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Part 3: Hydro-Meteorological Network Design
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Part 3: Hydro-Meteorological Network Design

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1 Introduction

At present, the collection of environmental information is increasing in importance. Environmental modelling and defining measures relating to environmental protection policies are usually taken on the basis of the collected information. Especially in the more developed countries, hydrologists and meteorologists are in this respect privileged since often long records of hydrological information exist. Hydrological information like precipitation data, runoff data, groundwater table data, piezometric data, etc., is gathered and stored throughout the years by monitoring gauging stations of a (well designed) network. In developing countries however gauging stations are often badly spatially distributed, not well managed and often not included in a network. This causes regions sometimes to be 'over-gauged' by independent (interrelated) agencies or at the other hand regions sometimes to be undergauged or not monitored at all. Many water resources management projects are (still) designed with inadequate and incorrect data or even with virtually no data at all. As a consequence of this, it is likely that wrong water management decisions will be taken, that wrong design criteria will be applied, and that inappropriate and uneconomic designs will be developed and operated.

The designing of efficient and economic networks is therefore an important issue for hydrologists and civil engineers. The system or network of hydrological gauging stations provides the necessary information to be able to understand and to describe the hydrological phenomena and processes under study.

2 Network design

2.1 History of network design

The first outline of the collection of hydrologic data in terms of a network can be credited to Walter B. Langbein who presented the paper 'Stream gauging networks' in 1954. In this paper a network design concept was introduced for surface water gauging networks. Ever since, policy makers, engineers, hydrologists, etc., became aware of the importance of data collection. Network design was identified as a major research topic for Scientists and researchers. Several meetings were organized to discuss scientific frameworks for network design and operation. Two organisations who stimulated research were 'the International Association of Hydrological Systems' (IAHS) and the 'World Meteorological Organisation' (WMO). One of the first symposia dealing with the problem of network design was organised by the IAHS and dated 1965. The WMO dedicated a symposium to network design in 1972 and published the casebook 'Hydrological Network Design Practice' [WMO, 1972]. In 1978, 1981 and 1988 supplements were added to this casebook since the subject (still) gained attention from researchers. For the past decade, hydrologists focused on the implementation of statistical methods in network design. Of great importance hereby are the statistical network design methods developed by Gandin, Kagan, and Mejia and Rodriguez-Iturbe, and the application of the geostatistical estimation techniques described by Matheron.
2.2 Design considerations

The common goal in monitoring any network of gauging stations is to understand and to describe the behaviour of the phenomenon or process under study. Hydrological and hydro-meteorological phenomena and processes like precipitation, evaporation, surface runoff, groundwater discharge, piezometric levels, etc., have very different characteristics and depend on many factors such as climatic factors, topography, geological factors, etc.. In general, one can say that any phenomenon can be characterised by a spatial and temporal distribution over the area under study. Network design deals with the understanding of these spatial and temporal distributions in order to understand and to describe the dynamics of the phenomenon.

The ideal situation from a monitoring point of view would be the operation of a very dense gauging network supplied with continuous registration equipment. Such a network however would be very expensive in operation and for many study objectives over-dimensioned. In practice many networks have been designed with special emphasis towards minimum network operational costs and towards conveniences relating to network operation. It is evident that many networks are unbalanced in their number of stations and the spatial distribution of the network station configuration. It is also clear that the true understanding and description of the phenomenon under study will never be achieved.

Two genuine questions in network design for any hydrological and hydro-meteorological study deal about:

- the number of stations (i.e. network density), and
- the spatial distribution (locations) of stations within the area under study.

For answering these questions many aspects towards network design must be regarded. Aspects relating to physical, practical, and economical considerations have major influence on the design process. For example, the spacing of a raingauge network must be based on: climatic characteristics; topography of the study area; the raingauge site accessibility; availability of observers; the costs of network operation; data processing capacities; the monitoring goals; etc..

Unfortunately, very important issues like network performance and data accuracy have been ignored for many years. For the past decade special attention is paid to the necessary network density and to the spatial distribution of the individual gauging stations in relation to acquired gauging accuracies and defined performance criteria for specific hydrologic investigations. So, the questions as to the optimal network density also relate to scientific (required accuracy) considerations.

When (re)designing a hydrological network it is necessary to collect as much knowledge as possible on the characteristics of the phenomenon under study and on the physical properties of the study area. Complete network design should involve the specification of a number of operational aspects:
| 1. Sampling variables | (rainfall, evaporation, water levels, etc.). |
| 2. Number and location of sites | (site accessibility, available observers, costs, etc.). |
| 3. Frequency of measurement | (continuous, minute, hour, day, week, etc.). |
| 4. Duration of measurement | (project period, year, 10 year, 25 year, etc.). |
| 5. Techniques and instrumentation | (manual/automated, tele-metric, digital/analogue, data logger, etc.). |
| 6. Data processing system | (manual, computer, centralised, decentralised, real time processing, data distribution, data format, etc.). |
| 7. Measurement service | (consultant, state department, local service, transport, etc.). |

2.3 Social and economic aspects of networks

Social and economic aspects have often major influence on the design of hydrological networks. Two underlying questions relating to network design are 'is a society willing to invest in a gauging network?' and 'till what extend can policy makers invest?'. Although trivial, in general this depends on the societal benefits (i.e. 'the value') that information of hydrological phenomena can have. An additional question relating to network operation is 'can a network be operated by the local people?'; people must be able to manage the stations, to carry out the observations and to maintain the equipment. A few examples of frequently encountered mis-design aspects will be presented.

- An important source of mis-design is caused by the accessibility of the stations. In some cases a station is well accessible under normal conditions, but under extreme events, e.g. floods, the region may not be accessible. Ironically, in case of a calamity the information need about the behaviour of the phenomena is highest.
- In mountainous regions it is not surprising that only a few stations in the higher zones exists since gauging stations are often installed in valleys due to easy accessibility. It is clear that such a network will not produce data representative for the phenomenon over the region as a whole.
- In remote areas often fully automatic stations are necessary. Power supply for data acquisition and transmission is here of essential importance. The question of justification of installing expensive automatic stations remains however.

