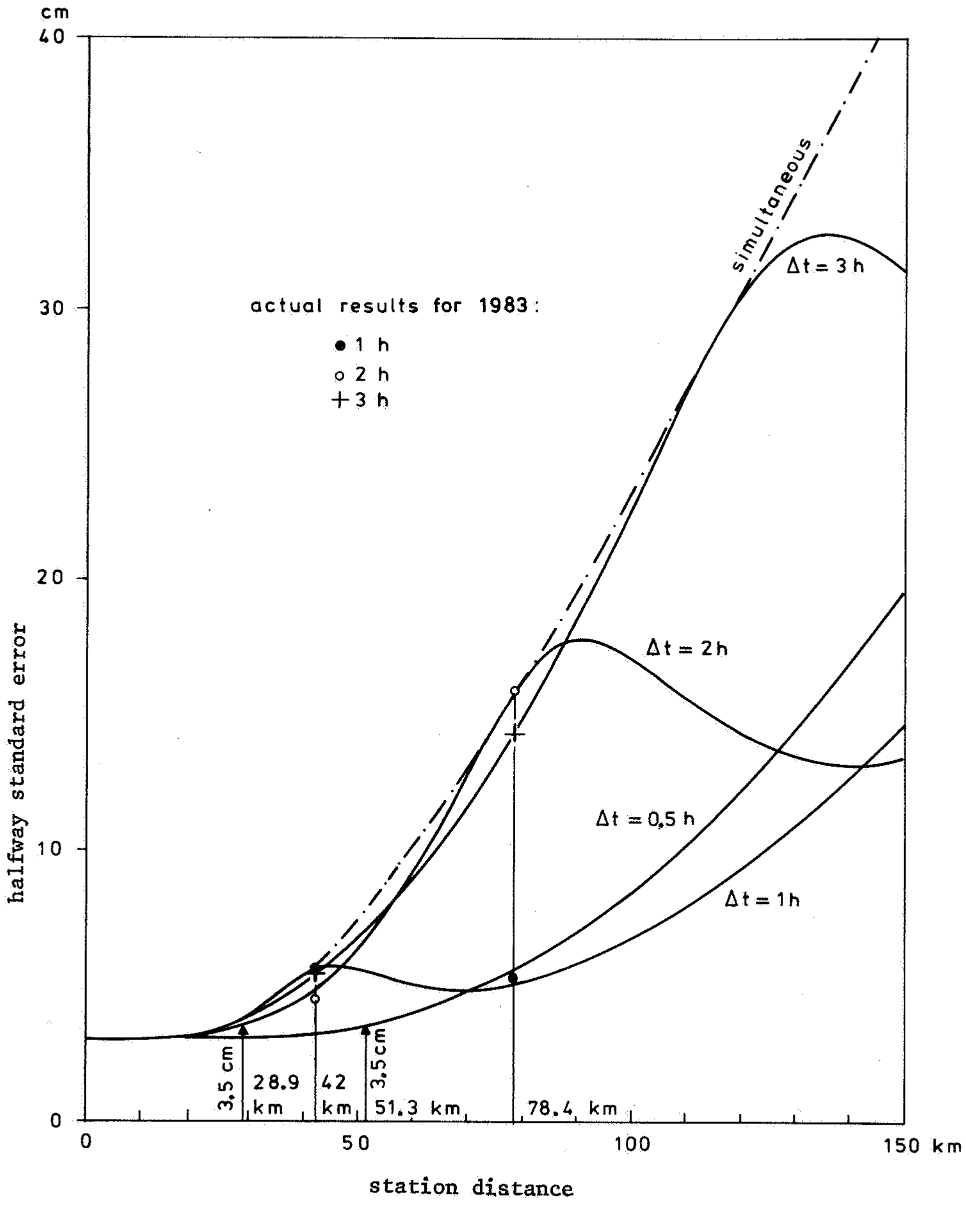

Figure 7-2 Curves of halfway standard errors $\sigma_{\Delta y}$ vs gauging station distance for time intervals of 0.5h, 1h, 2h and 3h (Western Scheldt tidal estuary)

7.1.2 River discharge networks

As was stressed before, networks for river discharges can have a lower density than those, required for water levels. However, the principle that values at non gauged intermediate sites could be reconstructed with adequate accuracy here holds too. Here similar questions, concerning the adequacy of the accuracy arise, to which similar approaches can be applied.

At rivers used for irrigation the location of stations must ensure the acquisition of data on streamflow, upstream from the zone of water diversion, at main water-intake structures of a large irrigation system, downstream from the inflow of main tributaries, at the beginning and the end of water diversion channels and also at intermediate sites between those afore mentioned. The stations should be located in such a way that the natural and artificial changes of streamflow between the stations would make a certain amount of the discharge at the upstream gauge, depending on the required accuracy.

At rivers or river stretches with insufficient water storage, just only covering water consumption needs, the station network should provide data for the computation of channel water balances.

In the near future automatic systems of operation of irrigation, hydroenergetic and complex water-management watershed units will be developed. Such systems are either in action already or are under development in the USSR, USA and other countries. Under such conditions the station network location depends on the requirements of the automatic system of operation for the amount and content of hydrological information, and here too on the observational accuracy.

If the above procedure would lead to many stream gauging stations, i.e. to a rather expensive network, one might examine whether some kind of regionalization might be feasible. In that case one tributary is gauged and subsequently its result is considered to be representative for a number of other, as a rule smaller, tributaries.

Obviously this will lead to a less accurate result than for the case, whereby all or most tributaries are gauged. Here too one should aim at an optimum result, counterweighing the number of stations (network density) in a certain area against the accuracy obtained. This problem could be approached by a cost-benefit analysis.

Runoff data of a certain area, expressed in depth per time unit, can be derived from discharge data by dividing through the area of the upstream basin. Thus a discharge of Q m^3/s, coming from a basin of A km^2 corresponds with an annual runoff q mm of:

$$q = \frac{Q}{A} \times 31500 \text{ mm/a.} \qquad (7.2)$$

In this case the network density should preferably approached from a water balance point of view, i.e. in correspondence with those of precipitation and evaporation networks. Now the network density could better be expressed in the number of stations per unit area, in contrast to the density of water level or discharge stations, that will preliminary be expressed in the number of stations per unit length.
The design procedure can also in this case be based on the relation between network density and the associated errors (Karasev, 1968).

7.1.3 Planning, design and long-term changes

Streamflow networks have often been designed to obtain more information about mean flows, floods or low flows. On the other hand, sometimes networks can be reduced because additional measurements do not result in much better design values.
For planning and design it is not always necessary to have a long record at the site of interest. Sometimes additional information can be obtained from long records at nearby stations. Further, regional information of streamflow characteristics can be used to get an estimate at an ungauged site or to improve estimates at sites with insufficient data.

Such regional information may consist of a regression relation between streamflow characteristics (mean discharge, mean annual maximum) and catchment characteristics (area and mean slope upstream from the site, soil and precipitation indices). Quantile estimates of extreme values may be obtained by using a regional curve of quantiles of standardized maxima (NERC, 1975; Greis and Wood, 1981). This requires, however, that the coefficient of variation does not vary within the region (Hosking et al., 1985).

Station discontinuance based upon correlation links with other stations in the network has been considered by Maddock (1974). As with interpolation between gauging stations, a network can be reduced when there is large spatial correlation between measurements of neighbouring stations. However, the effect of correlation on standard errors of estimates of the mean, the variance or quantiles is not the same as for the accuracy of interpolation. The accuracy of estimates of flow characteristics using a correlated longer record from a nearby site is discussed by Moran (1974), Cooper and Clarke (1980) and Vogel and Stedinger (1985).

The standard error of the estimate of a streamflow characteristic from a regional logarithmic regression has been used as a measure to compare different network lay-outs in the NARI technique (Network Analysis for Regional Information). A simulation experiment to study the influence of the number of stations, the length of records and the model error on the accuracy of the estimate has been described by Moss and Karlinger (1974) and Moss et al. (1982). Extensive simulation experiments can be avoided by using a generalized least squares procedure to estimate the parameters and to determine the precision of the regression model (Stedinger and Tasker, 1985).

Another objective of a network can be to detect long-term changes, e.g. due to climatological and geophysical changes or to human activities.

In the latter case two different types of stations should be included:

- stations in areas influenced by human activities;
- stations in areas not influenced by such activities (benchmark stations).

The data from the benchmark stations are used to remove a part of the variation in the record of the influenced area. This may result in a considerable improvement of the trend detectability, especially when there is strong correlation between the records of the two sites. Besides that some correlation is required, it is also necessary that benchmark stations are situated in areas where no important changes are expected. Feasible gauge locations might be found in nature reserves.
In principle, for all kinds of trends, the effectiveness of a benchmark station can be related to the quantity Q defined by Eq.(4.17). In contrast with detecting trends in water quality data such an approach has not been considered yet for long-term changes in water levels and discharges.

7.2 Networks for surface water quality

T. Schilperoort*

7.2.1 Monitoring objectives

Most routine water quality networks have objectives which can be classified as follows:

- to provide a system-wide synopsis of the actual water quality;
- to detect long-term trends;
- to enforce quality standards and to detect violations;
- to identify unknown sources of pollutants;
- to monitor the water quality and to establish an early warning system;
- to formulate short- and long-term strategies in order to prevent or correct undesirable developments of the quality;
- to assess the effect of any corrective action.

Besides these routine objectives, water quality data are strongly needed for the purpose of model building, verification and validation, and to improve the understanding of the many, still poorly understood, water quality processes.

7.2.2 Physical aspects[1])

As quality varies from place to place within most water systems, single sampling locations are not representative of the entire system and locations appropriate to the needs of a particular system, must be selected. Considering that the nature and extent of spatial heterogeneity may vary with time, local knowledge and understanding of the system are necessary.

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[1]) This Section is based on a note of Rosenthal (1982).

The main causes of a heterogeneous distribution of quality in water systems are the following:

- If the system is composed of different bodies of water, these may be unmixed or in course of mixing.
- Another type of heterogeneity is characterized by a non- heterogenious distribution of certain determinands in an otherwise homogeneous water system.

When no detailed knowledge is available for a particular system, a preliminary investigation has to be made to assess the degree of non-homogeneity. Test of the nature and degree of heterogeneity should be preferably repeated to check whether they vary with time.

Hydraulic and hydromorphological considerations have to be taken into account when planning quality networks. As a rule, non-uniform hydraulic conditions have to be avoided. The selection of sites has to be such as to obtain as much as possible uniform conditions.

When mineralogical conditions in a given catchment area are particular ones, natural waters may become loaded with significant amounts of various chemicals. Such natural mineralogical effects may interfere with the detection of water-quality changes. Therefore, when selecting a sampling site in such regions, it is necessary to separate the effects of natural geochemical anomalies of the waters from those caused by the mineralogical phenomena prominent in the monitored area.

When the desired location has been selected, the particular position from which to sample must be also decided. If there is any possibility of non-homogeneous distribution of quality at the chosen location, it is necessary to determine the nature and magnitude of the heterogeneity. If the quality is homogeneous, a limited number of samples is required.

If heterogeneity is present, two approaches are possible:

- alternative locations are sought and tested until a suitable and homogeneous one is found;
- the location originally selected is used and samples are routinely taken from several positions chosen so that they are properly representative for the quality at the location.

When considering the spatial distribution of sampling positions, account must be taken of the hydraulic conditions which can be characterized approximately as follows:
- homogeneous;
- stratified flow;
- plug-flow;
- longitudinal mixing;
- lateral and longitudinal mixing;
- patchy.

The number of sampling positions needed to obtain the required information, tends to be smallest for completely mixed water-bodies and greatest for patchy systems.

Various types of water systems require different approaches to sampling networks. For streams and rivers sampling locations are chosen with respect to the actual and desired uses of these water-bodies. Generally, sampling at or near the surface, bottom, banks and stagnant areas, should be avoided. Bottom sediments should not be disturbed and non-representative films floating on the surface, should be avoided. When samples must be collected from locations where quality is not uniform through the cross section of the river, samples should be taken at an appropriate number of points to give proper representativeness considering flow-rate over the cross-section.

Water-bodies such as lakes and reservoirs are subject to several types of heterogeneities caused by such factors as inflow of feeder streams, isolated bays, wind action causing irregular distribution of various types of pollutants. Another characteristic feature is the vertical stratification of the water body which is due to the differential heating of the surface layers by solar radiation. This leads to marked differences in the water quality at various depths of the investigated water-body. This implies changes in the density of the water impending vertical mixing of the waters. The bottom waters may eventually become anaerobic and other substances are then released into the water from the bottom sediments.