Redesigning a network is often confronted with contradictory interests. Very often it is difficult to extend a network although the need towards additional stations is obvious. On the other hand situations can occur that it is difficult to abandon the measurements at a station even if the obtained data are no longer required from a hydrological point of view. In this perception the question becomes relevant whether the information produced by a network is balanced by the costs of network construction and network operation like maintenance, management and data processing. In order to be able to judge the value of the collected data it is important to review the information content in relation to objectives (i.e. goals) for which these (additional) data will be used.
Apart from specific study purposes the establishment of a too dense network should be avoided. The additional information gained by highly correlated (neighbouring) stations is relative expensive since, due to the existing correlation not all stations have to be maintained. On the other hand a too sparse network can only give indicative information about the phenomena of interest. In this case the 'optimum' network depends on the monitoring accuracy one is satisfied with. This accuracy must reflect and balance the societal benefits (i.e. significance) for which the data are collected.

A lack of information about the phenomenon can lead to wrong managing strategies resulting in economic losses. Compared to the ideal situation whereby all possible information is available one can speak of the economic loss or also called the 'information loss' [v.d. Made, 1986]. The information loss can be decreased by an extension of the network which in its turn increases the costs of operation. If the network is designed and constructed in such a way that both the costs of network operation and the total information loss are minimal, than the economically optimum network configuration is found. The economic loss due to the information loss is often difficult to assess since the quantification of the societal benefits can be based on subjective criteria.

The commonly applied strategy in designing the economically optimum network configuration, is:

- to build the most efficient network in terms of number of stations, station distribution, gauging interval, site accessibility, etc., within the budgetary limits, and;
- to design a network configuration in such a way that the errors of spatially interpolated data are smaller than a (arbitrary chosen) fixed criterion.

Both these strategies have their shortcomings. The first is simple to achieve, but does not take into account a performance criterion i.e. the errors of estimate, thus the extent of information loss. In the second approach the errors of estimate are fixed and so the presumed information loss; although the number of stations may not be a limiting factor for describing the spatial and temporal behaviour of the phenomenon under study. In practice it is difficult to assess a 'set point' value as design criterion for an acceptable standard error.

2.4 Hydro-meteorological network objectives and network types

Conscious design of a network requires a clear definition of the objectives and goals for network operation. The objectives and goals relate to the requirements of the data quality and the necessary knowledge to understand the phenomenon under study. There are three major uses of hydrological data:

- Planning;
  Planning usually focuses on describing the behaviour and the natural variability of phenomena; extensive data from high quality are required on a prolonged time series. An example of data use for planning purposes is the design and dimensioning of a storage reservoir to overcome dry periods.
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- Operational management;
  Operational management requires less data than planning purposes, but data must preferably become available at a 'real time' time scale. The data quality must be high and also become available at a continuous time base. Operational management often utilise data for updating hourly and daily water management strategies and/or for very near future forecasting.

- Research;
  Research purposes need data of high quality. Data is often used for a better understanding of certain phenomenon and/or processes. For specific studies, mostly in small areas like a single catchment, is data needed at all time levels. Trends over longer time periods as well as real-time behaviour of events may be studied.

The gauging criteria accompanying these data uses have different characteristics and also levels of accuracies. This results in networks with different station distributions and densities where each network is designed for their own objectives. The design of three independent networks however, is not appropriate. An integration of approaches should be aimed at. Rodda in 1969 suggests that the optimal situation can be reached when in the network design process three levels of accuracy are distinguished:

- Principle or base station (i.e. first order) network; a low density network designed over a large region. Information obtained by the base stations is often applied for broad-scale national planning purposes. The first order network furnishes the basis for statistical studies and thus should be observed at a continuous time base for a period of time.
- Secondary order network; a densified network designed over a single sub-region, very often a basin. Stations should be operated for a limited number of years, although long enough to establish a good correlation between the secondary stations and the base stations.
- Third order network; a network designed to collect data for a specific, clearly defined objective. Networks have the highest station density where the length of operation of additional stations is determined by the monitoring objectives.

2.5 Minimum and optimum networks

In developing countries the need for collection of hydro-meteorological data through a well designed network is gaining in importance. When setting up a network the number of stations and the extent of the initial network is of major importance since this strongly influences the optimization process. An overall procedure in network design and development is a) the establishment of a minimum network, b) to operate this network for a number of years, and c) to redesign the network in order to establish the optimum network. A minimum network includes a minimum number of stations which, based on experience in similar regions, is considered to be necessary for appropriate management of the water resources. Very important is that the records of all gauge stations will be of good quality since otherwise the produced data and so the network may be of too little value.

Once a minimum network is established it is important to optimize this network. This includes the installation of additional (i.e. secondary) stations at one or more representative
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sites and the exclusion of superfluous stations. The optimum network can relatively easily be established by the modification of densified networks with long data records. The aim of optimum networks is to determine, with sufficient accuracy, the characteristics of the basic hydrological phenomena. By characteristics are meant all quantitative data, averages, and extremes that define the statistical distribution of the element studied [WMO, 1974]. For practical purposes one should be able to study the spatial and temporal process variability anywhere in a region. Especially in more developed countries are optimum networks requested due to the high costs of network operation.

Not only the establishment of an optimum network is important; also the continuity of network operation should be guaranteed. The network should be well maintained and individual stations should be checked for their consistency in producing data records.

For precipitation networks in any region the minimum network should consist of three kinds of gauges [WMO, 1974]:

- Standard gauges; gauges have to produce medium to high quality data and have to be monitored daily or twice-daily.
- Recorders; recorders have to produce high quality data and are, preferably, equipped with an automated continuous recording device. In warm climates it is advised that 10% of the stations should be equipped with recorders, in cold climates is 5% considered to be sufficient. The highest density of recording stations should be achieved in the areas where intense and short duration events are expected. Such stations will provide valuable information on the spatial and temporal variability of the phenomenon (i.e. intensity, distribution and duration).
- Storage gauges (totalizers); these instruments are monitored at long time intervals since only totalized distributions have to be measured. Storage gauges are often used in sparsely settled and remote regions such as deserts and mountainous terrain.

2.6 Network redesign

The advantage of optimising networks is twofold: the information of additional stations may be necessary to characterize the process; and, there is no reasoning in maintaining a dense network at high costs while the information loss by excluding stations is minimal. The base network however is vulnerable, since the loss of a station can have serious consequences regarding the accuracy of network operation and the continuity of time series which often must be guaranteed. The (re)design of the base network should therefore be carried out with high precision.

In cases where satisfactory correlation links exist between the base stations and the higher order stations the performance of higher order networks are very often strongly dependant on the performance of the base network. The exclusion of stations of a higher order network is here acceptable since prolonged time series are still guaranteed by the established correlation link between one or two base stations and the higher order network stations.
On the basis of data produced by an initial network can indicative information on the variability and the coherence (correlation) of processes be determined. The network performance of an initial network can so be analyzed by different methods like (geo)statistical analysis and rational reasoning. In the redesign process, the initial network configuration has to be optimised based on the performance analysis and the predefined design criteria of network accuracy and reliability, e.g. a given maximum standard error of estimate. The design criteria on its turn depend very much on the objectives and goals for network establishment and operation, and so on the socio-economic aspects of network design. The techniques used for network redesign result in a theoretical optimum network. Such a theoretical network must be modified regarding the possible gauge locations and the practical boundary conditions of network operation. With the changes of socio-economic needs and local conditions in time the need to measure data changes too. Networks have than to be revised, making the network design process a continuous process. Figure 1 presents a flow diagram of permanent network design [after J.W. van der Made, 1987].

**Figure 1: Flow diagram of permanent network design**
3 Design of rainfall measurement networks

3.1 Introduction

Rainfall forms a very important variable in many hydrological studies. Studies after water-balances, rainfall-runoff relations, eco-hydrology, reservoir design, etc., utilize and/or depend in some degree on a description of the rainfall distribution as a model input variable. Research and practical experience indicate that the inaccuracy of rainfall data is an important error component in many hydrological models. Although errors in the monitoring of rainfall stations are due to many factors, i.e. instrument error, human error, spatial and temporal sampling distribution, it seems clear that the design of a good measuring network can greatly improve the quality of the data and so model outcomes.

Rainfall data can serve many hydrological applications in modelling, simulation and forecasting. Examples of data uses are:

- processing and mapping of extreme events,
- estimation of areal averages of rainfall events,
- estimation of the total precipitation depth over long time periods (long term areal average),
- use in water quality modelling,
- rainfall-runoff modelling, groundwater modelling, climatological modelling, etc.,
- point estimation (interpolation) of data for generating rain fields.

Raingauge data only represent a small sample of the total rainfall distribution, making the gauged values a statistic which is subject to variation and error. This statistic is usually expressed and estimated by using the variance or the standard deviation of the mean. One of the objectives in network redesign is the optimization of network performance by minimising the variance of the mean through the selection of the appropriate number and suitable sites of the gauges. Alternatively, if the network is fixed (i.e. established and optimized), this variance is used as a measure of the accuracy of the areal rainfall.

The questions, 'How many gauges are necessary?' and, 'Are the gauge stations at the most appropriate locations?' are of course dependent on 'What are the precipitation measurement requirements for data processing in catchment modelling?' and/or 'To what degree should the spatial variations of rainfall processes be specified to determine these quantitative effects on hydrologic processes of runoff, evaporation, sediment movement, etc.?'? Perhaps the first use of recorded data of a network should be to determine the required density and configuration of a network; it may take many gauges to show that only a few gauges are needed!

3.2 Basic design methods

The problem of optimal rainfall data collection has been a concern of hydrologists for many years. This concern has been reflected in the vast amount of literature that has been published
on different aspects of rainfall data collection. Through this research, network design principles have evolved and will continue to evolve. It was Friedrich in 1965 who stated that:

'It is not useful and even impossible to determine overall principles for the design and realization of networks of hydrological stations which would be of universal validity and applicability.'

Ever since, many principles and techniques for network design have been proposed, although only a few techniques claim universal validity and applicability. To show the different developments of network design some research efforts will be reviewed briefly.

- WMO; the WMO [1974] recommended for general hydro-meteorologic purposes the following minimum densities for precipitation networks which are based on field experiences and performance of comparable networks.

1 Flat regions of temperate, mediterranean, and tropical zones; 600 to 900 km$^2$ per station.
2 For mountainous regions of temperate, mediterranean, and tropical zones; 100 to 250 km$^2$ per station.
3 For small mountainous islands with very irregular precipitations; 25 km$^2$ per station.
4 For arid and polar zones; 1,500 to 10,000 km$^2$ per station.

- Index approach; for each 'homogeneous' area should one gauge be installed. The approach is based on the condition that gauges have the highest possible correlation with the effects that are being measured. Each gauge should be highly correlated with surrounding effects but uncorrelated with other gauges.

- Mathematical approach; a different category of network optimization techniques is formed by the mathematical techniques. These techniques depend heavily on the incorporation of a data statistic in the optimization procedure. Sometimes socio-economic and operational aspects are also taken into account in the optimization. Two well known examples of mathematical techniques are the 'MIT studies' and the 'Kriging technique' which will be discussed in (§ 3.3) and (§ 3.4) respectively.

3.3 MIT studies

At the Massachusetts Institute of Technology (MIT), a series of studies has been initiated for designing precipitation networks by incorporating the correlation structure of precipitation. Eagleson [1967] started the development of standard curves for estimating the number of raingauges needed for flood forecasting and water yield studies. Rodriguez-Iturbe and Mejía [1974] formulated a method for the design of precipitation networks that incorporates a correlation structure of the rainfall process in time and space. They developed a general framework to estimate a) the variance of the sample long-term mean areal precipitation and b) to estimate the mean areal rainfall of a single storm event. The variance is expressed as a function of correlation in time, correlation in space, length of operation of the network, and geometry of the gauging stations. The number of raingauges needed in a domain are

9
estimated through this variance, the best locations for the raingauges however still need to be defined through additional analyses e.g. topographic and/or social.