The concentrations of many determinands may thus vary with depth so that sampling positions are needed to characterize the quality of water at a particular location. A minimum of 3 samples is generally essential (1 m below surface, 1 m above bottom and at an intermediate point). During those periods when the water-body turns over, its quality becomes vertically homogeneous and one sampling position at a given location is then generally sufficient. The measurement of water temperature or of dissolved oxygen at different depths, provides a rapid means of assessing the degree of stratification.

In the investigated water systems, regular cyclic variations of quality may occur with periods of one day, one week or one year. Diurnal fluctuations can occur in rivers, lakes and effluents. Persistent cyclic variations with other periods may also occur i.e. resonant periodicities in density-layered-water bodies or regular variations due to discharges in industrially exploited rivers. If cyclic variations occur, biased estimates of quality will be obtained unless sampling times are carefully chosen. In certain cases, the objectives of the program require sampling at particular times, i.e. samples corresponding to the worst quality or particular flow rates. Requirements of this type are best considered on the basis of local knowledge.

7.2.3 Dimensionality of the network

When designing water quality networks, multidimensional network design techniques have to be considered in principle because of two reasons:

- the multiple (spatial and temporal) dimensions of the physical, chemical and biological processes affecting water quality;
- the necessity to use multiple variables to describe water quality quantitatively.

This second feature distinguishes water quality networks from other hydrologic networks where usually only a single or a small number of variables are measured.

In some instances, where links between variables are unimportant (which might be the case, for instance, for a few inorganic constituents) multiple univariate design is possible, and dimensionality may not be a problem. More commonly, however, water quality variables are dynamically linked, and this must be considered explicitly in the design methodology. Further, even where multiple univariate analyses are possible, logistical considerations normally constrain the designer to coordinate sample location and frequencies for the individual variables, so interdependence of variables normally must be considered at this level in any event.

Referring to Section 4.6, this implies that design techniques which incorporate physical knowledge, like Kalmanfiltering, are especially worthwile to be used for waterquality networks. Some results on this issue can be found in the literature (Chiu, 1978).

In the next section, however, the application of some simpler techniques will be illustrated, with the obvious consequence that only a part of the total design problem is solved.

7.2.4 Some examples of network design

In this section, two examples are presented, which are taken from the activities of the Delft Hydraulics Laboratory with respect to optimization and design of monitoring networks.

The first example relates to the optimization of the routine water quality monitoring network of the main surface waters in the Netherlands (Schilperoort et al, 1982). This network includes almost 400 sampling stations with a sampling interval ranging from 1-4 weeks. The number of water quality variables analyzed in each station varies from 15 to 100. Initially, only the sampling frequencies for a limited number (18) of water quality variables were optimized. Some results of this frequency optimization will be described here.

The main objective for which the sampling frequencies were to be optimized, was identified to be the detection of long term trends. Quantification of this objective yielded a minimum detectable trend of 20% of the mean annual value, to be detected over a 5-year period with a probability of 80%. An obvious measure of the monitoring effectiveness, therefore, is the trend detectability of the network which is related to the quantity $Q\ (\Delta,T,Tr)$, defined by Equation (4.17), according to

$$E(\Delta,T,Tr) = \Phi\{Q(\Delta,T,Tr) - \xi(\tfrac{\alpha}{2})\} \qquad (7.3)$$

where Φ denotes the standard Gaussian distribution function and $\xi(\frac{\alpha}{2})$ a normal percentile point. In order to relate this trend detectability to the sampling frequency, the temporal correlation structure of the relevant water quality processes must be taken into account. It should be noticed, however, that variations in discharge may confuse this correlation structure considerably. This is illustrated quite clearly in Figure 7-3. In this figure the trend detectability for chloride at Lobith (river Rhine) is shown, calculated from both original data and data, corrected for discharge variations.

While the original data suggest that the 80%-detection objective cannot be met at all, the corrected data clearly show that even a 7-week sampling interval is still sufficient to meet the objective, instead of the weekly interval as used before. It should be stressed, therefore, that a good data processing is an indispensable link in the optimization process of monitoring networks.

Moreover, this example shows the need of integration of a water quality network and a water quantity network.

The second example relates to the design of river and coastal water quality monitoring networks, with the aim to support coastal zone management of the Emilia-Romagna Adriatic coast in the northern part of Italy (Delft Hydraulics Laboratory, 1983). For both the river and coastal network, the sampling frequencies had to be designed in relation to the objective of trend detection.

Moreover, the sampling locations of the coastal network had to be designed in such a way that the density of the network should be adequate to permit the assessment, to an accuracy consistent with its purpose, of the water quality state anywhere in the coastal area.
Using the same theory as in the preceding example, design curves were constructed from which the sampling intervals can be read, which are required to comply with a detection probability P for a trend magnitude of Tr/σ times the process variability σ, over a period of 5 years.

In Figure 7-4 these curves are shown for processes having a correlation coefficient $\rho_1 = 0.85$ for weekly observations. To apply these curves, one must be able to make some crude estimates of the main characteristics of the processes to be monitored, for which physical knowledge is indispensable.

To design the sampling locations in the coastal area, various network options were judged on the basis of the accuracy at which the water quality, anywhere in the coastal area, could be reconstructed from the network observations. For that purpose, the interpolation variance, calculated using the theory of kriging interpolation and normalized with respect to the process variabilities, was chosen as an adequate measure of monitoring effectiveness. In Figure 7-5 isolines of this relative interpolation variance are shown for one specific network configuration, both in case of an isotrope water quality state (Figure 7-5 a) and in case of an anisotrope state due to a strong north-south circulation (Figure 7-5 b). By comparing these results for various network options, an optimal initial design of the network layout was found.

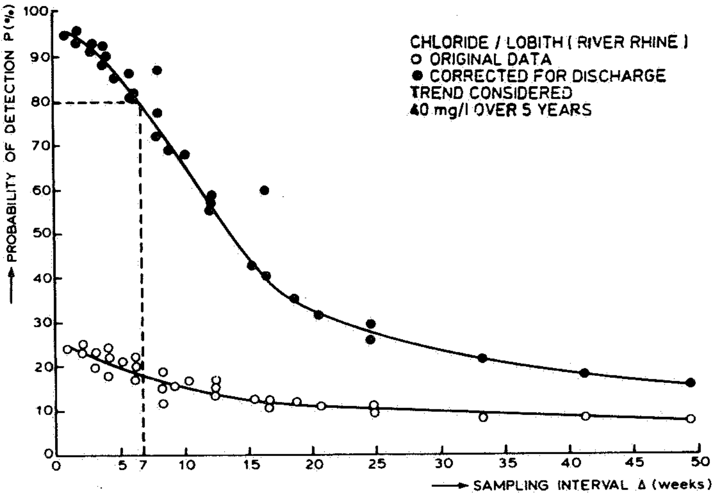


Figure 7-3 The probability of detection as a function of the sampling interval (chloride, river Rhine)

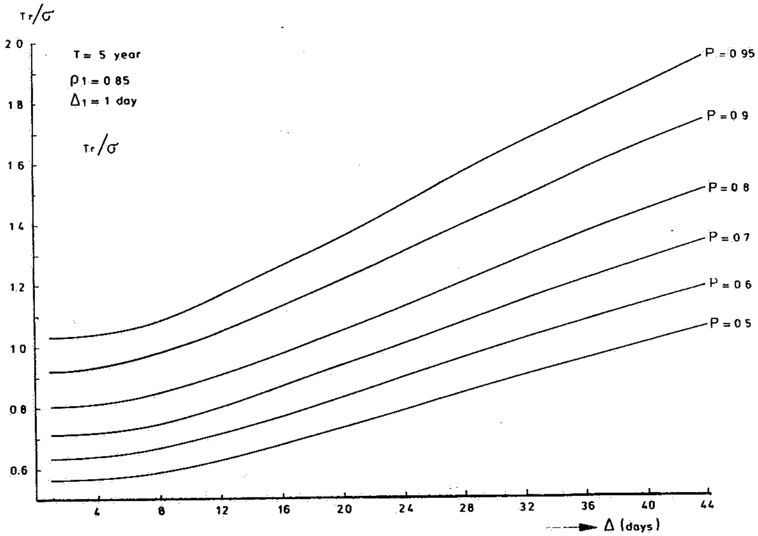


Figure 7-4 Detectable Tr/σ ratios as a function of the sampling interval for different detection probabilities P

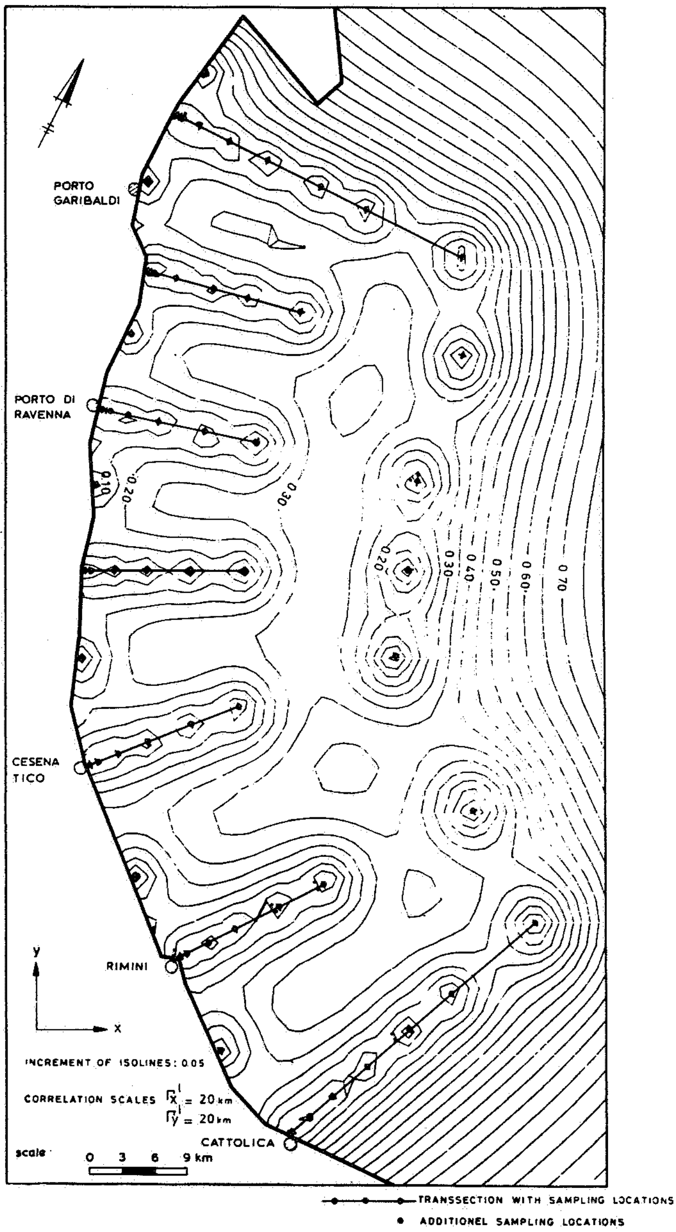
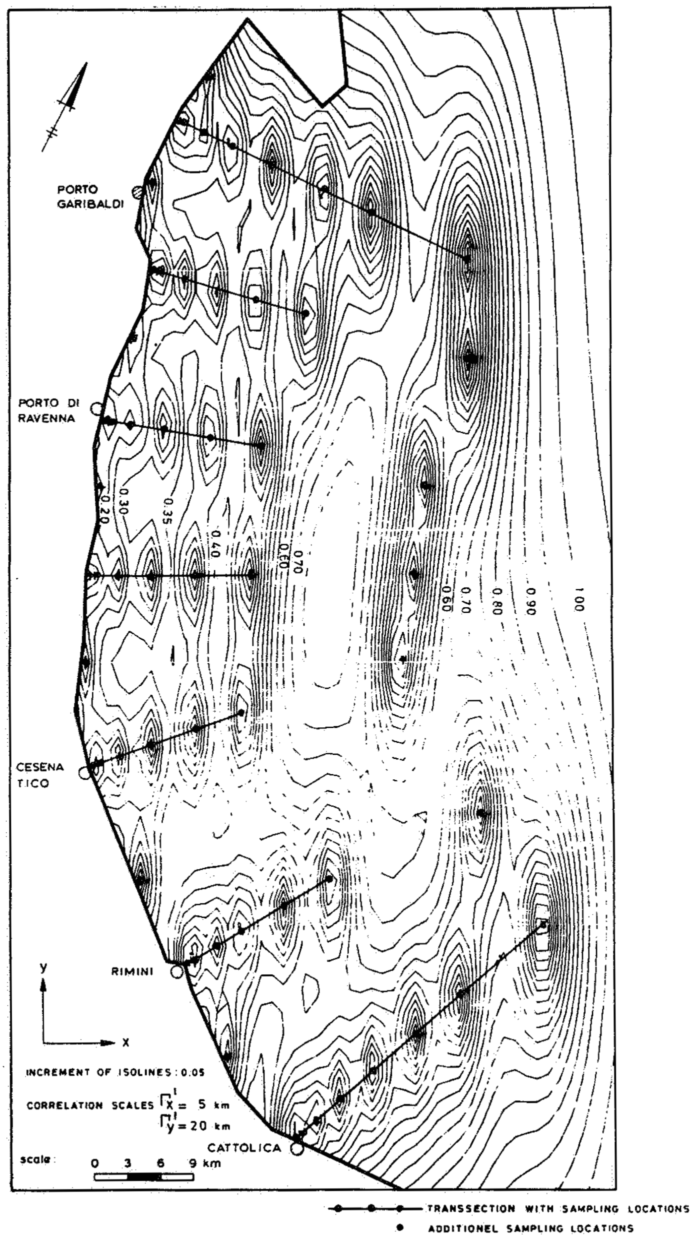