Bras and Rodriguez-Iturbe [1976] reformulated the precipitation network question to include the Kalman-Bucy filter to remove some of the restrictions encountered in earlier studies. The procedure combines accuracy (taking into account the process and instrument uncertainties) and the cost considerations.

Lenton and Rodriguez-Iturbe [1977] proposed a two stage methodology, wherein the optimal configuration of the network is determined first, followed by the optimal estimator weights for calculation of areal precipitation.

Bras and Colon [1978] removed the requirement for complete information on long-term average precipitation over the entire area of interest.

In this section the fundamental aspects of the method of Rodriguez-Iturbe and Mejía [1974] as published in 'The design of rainfall networks in time and space. Water Resources Research vol 10, no 4, August 1974, pp. 713-728.' will be presented. Some of the figures and formulae used have been adapted from this article. In the article a distinction is made between long-term mean areal precipitation during a certain interval of time (month, year), as very often needed in water balance studies, and the mean areal event rainfall as e.g. needed in flood forecasting studies.

### 3.3.1 Gauging of rainfall processes

The rainfall process is considered as a multidimensional random field function $Z(x, t)$ describing the total precipitation depth at location $x$ and time $t$.

The estimation of a rainfall depth through the gauging of a number of (network) stations can be achieved by:

$$
\bar{Z} = \lim_{T \to \infty} \frac{1}{T} \frac{1}{A} \sum_{i=1}^{T} \int_{A} Z(x, t) dx
$$

where:

- $T$ is the number of time periods (i.e. month, years, seasons) of network operation,
- $A$ is the size of the area under study

In modelling the above expression the usual procedure is to discretize in space by creating a rectangled grid. With a uniform discretization, equation (1) is approximated by:

$$
\bar{Z}^* = \frac{1}{T} \frac{1}{N} \sum_{i=1}^{N} \sum_{t=1}^{T} Z(x_i, t)
$$

where:

- $N$ is the number of stations in the network.

### 3.3.2 Long-term mean areal rainfall

For the determination of the long-term mean areal rainfall it is assumed that the overall rainfall process is stationary and furthermore that its correlation function is separable in terms of its spatial and temporal structure. The second assumption means that the covariance structure of $Z(x, t)$ can be written in the form:
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\[ C[Z(x_i,t), Z(x_j,t')] = \sigma_p^2 \cdot r(x_i-x_j) \cdot r^*(t-t') \] \[ \text{[3]} \]

where:
- \( \sigma_p^2 \) is the point variance of \( Z(x_i,t) \),
- \( r(x_i-x_j) \) is the spatial correlation structure,
- \( r^*(t-t') \) is the temporal correlation structure.

The temporal correlation structure of [3] of rainfall for intervals of weeks, months or years appears to be quite weak. It can be approximated by a simple Markovian scheme:

\[ r^*(t-t') = \rho |t-t'| \] \[ \text{[4]} \]

where \( \rho \) represents the first (i.e. lag-one) autocorrelation coefficient which is practically always less than 0.25.

The spatial correlation structure of [3] is a function of the distance between points, \( v \). For isotropic homogeneous random fields, the correlation is only a function of \( v \) and decreases as the distance between points increases. A commonly applied function\(^1\) follows the form:

\[ r(v) = e^{-hv} \] \[ \text{[5]} \]

where \( h \) (km\(^{-1}\)) is an exponential decay factor of the correlation function. The question is what value to give to the parameter \( h \). Rodriguez-Iturbe and Mejia stated that the spatial correlation is related to the size of the area being analyzed. A specific distance that characterizes the size and shape of the area being studied is the mean distance between two randomly chosen points in that area; the so-called 'characteristic correlation distance'. The mean distance between two points of a unit area of the same shape is calculated by Matern [1960]:

<table>
<thead>
<tr>
<th>Table 1: Mean distance of unit area</th>
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<tr>
<td>rectangle, ( \lambda )</td>
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where \( \lambda \) is the ratio of the sides of a rectangle which approximates the shape of the catchment. In case of rectangular catchments the mean distance between two points of a study area is now defined as the ratio of a diagonal of the rectangular catchment and the unit area of such a rectangle, multiplied by the mean distance \( v \) of the unit area.

\(^1\) A second correlation function applied in the article of Rodriguez-Iturbe and Mejia is \( r(v) = bvK_0(bv) \) where \( K_0 \) denotes a modified Bessel function, \( b \) is a constant and \( v \) represents the distance between points.
Example: A catchment covers an area of 64 km$^2$. If this area is approximated by a square than the diagonal of the catchment is 11.3 km. A squared unit area (1*1) has a diagonal of 1.41. The characteristic correlation distance becomes $11.3/1.41 \times 0.5214 = 4.18$ km.

If the catchment is approximated by a circle ($d = 9.03$ km) we obtain for the characteristic correlation distance $9.03/1.13 \times 0.5108 = 4.09$ km.

With the previous concepts regarding the correlation structure of long-term mean areal rainfall, a framework is presented for estimating the sampling requirements (number and locations of stations) of a network.