Figure 7-5a Water quality monitoring network (offshore region).
Lines of equal relative interpolation variance



Figures 7-5b Water quality monitoring network (offshore region). Lines of equal relative interpolation variance

8 NETWORKS FOR GROUNDWATER

8.1 Networks for groundwater quantity

G.K. Brouwer*

For a nation wide groundwater level network some general approaches will be outlined to arrive at a suboptimal network. As groundwater variability mainly follows from physical laws an error measure in statistical sense can be hardly obtained due to incomplete knowledge of stochastic groundwater flow. Some recent progresses made in this field will be introduced in some length.

8.1.1 Monitoring objectives

Monitoring objectives for a nation wide network should follow from management of groundwater as a resource, effects of constructions (man made lakes, polders etc.), cultivation of land and environmental protection. The objective formulation is also related to natural influences on the geohydrological system, such as climate and sometimes tides and earthquackes. Last but not least, knowledge of the regional geohydrological system is indispensable for stating the objective(s).
The management generally takes place on a long term base and generation of management oriented information has to be seen as a permanent activity. Depending on the monitoring objective(s) an optimal or a suboptimal network is obtained.

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An optimal network is a network with maximum expected net benefit of the monitoring effort with or without a budget constraint. According to Rodríguez-Iturbe (1972) network optimization for a base level network can be hardly fullfilled due to lack of information with respect to economic development.

Loss in benefit analyses for a nation wide groundwater network are scarce or not yet existing.

A suboptimal network could be either error constrained or budget constrained.

Considering suboptimal networks the type of error has to be defined. In the common case, the interpolation error of piezometric head in time and/or space is used. But also errors in the mean, trend, extremes in time and/or space could be relevant.

In case several monitoring objectives have been formulated, multicriteria models may lead to a common error measure, while policy considerations can be taken into account.

Formulating the allowed error will be influenced by the intensity of needed study. Davis (WMO, 1972) formulated the following categories: reconnaissance, general investigation, intensive study and continuing surveillance. Furthermore it can be anticipated beforehand that the allowable error can be made region dependent.

Specific stresses on a small scale on the geohydrological system may also need monitoring. The required network is called a specific network. However as specific networks partly rely on the nation wide network an important objective for the nation wide network is its reference function.

8.1.2 Network characteristics

Network characteristics of groundwater observations locations are:

- structure (triangular, square, line, random),
- density (in three dimensions),
- observation frequency,
- construction of observation wells (not to be dealt with in this study).

These characteristics should partly follow from a preliminary design where monitoring objectives and costs have been analysed in a (sub) optimal way. Additional factors and considerations lead to a detailed design (Bachmat, in prep.) and will be shortly introduced here.

Network structure should be directly related to the direction of maximum variability of groundwaterlevel and chloride content. Shortest distances are reasonable in the direction of highest variability.

Line wells should be perpendicular to a coastline or river, whereas a radial structure for a groundwater withdrawal site is recommended. The density of the network should be highest in regions with a high variability in piezometric head. Further details can be found in Brown (1978), WMO (1972, 1981a) and Bachmat (in prep.).

The observation frequency depends on the time base of phenomena under study. Short time phenomena may need continuous monitoring, long observation intervals are advised for slowly in time varying processes (Heath, 1976). However, observation frequency may be non uniform due to superimposed variability scales.

8.1.3 Data analysis

There should be an equilibrium between data and the model used to analyse the data. According to the conclusion of the MIIGS symposium (Brouwer et al, 1983) the development of hydrogeology nowadays depends much more on the collection of representative data and the methodology to analyse this data than on the further development of model techniques.

A perfect model needs only a restricted amount of piezometric head data. On the other hand no model is necessary, if the piezometric head in time and space would be fully known from a dense network with high sampling frequency. In practice, always an intermediate situation exists. The main point is then: is variability in piezometric head conductivity, storativity (and density of brackisch/salt water) covered with the already existing data.

As hardly models exist which can estimate the variability of piezometric head based on variability in conductivity etc., the variability of piezometric head can only be derived from piezometric head data in a quantitative way and in a qualitative way from knowledge of system variability.

Collection and screening of relevant available data is the first step in data analysis. The various information sources (Table 8.1) should lead to a global understanding of the geohydrological system. Especially the relation with piezometric head should be evaluated.

Table 8.1 Hydrogeological data globally related to hydrogeological system characteristics. Main relations with variablility in piezometric head are indicated with a star

		piezometric head		
information	system charateristic	level	variability	
			space	time
geology	conductivity, storativity	*	*	
soil	boundary condition	*	*	
topography	boundary condition	*	*	
hydrochemics		*		
(incl. isotopes)				
vegetation		*		*
surface water	initial/boundary condition	*	*	*
climatology		*		*
man induced changes	conductivity, storativity	*	*	*
pumping tests etc.	initial/boundary condition			

A differentiation in hydrogeological systems, based on topography and climatology, was given in Brown (1978).

The effect of scale should be taken into account (Toth, 1963,Engelen 1981). For the basic network probably regional and subregional flow systems are of direct concern where local flow systems are not. Large scale withdrawals, cultivation over extensive areas are man made influences on the flow system and should also be analysed.

In the optimal case with no restrictions on the available data saturated flow should be analysed with the three dimensional and time dependent groundwater flow equation following from Darcy's law and the continuity equation.

Dimension reduction and coarse discretization in numerical simulation are generally accepted but should be carried out with care. Dimension reduction could be introduced when conductivity for aquifers and aquicludes differs more than two orders of magnitude. This simplification in horizontal and vertical flow leads to minor errors (Chorley and Frind, 1978).

For transient flow in a phreatic aquifer it was concluded (Sagar, 1979) that uncertainty in the initial condition is a major source of uncertainty in piezometric head.

For a heterogeneous formation under confined conditions reduction of the transient flow problem to a steady state problem is generally only valid for three dimensional flow and not for two dimensional flow.

For periodic flows with a relative small unsteady head gradient with respect to that of the steady one, a reduction of the groundwater flow problem to two dimensions however is considered valid (Dagan, 1982).

For two dimensional steady state confined groundwater flow in a bounded domain, Smith and Freeze (1979) found that the standard deviation in hydraulic head increases with an increase in either the standard deviation in hydraulic conductivity and the strength of spatial correlation between conductivity values. Also the uncertainties in the predicted hydraulic head are strongly influenced by the presence of a spatial trend in the mean hydraulic conductivity.

After definition of aquifers and aquicludes in the region of study a practical approach is to model the covariance of piezometric head in time and space (see Section 4.6).

In the common case a groundwater level network does already exist. For clarity then two situations can be identified given the maximal allowed standard deviation in time and space: network reduction and network extension.

Network reduction

The groundwater level interpolation error in time is estimated for each aquifer as indicated by already collected groundwater level data. When the standard deviation of the interpolation error at an existing observation location is less than a prescribed value then this observation location or screen can be skipped from the existing network. In Figure 8-1 the prescibed values are 15 cm and 10 cm for respectively high and low areas whereas the amplitude of the annual fluctuation amounts to 0.75 m - 1 m. For these values the network can be considerably reduced. With the Kalman interpolation technique the relations between network-characteristics (structure, density, observation frequency, observation error) and the objective, translated in a maximum allowed standard deviation of the interpolation error, could be obtained (Brouwer, 1983).

Network extension

From the existing groundwater level data for each aquifer the standard deviation of the interpolation error in space of a specific date has to be derived. If this standard deviation of the interpolation error is larger than the stated value following from the objective than an extension of the existing network is needed.
Most advantageously the interpolation error in space can be obtained by the kriging technique and applying the fictitious point method (Delhomme, 1978). An impression of the interpolation error in space is given in figure 8-1 (network extension). The piezometric level varies here from 10 m above NAP (Dutch Ordnance level) to slightly below NAP.

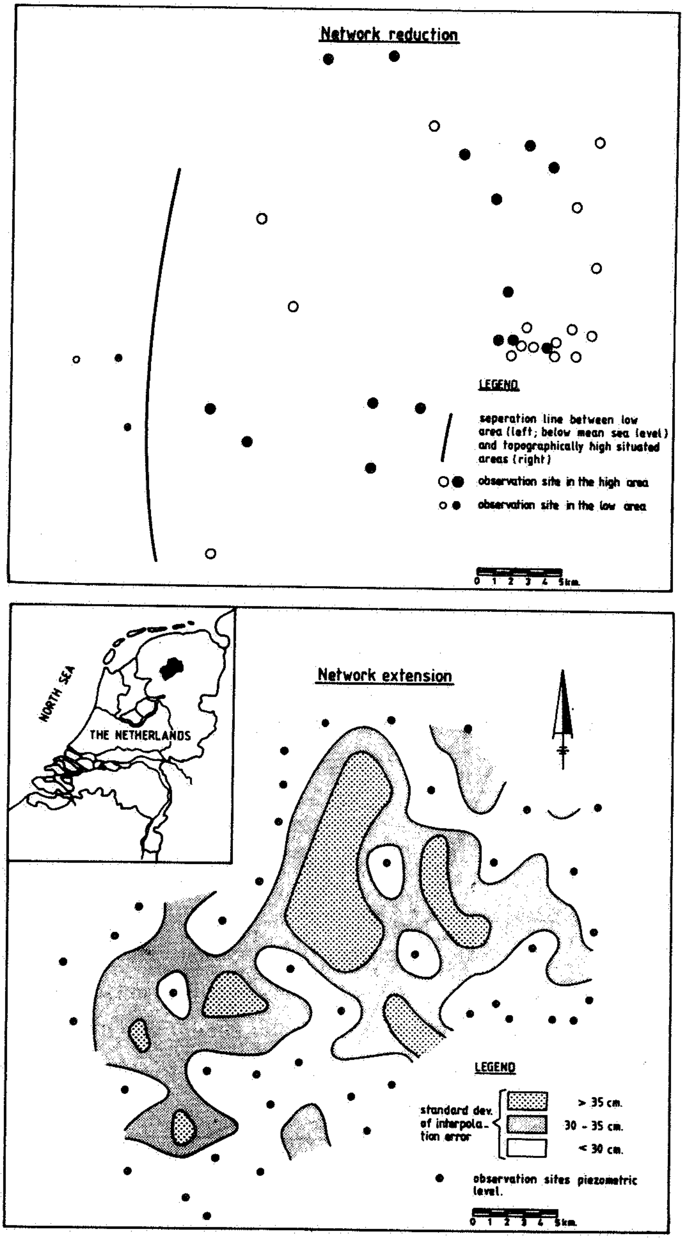

Figure 8-1 Network reduction and network extension for a restricted area in the Northern Netherlands. Stations indicated by open dots in the upper figure can be removed when a standard deviation of the interpolation error 15 cm (high area) or 10 cm (low area) is allowed. Areas in the lower figure with a great standard deviation of the interpolation error are preferable for new measurement sites

8.2 Networks for groundwater quality

W. van Duyvenbooden*

8.2.1 Introduction

Groundwater quality can differ widely, depending on natural factors like soil- and hydrogeological conditions, presence and nature of pollutants and pollution sources. Often a very sharp boundary is found between types of groundwater of totally different origin and composition. Even at short distances of less then 1 meter, significant differences in groundwater quality can occur.
For this reason it is not possible to design a uniform set-up for networks, even in the case where their objectives are identical. Furthermore, network design is strongly dependent on the objectives of the network.