If $f(x_i, t)$ is the difference between rainfall depth at point $x_i$, during year, month, or season $t$, and the mean (in space and time) of the process. The hydrologists wants to estimate the regional mean of this difference;

$$
P = \lim_{T \to \infty} \frac{1}{AT} \sum_{i=1}^{T} f(x_i, t)dx_i \quad \text{by} \quad P^* = \frac{1}{NT} \sum_{i=1}^{N} \sum_{t=1}^{T} f(x_i, t)
$$

$P$ Has zero variance and can therefore be considered as a constant. Without loss of generality the following considerations can be made since it can be proven that $P$ equals $P^*$. The variance of the measured point values is denoted by $\sigma_p^2$.

$$
E[f(x_i, t)] = 0
$$

$$
E[f(x_i, t)^2] = \sigma_p^2
$$

The precision of the estimation of the regional mean $P^*$ is given by the variance of $P^*$:

$$
\text{Var}[P^*] = E[\text{P} - P^*] \quad \text{or} \quad \text{Var}[P^*] = \frac{1}{NT^2} E \left[ \sum_{i=1}^{N} \sum_{t=1}^{T} f(x_i, t) \right]^2
$$
The variance of $P^*$, which is equal to the variance of $Z^*$, has to be evaluated as a function of the correlation structure of the process in both time and space, the number of stations in the network $N$, the sampling geometry of the network, and the length of operation $T$ of the stations:

$$Var[P^*] = \frac{1}{N^2 T^2} E\left[ \sum_{i=1}^{T} \sum_{j=1}^{N} f(x_i,t) f(x_j,t') + 2 \sum_{i=1}^{T-1} \sum_{i=1}^{N} \sum_{j=1}^{N} f(x_i,t) f(x_j,t') \right]$$

$$= \frac{\sigma^2_p}{N^2} \left( \sum_{i=1}^{N} \sum_{j=1}^{N} \rho(x_i-x_j) \right) * \frac{T}{T^2} \left( \sum_{i=1}^{T} 1 + 2 \sum_{i=1}^{T-1} \sum_{j=1}^{T} \rho^{i-j} \right)$$

$$= \frac{\sigma^2_p}{F_1(T)}[F_2(N; Ah^2)]$$

where the variance of the regional mean, $var[p^*]$, is expressed as a function of the point variance of the process multiplied by two reduction factors, $F_1$ due to sampling in time and $F_2$ due to sampling in space.

Figure [3] shows $F_1$ as a function of the lag-one autocorrelation of the process, $\rho$, and $T$.

![Figure 3: Variance reduction factor $F_1$ (adapted from Rodriguez-iturbe and Mejía).](image)

The variance reduction factor due to spatial sampling, $F_2$, depends on the correlation structure in space, the sampling geometry, and the number of stations. Two types of sampling schemes are considered in this study:

- In the 'simple random-sampling' type of network each station is located with a uniform probability distribution over the whole space $A$ independently of the other stations.
- In the 'stratified random-sampling' case the space $A$ is divided into a number of non-overlapping comparable subareas. From each subarea, $k$ points are chosen randomly where the rain gages will be located.
Figures [5] and [6] show the variance reduction factor $F_2$ as a function of the number of stations and a non-dimensional area, $Ah^2$, for simple and stratified random sampling.

**Figure 5:** Variance reduction factor $F_2$ due to spatial sampling with simple random design used in the estimation of long-term mean area rainfall with $r(v)=e^{-av}$ (adapted from Rodriguez-Iturbe et al.)

**Figure 6:** Variance reduction factor $F_2$ due to spatial sampling with stratified random design used in the estimation of long-term mean area rainfall with $r(v)=e^{-av}$ (from Rodriguez-Iturbe et al.)
The figures [3], [5] and [6] provide an analytical tool for trading time versus space in the estimation of long-term spatial averages of precipitation. Their use in network design will be illustrated with an example.

*Example of network design for estimating the long term mean areal rainfall*

In the centre of the island of Cebu, the Philippines, exists a raingauge network covering an area of approximately 1050 km². In the area are 17 gauging stations operated as shown in figure 7.

**Figure 7: Location of raingauges in Central Cebu**

During a ten year period, 1981-1990, all stations have a continuous time series. The region of central Cebu can be approximated by a rectangle with side lengths of 35*30 km. This area with a diagonal of 46 km, can be approximated by a rectangle with a side ratio of 1. A rectangled unit area has a diagonal of 1.41, and thus the characteristic correlation distance (table 1) is 0.5214 * 46/1.41 = 17 km. The average exponential correlation structure over the 17 stations, \( r_{(17)} \), was found to be 0.42 and needs to be fitted for distances of the order of 17 km.

\[
r_{(17)} = e^{-h17} = 0.42
\]

The correlation parameter \( h \) was found to be 0.051. Thus the equation to be used for describing the spatial correlation structure for the Cebu region becomes:

\[
 r(v) = e^{-0.051v}
\]
the whole area has to be estimated. For the yearly rainfall depth, as applied in this example, was the obtained autocorrelation coefficient 0.21 which is quite high for annual rainfall records. This high value can be caused by the relative short period of network operation, 10 years is considered short, or the existence of a trend.

The variance reduction factors $F_1$ and $F_2$ are presented in the tables [2] and [3].

<table>
<thead>
<tr>
<th>$T$</th>
<th>$F_1$</th>
<th>$T$</th>
<th>$F_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>15</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>0.60</td>
<td>20</td>
<td>0.075</td>
</tr>
<tr>
<td>5</td>
<td>0.28</td>
<td>50</td>
<td>0.030</td>
</tr>
<tr>
<td>10</td>
<td>0.15</td>
<td>100</td>
<td>0.050</td>
</tr>
</tbody>
</table>

The combined reduction factors represents the total reduction of the point variance $\sigma_p^2$ when the long-term areal mean variance is estimated by $N$ network stations and $T$ years of network operation. The accuracy and reliability of the various network designs can so be assessed.

Table [4] presents the combined reduction factors $F_1*F_2$ for the Central Cebu area. In case 20 stations are in operation for a period of 10 years, the combined variance reduction factor is 0.069.