In this section attention will be given to some relevant aspects and a general approach for network design.
For more information reference is made to the extensive literature in this field (Everett, 1980 and 1981, Nacht, 1983, Pfankuch, 1982, Scalf et al, 1981, Tinlin, 1981). Also is referred to publications, describing the situation in the Netherlands (Duyvenbooden, 1981, Duyvenbooden et al, 1981 and 1985).

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8.2.2 Methodology

Proper design of a groundwater quality monitoring network requires a well-considered methodology. It may be clear that in the first place it is necessary to define the proposed nature and objectives of the network. In this respect attention should be given to the need for information and monitoring devices already available. In general, most networks have at least one or more of the objectives mentioned in Section 7.2.1 for the surface water.

In principle it is possible to make a distinction between networks with a limited, local purpose and regional networks with a more general nature. Local networks are mostly directed at monitoring the possible effects of point sources of pollution on groundwater quality. Regional networks are mostly directed at the effects of pollution sources with a more diffuse nature and/or groups of local sources in the area.
On subregional scale networks can be directed at the protection of groundwater in the recharge areas of groundwater pumping stations.

A chronological, stepwise procedure for designing a network, is given below. In this connection is also referred to Chapter 2, but this time in particular focussed on groundwater quality monitoring.

- Definition of the objectives of the network

  In this respect groundwater utilization and environmental factors are of importance.

- Selection of the area for monitoring

  Primarily this selection is based on priority considerations. In this respect utilization of groundwater, number of pollution sources, types of pollutants and the possible effect on the environment are of importance. In practice the boundaries of these areas are based on physiographical (extension of groundwater basin, potentially influenced area) and administrative considerations (political boundaries which cross the boundaries of a groundwater basin).

- Definition of the hydrogeological situation

  Knowledge of the hydrogeological situation provides insight into the potential pathways of pollutants in the subsoil and is necessary for a right choice of monitoring points. Furthermore the hydrogeological situation determines extension and boundaries of the groundwater basin under consideration.

- Definition of groundwater usage

  This not only includes location and abstraction of pumping centers within the area to be monitored, but also zones where the polluted groundwater can influence the environment (seepage, drainage to surface waters).

- Identification of pollution sources and pollutants

  Not only attention should be given at existing local sources like waste disposal sites, but also at former industrial areas, feedlots etc., diffuse pollution sources (agricultural use of soil, air pollution, salt and river water intrusion) and potential pollution sources (which can pollute groundwater due to incidents, calamities or technical failures). Shape of pollution sources and way of screening from the environment is mostly determined by human activities related to the pollution, and type and risk of the pollutants present in the source.

- Evaluation of potential mobility, persistency and hazards of pollutants present in the area

  Depending on soil conditions pollutants will be more or less retarded and/or degradated in subsoil; certain pollutants are very mobile and persistent.

  For example positively charged ions can, depending on ionexchange capacity of a soil, be retarded by adsorption or ionexchange. Depending on persistency organic pollutants can be degraded; other pollutants can be reduced or oxidized. Rapidly degrading pollutants will not be found in groundwater; perhaps degradation products will be present.

If there is sufficient adsorption capacity in the top soil, also strongly adsorbable pollutants will be absent from the groundwater. Considering the potential hazards for men or environment, more attention should be given to monitoring pollutants which can cause troubles.

Based on the information gathered, it can be decided whether inclusion of a pollutant in the monitoring program will be useful or not.

- Collection and evaluation of already available groundwater quality data

  Natural groundwater quality is of importance with respect to possible utilization of groundwater. Thus it has its impact on the network design procedure. Available information on different watertypes present in the area contributes to a more optimized network design. This point concerns the inventory phase, described in Section 3.4.

- Evaluation of existing monitoring devices and programs

  Many times monitoring devices and programs already exist in an area. Review of the programs and devices shows monitoring deficiences. Efforts should be made to incorporate ongoing activities and existing devices in the design of the new monitoring program.

- Additional field investigations

  For a right choice of the locations of the monitoring points it can be desirable to carry out additional field investigations. In this respect attention should be given to the possibility and utility of geophysical measurements and remote sensing techniques. Besides, groundwater level measurements and groundwater sampling can be useful.

- Establishment and implementation of the networks

  To get an optimal monitoring system, it can be useful to divide the establishment of the network in several successive stages, thus making it possible to adjust the network to experiences from former stages.

- This stresses the iterative character of network design as depicted in Fig. 2-1. With respect to the implementation attention should also be given to aspects as type of monitoring wells, sample handling, methods of analysis data management and datahandling and interpretation of monitoring results.

8.2.3 Selection of locations

In case of local pollution sources usually heavily polluted leachate penetrates a restricted area of soil and groundwater. Due to the high concentration of pollutants and the fact that adsorption capacity of soil is restricted to local sources the physico-chemical conditions of soil mostly do not play an important role in the selection of monitoring locations. Based on hydrogeological conditions at least one reference well has to be placed at the upstream side of the pollution source. Attention should be given that this well is not influenced by this or other pollution sources. Furthermore one or more wells have to be situated in the central flowline downstream of the pollution source. Other monitoring wells can be situated at the downstream side of the pollution source, perpendicular to the central flowline. Because effects of point sources are often restricted to narrow flow tubes surrounded by non polluted groundwater, there never will be a quarantee that these flow tubes will be detected by the monitoring wells, even in a situation with a high network density.

Regional networks require an other approach for the selection of monitoring points. This is due to the fact in that more extended areas groundwater quality is primarily determined by type of soil and diffuse pollution sources, like agricultural use of soil and pollution due to emissions from the air. On local scale point sources can play an important role.
In fact, due to their physical and physico-chemical properties, three main categories of soil can be distinguished with relatively different types of groundwater, i.e. sandy, clayey and peaty soils. Besides there are the fractured rocks and solution porosity aquifers.

In sandy regions, types of groundwater can be found which closely reflect soil use, like natural areas, agricultural areas (and kind of agriculture) etc. and environmental effects of air pollution. Other specific types of groundwater can be found for example in dune regions and areas where groundwater is originating from bank filtration.

In regional networks directed to diffuse sources, a choice has to be made of the most important combinations of soil use and type of soil which should be considered for groundwater quality monitoring. Based on statistical considerations a number of wells can be placed in the selected combinations. In the field a well-considered choice of locations, based on hydrogeological considerations, has to be made in order to avoid that groundwater samples originate partly from other areas. For this reason, it is recommended to place the monitoring wells on the downstream side of the areas to be monitored. In this respect the relation between horizontal and vertical groundwater flow is of importance. Especially in areas with fractured rocks and solution porosity aquifers it should be taken in mind that the direction of groundwater flow is strongly determined by position and direction of fractures and holes.

8.2.4 Network density

In case of local networks directed to single local pollution sources, no general directions can be given on network density. It is strongly dependent on the specific situation and the objectives. When monitoring groundwater quality of an extended area directed on trend measurements due to the effects of all human activities in the area, it is recommended to divide the area in zones with specific types of groundwater, mostly related to type and use of soil.

In this way it is possible to restrict both the number of monitoring wells required and the sampling frequency. In this connection is referred to chapter 4, and to Nelson and Ward (1981).

8.2.5 Location of well screens

Locations and length of well screens is strongly dependent on the local situation and objectives of the network. In this respect, attention should be given to the vertical flow component of the pollutant or the polluted groundwater. Primarily, vertical flow is determined by local hydrogeological conditions, but also nature of the pollutant can play an important role.

In case of heavy fluids, for example chlorinated hydrocarbons, density flow may occur, resulting in rapid transport of the pollutant to the base of the aquifer. Concerning fluids with a lower density than the surrounding groundwaters, for example oil, there can be an upward gradient of the pollutants, resulting in pollution that density effects can influence the choice of depth of well screen.

Considering hydrogeological conditions, a distinction can be made between infiltration- and seepage areas. In seepage areas, there is an upward gradient in groundwater flow, thus preventing penetration of pollutants in deeper parts of the aquifer (except in case of density flow). In sandy areas, vertical groundwater flow is usually very low. In case of trend monitoring directed to the arrival of possible pollutants, well screens have to be placed in the upper groundwater.

In this respect, it is important to realize, that quality of very shallow groundwaters, close to the phreatic level, can vary widely in time and space, requiring a frequent sampling and many monitoring wells. For this reason it can be useful to place the well screens some what deeper, in groundwater with a more homogeneous composition. On the other hand it must be taken in mind that at large depths it is very difficult to recover the intake area of the groundwater sample taken.

In areas with fractured rocks and solution porosity aquifers, groundwater flow is strongly determined by fractures and holes. This increases the risk of an incorrect choice of location of a well screen.

The impression might be given that wrong decisions with respect to choice of monitoring depth could be avoided by using long well screens over the whole depth of an aquifer. In reality this causes problems due to the effect of short-circuit flow along the well screen (proportional to the length of the screen cubed) and mixing effects (dilution of polluted with non-polluted groundwater even to concentrations below detection limit). Depending on the objectives of the network it can be considered to place several relative short screens, till about 2 meter length, in a borehole. In that case, depth of the screens can be related to hydrogeological factors like the presence of more permeable layers and fractures, preferential pathways for the pollutants. In that way, it is possible to cover the whole depth of an aquifer ànd to monitor selected strata in that aquifer.

8.2.6 Selection of variables

In case of trend monitoring directed at the effects of pollution sources on an extended area, a general change in the quality of groundwater often can be established by determining the so-called macroparameters, generally substances which make up the major part of the various emissions and which also can occur naturally in the groundwater. Clearly, these parameters can be a part of the selection. In this scope chloride, sulphate, carbonate, nitrate, natrium, potassium, calcium, magnesium and ammonium can be mentioned. The same holds true for overall variables as electrical conductivity (EC), pH and indicative parameters for the presence of macro-organic compounds (for example dissolved organic carbon; DOC).

Furthermore it is of importance to have some overall variables for organic micropollutants and a selection of trace elements. Depending on type of pollution courses in the area specific variables can be added.

When monitoring the effects on groundwater quality of specific local pollution sources, information is necessary on presence, nature and mobility of pollutants in the pollution source. When monitoring the groundwater downstreams the pollutions source, the monitoring program primarily can be directed to some of the pollutants with a relatively large mobility in vadose zone and groundwater.

In fact these pollutants act as a tracer. After detection of these pollutants in the groundwater, the analytical program can be extended to the other pollutants present in the pollution source and their possible degradation products.

When monitoring minor constituents in groundwater, it is necessary to take into account the possible effects of materials used during sampling, way of sampling and samplehandling and type of boreholes and tubing and filtermaterials, i.e. materials brought into subsoil by drilling the borehole on the quality of the groundwater sampled.

8.2.7 Sampling frequency

Sampling frequency is closely related to velocity of groundwater. Especially in sandy aquifers, groundwater flow is often very slow (some meters till some hundreds of meters a year). Under such conditions frequent sampling in general will not be very useful. Often an annual sampling will be sufficient.

Short term variations can be reduced by a right choice of length of the well screen, monitoring depth and time of sampling. Depending on groundwater velocity, in case of fractured rocks and solution porosity aquifers the sampling frequency will in general be higher than in sandy developed aquifers. The sampling frequency can be determined objectively by statistical methods, as described in Chapter 4.

In case of monitoring the effect of single local pollution sources, a relation can be made between sampling frequency and the ratio between concentration of a pollutant in groundwater and the toxic dose or ermissible concentration.

In case of concentrations of a specific variable at about the detection limit, there will be a great uncertainty in the measurements. Important changes in such concentrations can be found only after a long period, since differences between measurements, done at short time intervals, will fall within the inaccuracies of the measurements.

So, for trend detection of low concentration no high measurement frequency is required. For comparison of analytical results, standard procedures for sample handling and analytical procedures are necessary.

8.3 Specific hydrological networks*

Specific hydrogeological networks are set up to meet the requirements of a particular water management system in the region whose groundwater is affected by the system's operation.

The purpose of any given specific network is to obtain information on the changes in groundwater regime caused by the operation of the particular water management system which directly affects the normal groundwater exploitation. Consequently, the specific network explains the predominantly homogenic changes in groundwater regime caused by the particular water management system. In order to assess the rate of the particular changes (whether positive or negative) which occur after the system has been put into operation, it is necessary to have similar information on the studies element of the groundwater regime for a minimum prior period, as a standard for comparison.

The following special requirements made on any specific network result from this precondition:

a. Each specific network should be designed simultaneously with the corresponding water management system;
b. Construction of the specific network should precede that of the water management system;
c. The specific network should be put into operation at least one year before the water management system;

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*) Condensed from an unpublished report by P. Becinsky, Bulgaria.

d. In designing, constructing and equipping the specific network, as well as in making the observations of the particular element of groundwater regime, the manuals, instructions and guidelines in force for the basic network are also used and observed;

e. Regime information from the specific network, while it is being used operationally, is also sent from the corresponding water management system to the archives of the basic hydrogeological network in order to create a data bank on groundwater regime of the particular region;

f. Specific networks are operated as long as the particular water management system is functional, after which some of the observation points may be transferred to the basic hydrogeological network, whereas others are closed, as determined by an assessment.

The general requirements for specific hydrogeological networks were considered above independent of the type of watermanagement system they were created with. But because the impacts of individual water management systems in groundwater regime vary, they should be considered in greater detail.

Water management systems can be grouped according to their impact into the following two types:

1. Those with a negative impact on groundwater regime (depletion of groundwater resources, recession, etc.);
2. Those with a positive impact on groundwater regime (raising the level, increasing resources, improvement of the chemical composition, etc.).

1. Water management systems with a negative impact on groundwater regime

This group includes groundwater withdrawal systems for domestic water supply and industrial use, for irrigating crops, drying marshland and draining mines, etc. Such systems generally work either gravitationally, e.g. the tapping of springs or construction of drainage ditches, or with pumps in boreholes.

All gravitational systems use less or the same amount of water as the natural groundwater runoff. At the design stage it is necessary to provide for suitable equipment to measure the discharge in the undisturbed regime. At the hydrogeological observation points the observation frequency is 3-5 times per month. In some cases daily yield observations are made. At high-yield water sources, normal hydrological stations are set up, as on a river.

When groundwater is pumped three cases can be distinguished: the amount of water pumped may be either smaller, equal to or greater than the aquifer's natural discharge. In the first two cases, alteration of the groundwater regime is within the limits of natural changes in groundwater replenishment and the groundwater reserves do not change. In the third case, constant pumping over a long period has a heavy impact, leading to exhaustion of the aquifer's static reserves. In such a case the groundwater level drops in the vicinity of the water management system and a so-called cone depression is formed.

Observation wells are constructed to monitor changes in groundwater level and the development of the cone of depression. The observation frequency for the various elements is the same as for gravitational systems.

For drainage systems, hydrogeological observation points (wells) are constructed in which only the groundwater level is observed in order to check the achievement of the design drainage rate.

2. Water management systems which have a positive effect on groundwater regime

Water management of this type comprises irrigation systems, medium and large-size reservoirs, systems for the use of chemical agents in agriculture, artificial replenishment of groundwater reserves, etc.

The putting of these systems into operation causes a greater or lesser rise in groundwater level but when chemical agents are actively used in agriculture, significant groundwater pollution occurs, especially by nitrates and other harmful chemical substances, through infiltration processes. Hydrogeological observation networks must therefore be constructed in regions affected by these systems.

In regions where irrigation is practised the hydrogeological network is designed to cover the area of the supply pipeline and the main irrigation ditches, the irrigated fields and certain areas beyond the irrigation system.

The distance between the wells is shorter in the area of the supply pipeline and the main ditches after which it increases in the irrigated fields. The network density depends on the depth of the groundwater level. These hydrogeological networks should give groundwater level observations 3 to 5 times a month and the chemical composition of the water not less than twice a year before the beginning and at the end of the irrigation period.

In areas surrounding reservoirs hydrogeological observation networks are constructed:

a. in the area of the dam a network to show the percolation under, through and around the wall, and

b. in the area of the reservoir's banks a network to show percolation through the bank.

Everything concerning the siting, density, length and equipment of observation wells depends directly on the technical characteristics of the reservoir's design and the hydrogeological conditions of the region and all these points are settled during the reservoir's design. The observation frequency in these specific networks on reservoirs is up to 3 times a month. Parallel observations are made of the water level in the reservoir lake.

9 INTEGRATED NETWORKS FOR VARIOUS COMPONENTS AND OBJECTIVES

J.W. van der Made*

9.1 General considerations

The networks, discussed in the preceding chapters concern different components of the hydrological cycle. The data produced by these networks are for use for immediate operational purposes or for long term policy and planning purposes. For many reasons it may be expedient to combine the networks to one integrated system, although not all uses require such a system. Some examples may illustrate this.

a. If an entire river basin is considered, the water balance of which is examined, all components of the hydrological cycle play a role, i.e. precipitation, evaporation, storage (snow, surface- and groundwater, soil moisture), runoff (surface- and groundwater) and finally the river discharges in tributaries and main rivers. In this case a fully integrated network or a network, operated in a good coordination between the responsible institutes is to be recommended. The same holds if the network is used for flow forecasting, in particular if all data have to be brought into one hydrological model.

b. For river water quality studies combined quality and quantity data are required for the calculation of the volume of dissolved elements, following from the product of content and discharge. In this case the networks concerned should be coordinated.

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This will be obtained most efficiently if these networks form an integrated system.
Besides it is recommended that the times of sampling correspond with streamflow measurements or, at least fall within a coordinated program.

c. In a low delta area the river discharges are caused mainly by precipitation fallen far upstream. Local precipitation only plays a minor role. In this case there is no strong need for integrated networks. The groundwater levels in this area too will not strongly influence the discharges and water levels in the main streams. Thus an integration of ground- and surface water networks is not required too. However there is a strong relation between the water levels in the river branches and in the water receiving body, e.g. sea or lake. Therefore an integration of the water level networks concerned is most desirable.

It appears that in some cases integration is desirable, but that in other cases this is not a strong requirement. Because of organizational and administrative reasons it even may be preferred to organize those systems separately, since integration of systems, which have no relation may hamper the efficient operation of both. It may be clear that for every area or objective the extent of integration should be considered separately. A general recommendation for integration of all hydrological networks does not seem appropriate.

When a network has to serve several objectives one may encounter the problem that these objectives may put different requirements on the data. Usually a number of the following requirements should be fulfilled:

1. immediate availability;
2. representativity;
3. high accuracy;
4. availability of long time series.

Table 9.1 denotes which of these requirements are of most importance for four different objectives.

Table 9.1 Some network objectives and requirements

objective	requirement			
hydrological forecasting	1	(2)		
operation of water management projects	1	2	(3)	
water balance compilation		2	3	(4)
study of long term changes		(2)	3	4

The essential requirements are given without brackets, the others in brackets. The table does not need further explanation.

For most objectives usually more than one component must be taken into account which may be the reason to integrate the measurements of these components into a single network. Further, serving more objectives by a single network may be questionable because of different requirements to the data, see Table 9.1.

Apart from the distinction according to the above objectives one can distinguish networks for water quantity and for water quality. Information about the water quantity as well as about the water quality may be required for all four objectives considered. The following examples may illustrate this:

- hydrological forecasting: when will a heavy pollution upstream affect a downstream area?
- operation of water management projects: have water intakes to be closed for reasons of polluted water?
- water balance compilation: what is the quality of certain water resources?

In this connection also the balances of some dissolved elements are of importance, e.g. the chloride balance.

- study of long term changes: To what extent is the water quality of a river or aquifer changing? In this connection can be referred to the examples of Section 7.2.4.

It is obvious that qualitative and quantitative aspects are interrelated closely. This should have its repercussion in the network configuration and measurement programs. For instance, in how far could a planned or existing water quality measurement station at a drinking water supply intake point be combined with a water level gauging station? In fact similar steps as when considering the various objectives should be taken in this respect.

9.2 Hydrological forecasting and operation of water management projects

Forecasts are issued to inform people about possibly coming events, so that they can prepare themselves for the problems that such events may cause. These events may concern river floods, storm surges, droughts pollutions, etc.

Of great importance in forecasting is the availability of the computation results as early as possible, preferably in on-line information, in order to have the possibility to issue warnings and to take other necessary steps in cases of emergency.

For reasons of efficiency in drawing up the forecast a certain simplicity in the network concept should be pursued as each station might be a source of disturbances. Therefore it looks preferable to work with a limited number of hydrometeorological stations instead of with a large number, with which a higher degree of accuracy might be arrived at. In many cases early, possibly raw, information is better than very accurate, but late (too late?) information. This is also true if the forecasts are based on computer operated models, although these can assimilate more information than manual operated methods.

For forecasting, in particular, complete and reliable information is of great importance. Therefore it is recommended to aim at a certain redundancy in the network, in order to replace missing or doubtful observations by others. The immediate availability of information is essential, especially for quickly developing phenomena, which may occur within a few hours, like flash floods in small river basins with impervious soils, or storm tides in estuaries and coastal zones.

In river flood forecasting, it depends on the conditions to what hydrological component the forecast network is to be focussed. In small basins, for instance, the quick availability of information about precipitation and/or snowmelt is of more importance than in large basins where conclusions might be drawn from streamflow data in the upstream area. Quantitative precipitation forecasts are required to obtain better predictions of flash floods.

Prediction errors of river flows should be taken as a measure for evaluating the raingage network density for forecast purposes. In Chapter 6 it was demonstrated that the accuracy of areal averages was quite sensitive to changes in the network density. However, if areal averages of precipitation are used as an input in rainfall-runoff models it is possible that the prediction errors of river flows hardly change with the number of gages in the catchment area, because of uncertainties in the rainfall-runoff relation (O'Connell et al., 1978; Bastin et al., 1984). Therefore a limited number of telemeasured gages is often sufficient for real time forecasting.

9.3 Water balance compilation

In water balances all components of the hydrological cycle are in principle included. For the compilation of water balances a good coordination of the networks for the various components is a minimum condition, a full integration of these networks into one system would be most effective. As a matter of fact all components considered must concern the same period.

An important point in water balance studies is the period concerned. There are annual, monthly, daily and even continuous water balances.

For long term planning one can make use of long term balances, for immediate activities of short term balances. The latter activities are closely related with forecasting and operation of watermanagement projects. For short term balances the requirements might to some extent be heavier than for long term balances because they have to follow the variations more closer. In this case the storage components play a role (storage in surface- and groundwater, soil moisture, snow and ice). However, as the long term balances form the basis for water planning, they should also be studied carefully; thus due care should be taken of the network that has to provide the data. What components are of importance depends on the area for which a balance is composed. For a river basin as a whole the main input and output components are precipitation, evaporation and runoff. When the water balance concerns a water body as such (lakes, river reaches), the water levels are necessary as an indication for the water volume. When the area of such a body is small compared with the volume, data of precipitation and evaporation may be of less importance, in particular when there is a big amount of inflow from upstream. It is clear that each situation will have its own conditions and requirements.

For most components of the water balance an areal average or total value has to be derived from point observations. An exception forms the stream flow or runoff component, since the river discharge data are in fact integrated values over the basin concerned. Especially for long-term water balances high accuracy is required. For instance, assume that the average annual water balance in a certain area takes the following form:

precipitation = 1500 mm
evaporation = 1200 mm
discharge = 300 mm.

Then an error of 20% in the precipitation amounts gives quite another picture of the water balance.

A useful exercise in water balance studies is to compare the accuracies of the various components. This may result in more or better measurements of the weakest link in the water balance.

9.4 Studies of long term changes

Long term changes may concern natural changes, e.g. due to climatological changes, and changes due to human activities. Networks set up for this purpose both are directed at trend detection. In these cases long series are a first requirement, so in many cases one will make use of long existing stations. For trends in mean sea level for instance use is made of series of 100 years and more.

Sometimes long term changes are examined by considering separate series. In this connection a network of stations is of less importance. However, with regard to conjunctive network design it should be considered in how far stations of networks, serving other purposes can be used for the study of long term changes, or, reversely, whether long existing stations can be included in a design of an integrated network.

9.5 Serving different objectives by one network

Fig. 9-1 shows a number of ways in which networks for hydrological forecasting and water balance compilations can be organized. In case A there is no coordination between the networks for both objectives. This is the situation of a special network for hydrological forecasting. The quality of the observations from this network may not be high enough for accurate waterbalance compilations. In case B the stations for hydrological forecasting coincide with those for waterbalance compilations. The two objectives do not require the same station density. For water balance compilations often a higher accuracy of areal averages is needed than for hydrological forecasting which results in a larger number of stations for the former. The stations used for forecasting differ from the other stations because special provisions are required to make the data quickly available.