<table>
<thead>
<tr>
<th>$N$</th>
<th>$T=1$</th>
<th>$T=2$</th>
<th>$T=5$</th>
<th>$T=10$</th>
<th>$T=15$</th>
<th>$T=20$</th>
<th>$T=50$</th>
<th>$T=100$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.000</td>
<td>0.600</td>
<td>0.280</td>
<td>0.150</td>
<td>0.100</td>
<td>0.075</td>
<td>0.030</td>
<td>0.050</td>
</tr>
<tr>
<td>2</td>
<td>0.730</td>
<td>0.438</td>
<td>0.204</td>
<td>0.110</td>
<td>0.073</td>
<td>0.055</td>
<td>0.022</td>
<td>0.037</td>
</tr>
<tr>
<td>3</td>
<td>0.650</td>
<td>0.390</td>
<td>0.182</td>
<td>0.098</td>
<td>0.065</td>
<td>0.049</td>
<td>0.020</td>
<td>0.033</td>
</tr>
<tr>
<td>5</td>
<td>0.580</td>
<td>0.348</td>
<td>0.162</td>
<td>0.087</td>
<td>0.058</td>
<td>0.044</td>
<td>0.017</td>
<td>0.029</td>
</tr>
<tr>
<td>10</td>
<td>0.500</td>
<td>0.300</td>
<td>0.140</td>
<td>0.075</td>
<td>0.050</td>
<td>0.038</td>
<td>0.015</td>
<td>0.025</td>
</tr>
<tr>
<td>20</td>
<td>0.460</td>
<td>0.276</td>
<td>0.129</td>
<td>0.069</td>
<td>0.046</td>
<td>0.035</td>
<td>0.014</td>
<td>0.023</td>
</tr>
<tr>
<td>100</td>
<td>0.450</td>
<td>0.270</td>
<td>0.126</td>
<td>0.068</td>
<td>0.045</td>
<td>0.034</td>
<td>0.014</td>
<td>0.023</td>
</tr>
</tbody>
</table>

In other words, it can be expected that this network will produce an estimate of the long-term areal mean with an estimated variance reduction of 7% of the variance of the single point precipitation (i.e. rainfall) depth. If this precision must be accomplished in a lapse of 15 years, the number of stations needed is 3 (variance reduction is 0.065). From table 5 it can be concluded that the variance reduction due to an increased length of network operation is larger than the reduction due to an increase in the number of network stations. Such a conclusion can be very important in network design when for example the costs of network operation are introduced.
The variance and the mean of the rainfall processes can now be estimated. Since the rainfall process has been assumed to be stationary, the point variance $\sigma^2$ of all the stations is a constant and can be calculated by the individual records of the data series. For central Cebu the obtained variance was 161982 mm$^2$. Where $F_1 F_2 = 0.069$, the estimate of the long-term areal mean variance is 11177 mm$^2$ (standard deviation of 106 mm).

In order to judge the magnitude of the variance of the regional mean rainfall depth ($\text{var}[p]$), one has to make an estimate of this mean rainfall depth too. This mean rainfall depth is calculated by a simplified procedure where only the spatial correlation coefficients, the length of record of each station and their values are taken into account. The mean areal rainfall depth can be derived from:

$$Z^2 = \sum_{i=1}^{N} \alpha_i \frac{1}{T_i} \sum_{t=T_{i_0}}^{T_{i_f}} Z(x_i,t)$$  \hspace{1cm} [12]

where the sum of the weights $\alpha_i$ equals to 1, the initial year of operation of station $i$ is $T_{i_0}$, and the final year of operation of station $i$ is $T_{i_f}$. The optimum set of weights can be found by solving the following equations:

$$\sum_{j=1}^{N} \frac{\alpha_j}{T_i T_j} r(x_i - x_j) + \lambda = 0 \hspace{1cm} i = 1, 2, \ldots, N$$  \hspace{1cm} [13]

$$\sum_{i=1}^{N} \alpha_i = 1$$

This scheme was applied to the Central Cebu region; the weights for each of the 17 stations are given in table [5]. The mean annual rainfall depth obtained by equ. (14) was 1308 mm.

**Table 5: Weights of stations for estimating the mean annual rainfall depth.**

<table>
<thead>
<tr>
<th>Station</th>
<th>Weight</th>
<th>Station</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adlaon</td>
<td>-0.0257</td>
<td>Lahug Airport</td>
<td>0.0297</td>
</tr>
<tr>
<td>Biga</td>
<td>0.0224</td>
<td>Lusaran</td>
<td>0.2090</td>
</tr>
<tr>
<td>Bonbon</td>
<td>-0.0099</td>
<td>Mactan Airport</td>
<td>0.0443</td>
</tr>
<tr>
<td>Bucanue</td>
<td>0.0387</td>
<td>Maribago</td>
<td>0.2460</td>
</tr>
<tr>
<td>Cambinocot</td>
<td>0.0317</td>
<td>RCPI</td>
<td>-0.0095</td>
</tr>
<tr>
<td>Camp-7 BFD</td>
<td>0.0354</td>
<td>Sinsin</td>
<td>0.0075</td>
</tr>
<tr>
<td>Carmen</td>
<td>0.0326</td>
<td>Tabunan</td>
<td>0.0965</td>
</tr>
<tr>
<td>Das/UG</td>
<td>0.2239</td>
<td>Talamban</td>
<td>-0.0036</td>
</tr>
<tr>
<td>Estancia</td>
<td>0.0311</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table [5] presents the weights each station has in the calculation of the mean annual rainfall depth by utilizing data for the period 1980-1991. The negative weights of some stations can be interpreted as a substraction of information in order to produce a minimum variance in the mean rainfall $P^r$.

Rainfall networks are in general not solely designed to measure the total rainfall depth over an area. Very often also information relating to the spatial and temporal distribution of the rainfall processes is needed. It is likely that in such studies a greater number of correctly distributed raingauges will be necessary.
3.3.2 Areal mean of rainfall events

The difference between the mean rainfall over an area and the storm centre point value has in general the following characteristics [Eagleson, 1970]. The difference:

- increases when the total rainfall depth decreases,
- decreases when the duration of an event increases,
- is greater for convective and orographic precipitation than for cyclonic rainfall,
- increases when the size of the area increases.

The question then posed is "On what rainfall events and storm characteristics should a network design be based on for the estimation of the mean areal event rainfall?". This question has not a general answer but must be linked to the socio-economic criteria relating to the problem one is dealing with.

The general framework for estimating the sampling requirements for the estimation of the mean areal event rainfall will be presented in the following text. In this case the mean rainfall depth over a certain area $A$ must be estimated:

$$Z(A) = \frac{1}{A} \int_A Z(x) \, dx$$  \hspace{1cm} [14]$$

where $Z(x)$ denotes rainfall depth on the point of spatial coordinates $x$ in the space $A$. In practice, the hydrologist often estimates $Z(A)$ by the arithmetic mean of $N$ measurement points (i.e. gauging stations):

$$Z^*(A) = \frac{1}{N} \sum_{i=1}^{N} Z(x_i)$$  \hspace{1cm} [15]$$

The performance of the network can be characterized by the variance:

$$E[Z^*(A) - Z(A)]^2 = \sigma^2_N$$  \hspace{1cm} [16]$$

where $\sigma^2_N$ is the areal mean variance. Since we are looking at single event rainfall, $Z$ can be considered as a random variable. This is major difference in estimating the rainfall depth when comparing to the estimating of long-term mean areal rainfall. Trivial is to say that also the time-factor does not play an explicit role in the network design. The significant design factors are the spatial correlation coefficient, the number of stations, the size of the area and the point variance of the stations. Analogue to the estimation of long term mean rainfall can be obtained the point variance for all stations as only depending on the reduction factor $F_2$ for spatial sampling.

$$\sigma^2_N = \sigma^2_F(N; Ah^2)$$  \hspace{1cm} [17]$$
Figures [8] and [9] show the variance reduction factor $F$ for simple- and stratified random sampling as a function of the number of stations and the combined correlation parameter $h$ and the size of the area $A$; $Ah^2$.

**Figure 8:** Variance reduction factor $F$ due to spatial sampling with simple random design (areal mean estimation)

**Figure 9:** Variance reduction factor $F$ due to spatial sampling with stratified random design (areal mean estimation)

### 3.4 Kriging

The application of Kriging in network design is inviting since the spatial variance and the spatial interpolation error can be estimated over any area under study. Kriging depends heavily on a function describing the spatial variability of the process under study. By incorporating this function in the spatial estimations it is possible to disregard actual data values of newly designed gauging stations in the design procedure. Information to be
produced by the redesigned network can also be analyzed based on this spatial variability function. The Kriging variance (i.e. estimation variance), which can be used as a tool for concluding on the reliability of an estimation, is the geostatistical representation of the phenomenon under study. The Kriging variance can be viewed as an index value in order to:

- decide on reinforcing the network,
- determine the optimal location of additional gauging stations (i.e. a measurement point),
- determine on the gauging station to be excluded from the network.

The magnitude of the Kriging variance is only depending on the geometric configuration of the data points and on the variable to be estimated. The variable can be, in case of local estimations, a point value \( Z \) or the average value of \( Z(x) \) over a mesh \( A_{\alpha} \), or, as in case of global estimation, the average value of \( Z(x) \) over the domain \( A \). So we can:

- consider an additional measuring point \( x_{n+1} \),
- build the Kriging system including the set \( n+1 \) data points,
- compute the corresponding Kriging variance without having to make any hypothesis about \( Z(x_{n+1}) \).

This 'fictitious point' method may be used in the three cases mentioned above.

**Local estimation**

When the purpose of a network is to obtain local estimates (i.e. punctual values or values over meshes), the problem of estimation becomes slightly different since at every point or mesh point of a discretized grid an estimation variance has to be calculated. An additional measurement point will, at distances smaller than the range distance of a semivariogram, have an effect on the estimated (spatially distributed) Kriging variance. For any grid point (or mesh) can the Kriging variance be calculated as effected by the additional measuring point. The main goal in network re-design by local estimation is to decrease the local maxima on the variance map. The optimum locations for fictitious stations are the locations with the highest variance.

**Global estimation**

When the purpose of a network is to estimate an average value over a given domain \( A \), an important optimisation goal is to determine the optimum location of the \( n+1 \) measurement point in order to achieve the smallest estimation variance for the estimated average over \( A \). This estimation variance for the \( n \) existing data points will be denoted by \( \sigma_n^2(x) \). In case a fictitious point \( x \) has been added to the set of existing data points the estimation variance will be denoted by \( \sigma_{n+1}^2(x) \). The relative reduction in the variance at any location, \( R(x) \), is defined as:

\[
R(x) = \frac{\sigma_n^2(x) - \sigma_{n+1}^2(x)}{\sigma_n^2(x)}
\]  

[18]
If the choice for additional stations is limited to a certain number of locations, the fictitious measurement point is successively located at each of these locations in order to determine the network configuration producing the largest variance reductions. If no additional criteria exist, the fictitious point $x$ can be moved across the domain $A$ and its immediate surroundings. The optimum location for an additional station can be defined by contouring the variance reductions over the domain.

**Estimation variance and network optimization**

The estimated variance within the Kriging algorithm can be an important factor for determining the optimum locations of raingauges. Obviously, the spatial description of the rainfall processes (i.e. the choice of the semivariogram model and its parameter values) is closely related to the unique set of available data. The geometric locations of the measuring points has therefore great influence on the spatial distribution of the estimation variance, especially since often the differences in measurement errors of individual stations are neglected. Based on the semivariogram model it is possible to view point variances as exclusively depending on the locations of (i.e. distances between) the raingauges. Hence it becomes possible to compute the estimation variance by the Kriging algorithm of any set of hypothetical data points without including the actual data at these measuring points. The estimation variance becomes so a valuable tool in network redesign.

Networks can be (re)designed based on an allowable areal averaged estimation variance or as maximum point variances at individual locations. To be able to model the spatial distribution of the estimation variance a minimum number of stations should be operated. In the process of redesigning the network the functional stations must be maintained where the non-functional stations must be excluded. Also newly designed stations must be added to the network. So the existing network of raingauges has to be adjusted in order to obtain the best (minimum) configuration of raingauges at the specified locations.