Finally, case C gives a situation in which stations for hydrological forecasting and water balance compilations partly coincide.

For instance, it may be that in some regions there is only interest in hydrological forecasting, wheras in other regions there is interest in both.

The scheme in Fig. 9-1 can be extended with networks for other objectives, like watermanagement, water quality, planning and design, and long-term changes. For each objective a suitable network configuration can be established and then, in a second stage, a decision has to be made which station could serve more than one objective. The results from the questionnaire in Appendix II show, however, that common practice in most countries differs considerably from this concept.

For instance, in most cases water quality stations are established at or near those sites where water quantity stations already exist. Although this might produce acceptable information, the question, whether this yields the most efficient and optimum solution, remains. Therefore it is recommended to keep this matter in attention and, in particular when a redesign is foreseen, to examine the feasibility of an integrated approach.

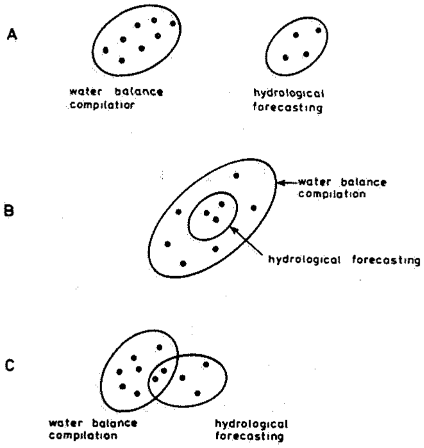

Figure 9-1 Ven diagrams of networks for hydrological forecasting and water balance compilation. The dots denote measurement sites.

10 SUMMARY AND RECOMMENDATIONS

The design of hydrological networks takes place between the field of the phenomena to be measured on the one hand and the needs to measure on the other hand. The design process between these two fields is described in Chapter 2 and is in particular clarified in Fig. 2-1. The behaviour of the phenomena, in particular their variability, which forms the real reason for continued measurements is discussed in Chapter 3. The change in variability, due to the hydrologic system is explained, whereby use is made of analogy with electrical systems. The behaviour of the phenomena in space and time, which is essential for the network configuration and density as well as for the sampling frequency requires a statistical approach, which is extensively dealt with in Chapter 4. On the other side of the design process, the needs and requirements of the society, social or economic aspects play a role. The central question here is whether the society is ready to do investments in a network, in relation to the expected benefit of the information, produced by this network. These matters are discussed in Chapter 5. The main problem here is to quantify the benefits of hydrological information in financial terms. Further research in this field is recommended. Preferably with the assistance of professionals in the field of social and economical sciences.
The various hydrological components require to a certain extent different approaches. In the chapters 6 to 8 networks for the main components precipitation - evaporation, surface water and groundwater are consecutively discussed. For the latter two both quantitative and qualitative aspects are dealt with.

Apart from a classification of the networks according to the variables to be measured one can distinguish the networks according to their objective, going from short term objectives, such as forecasting and operational management of water projects to long term objectives, such as trend detection. Again another distinction can be made in networks for water quantity and water quality data.

However, in many cases the same stations and networks can be used for several purposes. This raises the point in how far networks can be integrated and in how far conjunctive design is possible and desirable. This is the main subject of Chapter 9. The variables to be measured for various water management purposes are given in annex I.

The practices, used in a number of countries are summarized in annex II, which is the result of a questionnaire, issued by WMO in 1982. The conclusion of this is such that although a number of scientifically based methods and techniques have come available, these are only being applied in practice in a limited number of cases. This stresses the needs for the scienctists to make the techniques understandably to the field hydrologists and for the latter to develop a greater acceptance to the newly developed techniques in order to acquire information of optimum benefit for society.

Finally, the following points should be brought to the attention of the designer:

1. Before designing a network try to get as much insight as possible in the phenomena to be examined, its behaviour and the spatial and temporal correlation. On this base a provisional network can be set up. In this connection reference is made to Section 3.4. Later improvement is possible when an initial network has been in operation during some time and adequate insight into the phenomena concerned has been obtained.

2. Try to get an insight in the economical value of the data in order to judge to what extent the financial investments into a network of a certain density are justified. In this connection it is also of essential importance that optimum use of the acquired data can be made. This means that the network is to be planned in connection with a good accessible storage and retrieval system. A clear justification of a network will improve the willingness of the society and its policy makers to the realization of such a network.

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ANNEX I

ELEMENTS TO BE MEASURED FOR WATER MANAGEMENT PURPOSES

Composed by:
Bundesanstalt für Gewässerkunde,
Koblenz

Water management sector	Hydrological		Methods en Procedures
	Variables	Characteristics	
Public water supply (Drinking water and process water for industry and domestic use)		Degree of development	
Surface water (storage reservoirs, river water)	Discharge Water quality Water temperature	Channel dimensions Slope Bottom roughness	Means, minimum, frequency, duration
Subsurface water Groundwater	Groundwater level Infiltration Precipitation Water quality	Permeability Pore volume Grain distribution	Means, minimum/maximum, frequency, duration, groundwater budget
Springs	Delivery Water quality		Means, minimum, lowest 30-day mean
Power generation Water power River power station	Discharge Suspended sediment transport Water quality	Channel dimensions Slope Bottom roughness	Means, minimum, maximum, extreme value, statistics, frequency, duration, lowest 10-day mean
Storage reservoirs	Discharge Suspended sediment transport Evaporation		Means, frequency, duration, extreme value statistics, complete water-balance
Thermal power	Discharge Water temperature Water quality		Means, minimum, frequency, duration, extreme value statistics, lowest 5-day mean, evaporation loss
Flood control Flood retention basin	Discharge Accumulated runoff Precipitation	Vulnerability Degree of development	Maximum, extreme value, statistics, forecasting, time series analysis flood routing
Storage reservoirs	Discharge Accumulated runoff	Channel dimensions Slope	Means, maximum, extreme value statistics
Dams, dikes	Water level	Bottom roughness	Maximum, extreme value statistics, forecasting
Navigation	Water level Velocity Suspended sediment transport Water quality	Bottom level Channel dimensions	Means, minimum stages, maxium stages, frequency, duration, extreme value statistics, forecasting
Irrigation	Soil moisture Precipitation Evaporation Infiltration Runoff Plant water demand	Infiltration capacity Field capacity Wilting point	Frequency, duration, extreme value statistics, complete water balance
Drainage Subsurface drainage	Groundwater level Soil moisture Precipitation Evaporation	Field capacity Wilting point Transmissivity	Means, maxima, frequency, duration
Town drainage	Precipitation Intensity		Maximum, extreme value statistics, Probable Maximum Precipitation
Waste water disposal	Discharge Water quality	Area	Means, maxima, minima, frequency, duration, lowest mean of several days
Fishing	Water quality	Area	Means, minima, maxima
Recreation, leisure, sports	Water quality Discharge	Area	Means, maxima, minima, frequency, duration

ANNEX II

TECHNIQUES USED IN A NUMBER OF COUNTRIES

TECHNIQUES USED IN A NUMBER OF COUNTRIES

In order to get an impression about the state of network design approaches, WMO issued in 1982 a questionnaire on this matter among 12 selected Member Countries of CHy and 11 personel experts in various countries. Of this questionnaire 16 answers were received.

The questionnaire included only questions about the general approach to the problem. No numerical data were asked.

In the following the questions are given in the original tekst of the questionnaire, followed by a summary of the answers.

Question 1

In Chapter 3 of the WMO "Guide to Hydrological Practices" Vol. 1, 4th edition (WMO No. 168) under Section 3.1.2 "Network concept", it is stated:
"The aim of a network is to provide a density and distribution of stations in a region such that, by interpolation between data sets at different stations, it will be possible to determine with sufficient accuracy for practical purposes, the characteristics of the basic hydrological and meteorological elements anywhere in the region".

The WMO Technical Regulations Vol. III-Hydrology (WMO No. 555) under (D.1.1) 2.2 state that:
"The density of the network of hydrological observing stations should be adequate to permit the assessment, to an accuracy consistent with its purpose, of the elements of the hydrological characteristics of any region".

Question: In the national hydrological service(s) of your country, what is the interpretation given to the terms "sufficient accuracy" or "accuracy, consistent with its purpose"?

For instance, are concrete values used (e.g. "the allowable standard deviation after interpolation amounting to 5 cm"), or are some other computational methods applied, e.g. based on economic considerations or cost-benefit studies? In either case, please give a brief description.

Most answers to this question did not give concrete, numerical design criteria. The situation was judged on the basis of local conditions, requirements and personal experience. Although very satisfactory networks can be obtained in this way, no general directives can be derived from this approach.

In a number of countries there are design criteria, given as a ratio between the standard deviation of the interpolated value and the overall (marginal) standard deviation of the component concerned. These can be summarized as follows:

Bulgaria : For interpolated runoff data a standard deviation $\sigma_{\Delta x}$ is required, such that:

$$\sigma_{\Delta x} \leqq 0{,}50 \ x \ \sigma_x$$

where σ_x is the overall standard deviation.
The ratio $\sigma_{\Delta x}/\sigma_x$ is a function of the distance between the stations concerned.

Canada : (Atmospheric Environment Service):
For estimating the mean areal precipitation an accuracy of ± 15% is specified (WMO, 1978; Mapanao et al, 1977).

Chili : An esteemed information for interpolation should be necessary; this should be under 10%.

Japan : The accuracy for hydrological data should be within 10% of its observed value.

Netherlands: For calculated water level data a standard error of no more than 2.5 cm is aimed at, which value has been determined as the standard error of measurement.
Interpolated data of water quality components should have a standard deviation of 10-15% of the standard deviation of the component as such.

USSR : The error of interpolation of annual flow in the middle of the interval between observational sites should not exceed the standard error of its determining by hydrometric data (i.e. by local measurements), equal to 5%.

Although in the above examples numerical data are given these are not quite comparable since they concern different concepts and components. Further it is questionable on which motives these criteria have been based. However, notwithstanding these objections, the criteria give a certain handhold for designing and judging a observation network.

In the USA (Geological Survey) the concept of equivalent years of record is used, which expresses the accuracy of estimation in terms of the accuracy that would be expected from a gauged record at the estimation site. For major streams 25 equivalent years have been set for estimation of hydrologic variables, for minor streams 10 equivalent years were reguired.

In Canada (Inland Waters Directorate) cost benefit analysis were used for natural streamflow regime networks. Some consultants were charged with those studies. In the network a discrimination was made between long term stations, to be used for trend detection, and short term stations, to be used for the examination of regional differences.
In one approach the ratio between cost per unit network expansion and unit error reduction was minimized. This led to a network of 750 stations during 4 years in the western provinces and NW Territories. The standard error of estimate of the mean annual runoff arrived at 17,2%. If however a constraint was made, limiting the standard error to 15%, 950 stations would be needed during 9 years. Later on this study was extended to monthly means of the runoff.

By another approach a survey of data users was conducted in order to study the benefits of the data. Benefits were assigned as a percentage of capital costs and operating costs of projects and programs for which budgetary decision could be made by considering hydrometric data. The experience was that one-half of the data from regulated streams could be adjusted to natural regime values.

Their equivalent network, therefore, consisted of all natural regime stations plus an allowance for one-half of the modified regime stations. Data collection costs were calculated from the Water Survey of Canada 1977-78 budget allocations. Average benefit/cost ratios were calculated by province.

Marginal benefit/cost ratios were calculated for two assumed network size change situations, +20% and -20%. The marginal ratios were based on 1977 costs. However, only the projects with directly identifiable benefits from the data were considered. Error vs station density data were taken from the results of other studies and applied to the entire network.
Incremental costs were calculated for the years 1983, 1993 and 2003 assuming the network changes had been completed in 1977. It was also assumed that there would be no real growth in construction expenditures to the year 2003. Examination of the calculated marginal benefit/cost ratios indicated that network expansion in the three westernmost provinces would not be profitable at the present level of development. Network expansion in the Yukon and Northwest Territories would be economically beneficial. It was, however, conseded that the calculated marginal benefit/cost ratios did not allow for many non-quantifiable benefits, primarily those due to management for enforcement by public agencies.

A part of the stations considered were long term stations, which were used for trend detection. To asses the distance between the stations the information obtained was considered proportional to the expression $(1-R^2)$, R being the average correlation coefficient of annual runoff values. The relationship $R = 1-K\sqrt{d}$ was approximated using a sample plot of correlation for runoff against distances d (km) between stations. The coefficient K was establised to be 0,005 however depending on terrain conditions. A functional relationship between total information and total operation cost was defined. This function was maximized. This led to an optimum average distance of 237 km between the stations, corresponding with about 100 long term stations.

Compared with the total of 750 natural regime stations, mentioned earlier, the remaining 650 stations were assigned as short term stations. These stations are primarily for use in estimating the variation in hydrologic characteristics with physiographic characteristics. The life span of the short term stations will depend upon correlation with nearby long term stations as well as upon the models being used for data transfer.

Question 2

Indicate if in your country the observation of the various variables of the hydrological cycle are carried out in:

- separate networks for the elements concerned
- separate networks of different agencies and institutes
- separate and independent observing stations (individual stations not forming part of a network)
- a fully integrated observation network, operated for all or most related services and institutes, and covering all or most elements concerned
- an intermediate solution (please describe briefly in an annex)

The answers to this question are summarized in table I.
It appears that most answers show separate networks for different elements, managed by different agencies and institutes. Concerning the intermediate solutions separate comments were given, as summarized below:

Bulgaria: In general the network is integrated; for specific studies other solutions may be applied, depending on the purpose.

Canada : Studies were carried out how hydrometric and meteorological networks could be adjusted to each other on the base of correlation. One study yielded a result that 1000 meteorological stations were equivalent to 180 hydrometric stations.

Chile : Before 1960 there were two separate hydrological networks. Under a UNDP-WMO project an integrated network was realized and finished in 1965. There are separate networks for water quantity and water quality.

Panama : In the Panama-Canal-watershed the meteorological and hydrological networks are managed by the Panama Canal Commission. In the rest of the country there is an integrated network. Groundwater measurements are not carried out.

Table I Level of integration of hydrological networks

Country: Level of integration of the networks	Brazil	Bulgaria	Canada (Atm. Env. Service)	Canada (Inland Waters Dir.)	Chile	Fed. Republic of Germany	Hungary	India	Japan	Netherlands	Panama	USA	USSR	Venezuela	Switzerland	Sweden
Separate networks for the elements concerned				x		x	x	x		x		x	x		x	x
Separate networks of different agencies and institutes	x		x	x		x		x		x		x	x	x	x	
Separate and independent observing stations (individual stations not forming part of a network)				x									x		x	
Fully integrated observation network, operated for all or most related services and institutes, and covering all or most elements concerned		x							x				x			
An intermediate solution		x		x	x						x					

Question 3

Was a special methodology used for the design of the network(s)? If yes please provide a short description, if possible with reference to literature.

Five countries answered not to apply a special methodology, two countries, India and Chile, referred to the WMO criteria.

In Bulgaria the hydrometric network has been developed mainly in dependence with the requirements for the economic use of water resources. In the period 1953-1957, for the first time, a detailed estimation and reorganization of the network density and location were made. The estimation was carried out mainly by comparative analysis of network densities of regions with similar physical-geographical conditions, characterized mainly by their integral characteristics: mean multiannual precipitation values and run-off per unit area of the basin. In the period 1971-1975, the methodological grounds for network density optimization, and in 1976-1980, the scientific grounds for the location of the stations have been created. The applied methods are presented in detail in the scientific report "Methods for design of hydrometric network for run-off observations", Institute of Hydrology and Meteorology, Sofia, 1975) and in a number of publications (Georgiev, 1974; Gerasimov, 1977; Gerasimov and Mandadjiev, 1977).
Optimization criteria are grouped as follows: physical-statistical, economic and technical-exploitation.
Physical-statistical:
a. Criteria of the physical-geographical representativeness of the respective river basin; the representativeness is accounted differentially as a multidimensional function of the basin area, climatic region, prevailing soil-geological type, etc. or by the integral indicators as multiannual run-off per unit area, variation coefficient, mean-square variations of the mean multi annual run-off per unit area.
b. Criteria of admissible errors expressed in general by the inequality $E(x) \leqq E_g$, where $E(x)$ is the (probable) error of the spatial interpolation of the hydrological value x, E_g is the admissible error.

c. Criteria of the statistical significance of empirical function arguments $x_o = f(x_i)$, where x_o are run-off characteristics of a given point of the river for which water balance or forecast is done, and x_i are run-off characteristics of the examined drainage basin.

The first two criteria (a) and (b) are used for the design of the network.

The economic and technical-exploitation criterion is defined as minimum total losses for the economy from network construction and exploitation expenditure (amortization), upkeep and repair (exploitation expenditure) are losses from the lack of hydrological information due to the space-time incomplete set of hydrological observations. Due to difficulties of assessment of losses from the lack of information, it is recommended that boundary values should be used, even in case of a concrete water-economy system.

Much of the available literature on network planning in Canada makes use of or refers to the fundamental hypothesis upon which the Shawinigan Engineering Company Limited (1968, 1969, 1970, 1982) hydrometric network studies were based.
A special technique that is used here is the Modified Regime Network Investigative Technique. This is a specific adaption of the network to monitor an active or potential modification of the natural flow regime. The economic benefit, attributable to the use of improved record resulting from network expansion is weighed against the corresponding network costs. The design of some regional networks is described in a number of publications (Acres, 1976, 1977, 1982, Solomon et al, 1972).

Hungary gives a description of the groundwater network. The establishment of the national groundwater observation network was started around 1920. No particular methodology had been applied up to 1975. The aim was no more than to attain fairly uniform density in the lowland parts of the country.

After 1975 a new development policy has been developed, according to which groundwater observations are accompanied by general hydrological elements in the lowland, by stations of different types and equipment. In the course of designing - mainly in the interest of collecting data suited to generalization - the sites are selected by identifying typical, representative areas, where the impacts of factors producing a change are of similar character. In identifying the typical areas, the vegetation, the soil and depth to the groundwater are taken into consideration. By observing similar principles a regional soil moisture observation network has been established. (Major, 1980; Major et al., 1975).

In The Netherlands, the surface water level network, although already existing since over 100 years, was tested according to multiple linear regression equations. In this way a water level y is calculated by

$$y = A_0 + \sum_{i=1}^{n} A_i x_i$$

where x_i are the water levels at n principal gauging stations. These may be either simultaneous or time lagged measurements. The standard error of estimate of y should not exceed a fixed design value, which as a rule is assessed at 2.5 cm. The value of 2.5 cm corresponds with the standard error of measurement at a gauging station (Van der Made, 1982).

Apart from the network of principal gauging stations there are the additional gauging stations, which serve to assess and to test with adequate frequency the used relations and furthermore to provide some redundancy for the case of missing data. As a rule there is one additional station between two principal stations. However the construction of the additional stations is more simple than that of the principal stations.

For the detection of long term trends of water quality components, use is made of the method Lettenmaier (Schilperoort et al., 1982).

In the USSR the design of the basic streamflow network is based on considerations, described by Karasev (WMO, 1972). A basic streamflow network should ensure:

- Assessment of zonal characteristics of water resources: runoff values for individual years and mean long-term runoff value.
- Obtaining operational information on hydrological processes, in particular, on regime of water courses and azonal flow divergence.

In order to meet the first goal it is not necessary to organize observational gauges in each river basin in particular in the case of a relatively dense channel network. The problem is to create a sufficiently dense streamgauge network which can ensure reliable spatial interpolation of flow characteristics between observational sites.
The second goal can be met when gauges for measuring water levels, temperature regime, ice events, water quality, river bed deformations etc. are available. Azonal deviations of flow characteristics are studied in order to determine their dependence on various factors.
The influence of each factor can be taken into account by using a correction coefficient for zonal values. The latter proposal makes it possible to study zonal and azonal characteristics of spatial flow distribution in couple.
From the economical viewpoint it is unrealistic to design a network suitable for each practical need. Therefore, the problem is to design an optimum network which will be suitable for a rational combination of requirements.
A scheme of a network should correspond to the required accuracy of interpolation of flow characteristics. In this case the problem of network design includes the following aspects:

a. assessment of optimum network density (by area per observational site);
b. determining the location of observational sites on water courses of individual river system;
c. determining the order of network development.

In Venezuela the rainfall network is adjusted to the outflow hydrograph (Wilson et al., 1979), (Bras and Rodríguez-Iturbe, 1976 a).

In Sweden a strategy for the runoff network is developed (Jutman, 1981). Measures of runoff variability in space and time together with demands from users of data have been considered. Varying demands on the network made it necessary to divide the stations into three categories:

1. Stations in rivers influenced by regulations;
2. Stations in rivers uninfluenced by regulations, drainage area 100 km^2;
3. Stations in rivers uninfluenced by regulations, drainage area 100 km^2.

Approximately one half of the total number of stations belong to the first category. Rather few stations were suggested to be added to this category, the additional stations mainly for environmental control purposes.
Stations in small, natural rivers (second category) need to be water balance stations. This is due to the strong dependence of the physiography of the basin and local meteorological factors. Locations of water balance stations will be chosen according to a stratified sampling procedure. A map of hydrologic regime regions has been combined with a map showing a subdivision in natural geographic regions.
A method presented by Karasev (1972) is used for the third category. Statistical measures of runoff variability have been comparted with different types of errors involved to give the network density.

Question 4

Are the networks for water quantity and water quality designed and established so that they are coordinated with one another?

If yes please give a short description of the factors that were considered and the methodology applied, if possible with references to literature. This question might be dealt with in connection with question 3.

Some countries indicated that the networks were designed independently. Others did not answer the question. A summary of those answers which include more information is given in the following.

Bulgaria

Studies on water quality are carried out at some stations from the integrated observation network. Besides, observations of surface- and groundwater quality are carried out at a definite number of stations not included in the integrated observation network.

Canada (Inland Waters Directorate)

Stations in the national stream inventory network are always established near a water quantity station. Other water quality stations for specific project purposes would include water quantity measurements when required.

Chile

Only in some stations from the principal network quality samples are taken.

Hungary

On the streams the water quality sampling sections are in general at, or in the vicinity of, the streamflow gaging stations. The times of sampling and streamflow gaging are coordinated.

Netherlands

Water quality stations are located such that streamflow quantity data can be easily derived either from a station at the same location of from other stations. The latter concerns in particular the tidal zone, where streamflow data determination requires a more complicated approach than local measurements only.

Panama

The water quality network was established in 1976 taking into account the existing hydrometric network and the recommendations of GEMS/WATER program (UNESCO, 1978). Economic constraints, access conditions and travel time to the laboratory have also been considered.

USA

No special techniques are involved. The needs of the various data users are coordinated through the Office of Water Data Coordination.

Switzerland

Water quality measurements are always carried out in the vicinity of a station for water quantity measurements.

Sweden

Networks for water quality are designed so that data on water quantity are available or can be easily derived.

Question 5

Indicate the main purposes for which the network(s) data are used:

- documentation
- water supply
- agriculture and irrigation
- navigation
- hydropower
- hydrological forecasting

The answers to this question are summarized in Table II.

Table II Purposes of water data collection

Country: Purpose	Brazil	Bulgaria	Canada (Atm. Env. Service)	Canada (Inland Waters Dir.)	Chile	Fed. Republic of Germany	Hungary	India	Japan	Netherlands	Panama	USA	USSR	Venezuela	Switzerland	Sweden
Documentation		x	x	x		x		x	x		x	x	x		x	x
Water supply	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Agriculture and irrigation	x	x	x	x	x	x	x	x	x	x	x	x	x			
Navigation	x	x	x	x		x		x		x	x	x	x			
Hydropower	x	x	x	x	x	x		x	x		x	x	x	x	x	
Hydrological forecasting	x	x	x	x	x	x	x	x	x	x		x	x	x	x	
Water balance compilation	x	x	x	x	x	x	x	x		x		x	x			
Study of human influences	x	x	x	x		x	x	x		x		x	x		x	
Pure research		x	x	x		x		x	x	x		x	x		x	
Others		x				x							x[1]		x	

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[1] Pisciculture and recreation

Apparently the data are used for various purposes, depending on the country. It should be taken into account that the answer is strongly influenced by the service that answered the questionnaire, so that in the country concerned also other uses can be expected.

Question 6

Is an improvement or redesign of the network(s) foreseen? If yes, to what extent and based on what considerations?
If no, why not? (e.g. not required, financial restrictions, etc.).
The answers of the countries in which redesign is intended or carried out can be summarized as follows.

Bulgaria

The design of the network, drafted in 1980, is being improved further. See also the answer to question 3.

Canada

Improvements and redesign of networks are being carried out in regions where deficiencies in the existing data base have been identified and where major developments are foreseen to warrant network improvements. For example, network improvements are currently being planned for the Mackenzie River Basin, one of the largest river basins in Canada supporting diverse and productive ecosystems, abundant natural resources and associated land uses. Major developments in this basin in recent years included oil sands and other mining projects, hydro-electric power and pipeline and highway corridors. The approach taken in improving the various existing networks was to develop an integrated network of hydrometric, water quality, sediment and meteorological observations.

Improvements to the existing meteorological network are being rationalized by assessing the existing network and using optimum interpolation to determine network improvements required for a specified interpolation error.

Between 1968 and 1973, the Water Resources Branch, Inland Waters Directorate, Department of the Environment, in cooperation with provincial and other federal agencies, undertook through private consulting firms a series of hydrometric network planning studies covering various regions of Canada. These resulted in major study reports which included methodologies for transfer of hydrological information for stations and basins to grid points or average grid area values. Similar studies are now being reactivated in Canada.

A major evaluation and rationalization of the hydrometric network using the "Karasev" method is underway in the Province of Quebec.

Chile

Dirección General de Aguas (DAG) are studying the real situation of the southest part of the country, but there are financial restrictions for the implementation of these projects.

Hungary

The networks developed gradually by hydrological elements and in response to the prevailing actual demands are being integrated, with due regard to the requirement of water management, hydrological systems analysis and the operational organization of the network. The aim is to operate a reduced number, but multi-purpose stations. It is contemplated to develop from the existing stations the lowland hydrological stations as well as the stations observing the flux of chemicals. It is also envisaged to expand and/or set up the observation network on diversions and return discharges at the expense of the consumers.

India

It is aimed to improve the network density in respect of precipitation gauges considerably in near future particularly in mountainous catchments. These will be done with the consideration of latest theories such as the concept of error minimisation and correlation structure of precipitation field.

For discharge measurement network system approach is likely to be adopted. In this case a redesign is possible as that can be justified by financial and other benefit returns.

Netherlands

Concerning the groundwater data network can be remarked:

- A nation wide redesign of the groundwater level network is foreseen.
- No definite criteria have been agreed upon.
- Suggested criteria are based on the standard deviation of the interpolation error in time and space as estimated with the Kalman filter and kriging interpolation techniques (Brouwer, 1983; Brouwer and Defize, 1983).

The surface water network is being checked and if necessary improved on the basis of the principles outlined in the answer to question 3.

USA

Techniques that rely on measuring the cost effectiveness of networks have recently become available. These techniques are being used to analyze and revise operations of the various streamflow data networks operated by the Geological Survey.

USSR

In order to improve the observational network in the USSR much work has been carried out to develop "The prospective plan of rationalization of location and development of hydrological observational sites in rivers, lakes and reservoirs". This plan was based on the principle of network development ahead of economical development of a region and the principle of the dependence of necessary precision of water resources account (network density) on the existing and planned degree of their use for economical purposes.

The first principle, from a territorial viewpoint, means that the basic network should be organized over the whole territory of the country independently of actual and planned economical development of these or those regions - as a prerequisite of the assessment and future use of the national resources, necessary at the same extent as a topographic and geological survey. This principle also means that sites in definite water bodies should be organized prior to the projecting and creation of various economical objects.

The second principle means giving up the concept of more or less even distribution of observational hydrological network over the territory of the whole country as economically nonefficient in case the greatest part of the territory is occupied by poorly economically developed regions or those difficult to access.

Sweden

A coordination of the separate networks for different elements will be done. An automatization of the data collection and an extension of the hydrometric network is going on. Techniques for short period measurements (5-20 years) are studied.

Question 7

Are values for sites without observations derived from the observed data of other locations?

a) If yes, indicate the methods used:

(i) Simple interpolation in time and space
  - linear
  - power functions
  - other functions (please specify)

(ii) Statistical methods
  - single linear regression
  - single higher order regression
  - multiple linear regression
  - spline functions
  - optimal interpolation
  - kriging
  - Kalman filtering (eventually combined with other methods)
  - others (please specify)

(iii) Physical methods
  - Based on fluid mechanics
  - simulation by water balance modelling
  - others (please specify)

The answers are summarized in table III.

Table III Methods used for the determination of values at ungauged sites

	Country: / Method	Brazil	Bulgaria	Canada (Atm. Env. Service)	Canada (Inland Waters Dir.)	Chile	Fed. Republic of Germany	Hungary	India	Japan	Netherlands	Panama	USA	USSR	Venezuela	Switzerland	Sweden
Mathematical	Linear interpolation	x	x	x	x	x	x		x	x		x	x	x		x	x
	Power functions		x	x	x			x				x	x				
	Other functions		x						x				x				
Statistical	Single linear regression	x	x	x	x	x			x			x		x		x	x
	Single higher order regression		x	x	x	x			x		x			x			
	Multiple linear regression		x	x	x	x			x	x	x	x	x	x	x	x	x
	Spline functions										x 2)						
	Optimal interpolation		x	x	x			x	x		x 2)			x	x		
	Kriging										x						
	Kalman filtering										x 3)						
	Others																
Physical	Fluid mechanics				x				x		x 3)		x	x		x	
	Water balance model	x		x	x			x		x	x	x	x	x		x	x
	Others					x 1)								x 4)			

1) Unit hydrograph
2) Combination optimum interpolation and spline function (in study)
3) Combination streamflow model and Kalman filter (in study)
4) Hydrologic analogy model

Apparently the well known methods like linear interpolation are widely used. The same holds for single and multiple linear regression. More advanced methods, like optimal interpolation were introduced in a number of countries, just as water balance modelling. Probably more techniques are in development, but not yet in the operational stage.

In Canada (Atmospheric Environment Service) Gandin's optimum interpolation method has been used to assess and design networks of various meteorological parameters (Ottawa, Saint John and Mackenzie River Basins). Principal component analysis has been used in rationalization of meteorological networks for hydrological applications in the province of Quebec.

At the Inland Waters Directorate of Canada two kinds of methods for the calculation of hydrologic variables at ungauged sites are used.

Data transfer Methods

a. Isolines of hydrologic data: Without further refinement, this is simply the simulation of a record for ungauged areas through map interpolation of existing data.
b. Hydrologic-physiographic correlation: The entire spectrum of available hydrologic and meteorologic data can be utilized in this method. Data transfer can be enhanced by incorporation of regression techniques which relate available hydrologic and/or meteorologic data to terrain factors.
c. Parametric modelling: All meteorological data and runoff regulatory parameters may be used to construct runoff models. The parameters are, by correlation, related to the physiographic characteristics The system of parametric modelling ultimately recommended by Shawinigan Engineering (1970), employs the square grid method for referencing and storage of physiographic characteristics.

Hydrologic Regionalization

Shawinigan's 1969 network study of Ontario showed that hydrologic regionalization increases the accuracy of interpolated data and should be considered in network planning.

Two systems of Regionalization are considered. These concern:

a. Statistical Regions: Statistical hydrologic regions are regions within which a derived statistical relationship establishing hydrologic characteristics is valid within specified error limits.
b. Physiographic Regions: Physiographic hydrologic regions are regions within which the pertinent physiographic factors vary within narrow limits. A statistical region will usually encompass several physiographic regions. The factors which determine physiographic boundaries are more directly identifiable. Physiographic boundaries can therefore be delineated with greater precision than those by statistical relationships.

Question 8

If you have any general remarks about network design or some personal experiences in this field please briefly describe them.
There were two answers, which are summarized in the following.

Chile

It is very difficult in under developed countries to follow the international standards referring to the number of stations per km^2 which are used in the developed ones, specially due to financing problems and lack of the appropriate personnel; as generally the professionals are better paid in other kind of engineering works.
A continuous regional program for the training of the technicians from the hydrometeorological services of these countries, seems necessary, as well as the provision with modern equipment for the networks and the data processing.

India

In general in developing countries, project formulation is to be based on data generated by the network. But at the same time projects are also to be located in economically and otherwise backward regions. Thus stations are introduced only as per need, because of financial constraints. It is only as more projects come up and optimum use gains importance, one can improve the density and number of stations. Then alone the network concept comes in: thus in all situations, the start is on a low key progressively a proper network gets evolved. Initially to set up a complete network on general norms in many circumstances, is a luxury that can not be afforted.

In India various commissions look into the data collection aspects and these indicate changes so that ultimately a network that can progressively be enhanced emanates.

There are difficulties in installation of snowgauges. Large areas of upper catchments remain uncovered due to this reason. Concept of network has to be reviewed in the light of development programmes which are coming up shortly.

General conclusions

From the answers to the questionnaire it follows that clear requirements for the network design have not been formulated in most countries. As a rule, the integrated design of networks is only applied in incidental cases.
Advanced design techniques are coming to development, but the most simple techniques are most commonly used.
The water quality network as a rule has been installed later than the water quantity network. Generally the first has been adjusted to the last mentioned.
The networks serve a number of purposes, depending on the conditions and needs of the country concerned.
Finally it is of great importance that the developing countries get acquainted with all existing and new knowledge and that equipment and material becomes available.

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1. Investigations into the water balance of the Rottegatspolder
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3. Observations of groundwater levels
4. Investigations by drain gauges in The Netherlands
5. The water supply for crops II
6. The problem of the increasing salinity of ground and surface water in The Netherlands

No. 2 Proceedings of Technical Meetings 7-10, and
Report on the evaporation research in the Rottegatspolder 1947-1952 (with summaries in English), 1955.

7. The study of precipitation data
8. Model research on groundwater flows
9. Measurements and improvement works in basin of brooks
10. Geo-electrical research

No. 3 Proceedings of Technical Meetings 11-12 (with summaries in English), and
Report on the Lysimeters in The Netherlands I (in English), 1958.

11. The water supply of sandy soils
12. Quality requirements for surface waters

No. 4 Evaporation Symposium and
Report on the Lysimeters in The Netherlands II (with summaries in English), 1959.

No. 5 Proceedings of Technical Meetings 13-14 (with summaries in English), 1960.
13. Groundwater levels and groundwater movement in the sandy areas of The Netherlands
14. Water in unsaturated soil

No. 6 Proceedings of Technical Meeting 15 (with summaries in English and French), 1961.
The regime of the Rhine, the Ysselmeer and Zeeland Lake

No. 7 Proceedings of Technical Meeting 16 (with summaries in English), 1962.
The dry year 1959

No. 8 Proceedings of Technical Meeting 17 (with summaries in English), 1963.
The laws of groundwater flow and their application in practice

No. 9 Proceedings of TechnicalMeeting 18 (with summaries in English), 1963.
Water nuisance

No. 10 Steady flow of groundwater towards wells; compiled by the Hydrologisch Colloquium (in English), 1964.

No. 11 Proceedings of Technical Meeting 19 (with summaries in French and German), 1964.
Geohydrological cartography

No. 12 Proceedings of Technical Meeting 20 (in English), 1966.
Water balance studies

No. 13 Proceedings of Technical Meeting 21 (in English), 1966.
Recent trends in hydrograph synthesis

No. 14 Proceedings of Technical Meeting 22, 1968.
Precipitation data (II) and
Report on the Lysimeters in The Netherlands (III) (both with summaries in English)

No. 15 Proceedings and Information no. 15 (in English), 1969.
Soil - water - plant

Proceedings of Technical Meeting 23, 1968.
Seepage
(Will not be published).

Proceedings of Technical Meeting 24, 1970.
Flow in the unsaturated zone
(Will not be published).

No. 16 Proceedings of Technical Meeting 29 (with summaries in English), 1975.
Hydrological investigations for masterplan for the future watersupply in The Netherlands

No. 17 Proceedings of Technical Meeting 25 (in English), 1973.
Automatic processing of hydrological data

No. 18 Proceedings of Technical Meeting 26 (in English), 1974.
Hydraulic research for water management

No. 19 Proceedings of Technical Meeting 27 (in English), 1974.
The hydrological investigation programme in Salland (The Netherlands)

Proceedings of Technical Meeting 28, 1973.
Water quality of Dutch rivers with respect to water management
(Will not be published)

No. 20 Proceedings of Technical Meeting 30 (in English), 1976.
Salt distribution in estuaries

No. 21 Proceedings of Technical Meeting 31 (in English), 1976.
Groundwater pollution

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No. 29a Background papers for Technical Meeting 39 (in English), 1982.
(Netherlands contributions, related to the PAWN-study, for the ECE-seminar-1980).
Policy analysis for the national water management of The Netherlands

No. 29b Netherlands contributions, not related to the PAWN-study, for the ECE-seminar-1982 (in English), 1982.
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