When excluding a station, the redesign of the network has to be based on the $Z(x_n)$ stations where the $n$th station has been excluded. A logical statistical criterion for addressing the effect of the exclusion of a gauging site is the estimation variance at the gauge location calculated by the data of the other stations. The station to be excluded must have the lowest estimated Kriging variance of all stations. In other words one could say that the site to be excluded has to be highly correlated to the $n-1$ stations in order to give the least loss of information. By including newly designed stations the choice of one or more new stations can be very complex since often multiple local maxima of the estimation variances exist. One method of solving this problem is based on the discretization of the continuous problem. A finite set of alternative locations is specified where the best location(s) has/have to be selected. The procedure will be explained by an example which is adapted from "A method for optimal observation network design for groundwater management" by J. Carrera et al..

Suppose a network can be extended with three new stations. For selecting the sites, five alternative locations ($x_1$, $x_2$, $x_3$, $x_4$, $x_5$) are available. So the question is "define the best configuration including the three new stations when the criterium of the minimum estimation variance over the study area has to be satisfied". Figure 10 illustrates a flow chart of a 'tree search' procedure for the selection of the optimal locations. The procedure starts at the initial node of the flow chart A with 5 alternative locations. By
following the flow chart from node B to P all combinations of the two locations to be excluded are identified. The selection of the configuration of three possible locations with the minimum estimation variance is subject to the following observations:

- Moving forward along any line is equivalent to dropping one location (i.e. point) from the Kriging process. This is the case when moving from node A to B in figure 10.
- Moving backward along any line is equivalent to including an additional point into the Kriging estimation. In the previous case when moving from node B to A.
- From any node we should proceed backwards if:
  * The estimation variance of the remaining stations is higher than the smallest variance found so far since the variance does not become any smaller by dropping an additional point (a 3rd point). For example, assume that the algorithm is at node C, after having computed the variances corresponding to nodes A, B, G, H, I and J. Assume further that the minimum of those was at node H, and that the variance of node C is larger than the one of H. Then, since the variances of K, L and M will be larger than the one of C and, therefore larger than H, there is no need to compute them.
  * The number of measurement points included in the estimation node equals 3.

If all the possible nodes are passed, the end-node with the minimum estimation variance will be the optimal solution for the network design geometry.
The optimal network design is not only dependent on the optimum solution of processing the estimation variance. The costs involved in the implementation of the newly designed network is very often a limiting factor in the redesign process. It is also sometimes not advisable to implement a newly designed station due to practical considerations like availability of observers, accessibility of sites, available equipment, etc. The optimum network is often dependent on multiple criteria.

* Example of network optimization, Central Cebu

The global and local estimation methods described above are used to optimize the network consisting of 17 stations of the Central Cebu area as presented in figure 7.

- Global estimation: The global estimation technique is applied for finding the mean areal rainfall depth. In case the spatial correlation structure between the stations are not taken into account, the variance reduction due to the installation of the 18th raingauge would, arithmetically, be the ratio 1/18 or 5.5% when comparing to a point variance. The reduction factor is a constant for any location inside the area and therefore a spatial independent optimization criterion.

If the Kriging system for the 17+1 stations is applied for the calculation of the spatially distributed estimation variance than the distribution of the local relative variance reduction factor $R(xi)$ results in figure 11. The spatial distribution gives information about the location where a large reduction in the estimation variance can be expected when installing an additional (18th) station. The relative variance reduction factors range from 1% to 15% over the Cebu area. The maximum reduction is accomplished in the North-Western part of the area where the reduction will be over 15%.

![Figure 11: Variance reduction factors](image)

- Local estimation: When applying the kriging system in the local estimation approach, the estimation variances are used for the selection of optimum site for new raingauges. Figure 12 shows the spatial distribution of the standard deviations of the estimations obtained by the kriging system for the 17 existing stations.
When analyzing figure 12 one can see that, also for this case, the standard deviations are highest (>200) in the North-Western part of the area. So it must be concluded that an additional station must be installed in this area. If a new station is placed somewhere in the north western part, than the spatial distribution of the estimation variances becomes as presented in figure 13.

One can see that the reduction of the standard deviations is reduced dramatically in the immediate surroundings of this new raingauge.

For the estimation of mean annual precipitation depth has the WMO [1987] introduced guidelines concerning the allowable standard deviations for the selection of gauge locations. For regions with a high variation in topography and situated in a tropical climatic zone, the
allowable standard deviation must be in the range of 5-10% of the point variation. Based on this, the existing network will be optimized with the criteria that there may not be any standard deviation in the Cebu area higher than 150 mm (≈ 9.4%). To achieve this, stations are added at locations with high standard deviations, and existing stations are abandoned at locations with low standard deviations. This results in a new network with 32 stations with 17 stations added and 2 stations abandoned from the network. These abandoned stations are not necessary to satisfy the error criteria but they are not necessarily to be abandoned since these stations can be of use in another scope of work. The excluded stations are: Biga and Carmen. The theoretical optimal base network for Central Cebu is shown in figure 14.

Ordinary Kriging
Grid: 25*25
32 stations
Standard deviations
Proposed Network

Figure 14: Proposed base network, with standard deviations

4 Design of evaporation networks

Evaporation estimates can be based on direct measurement of (actual) evaporation rates or on the calculation of potential evaporation rates by semi-empirical formulas as developed by e.g. Penman. For obtaining evaporation rates by measurement are the so called 'evaporation pans' used. Thus, when referring to network design, the design of a network of evaporation pans is meant. Evaporation is very often gauged by the so called 'Class A' evaporation pan. This pan, 120.7 cm in diameter and 25 cm in depth, is a standardized evaporation pan and often used as an interim reference in a number of international comparisons of evaporation pans. When relying on semi-empirical methods it is common to incorporate meteorological variables like air temperature, wind movement, relative humidity or dewpoint temperature, and global radiation. The estimation of the evaporation rate by calculation becomes rather complex since a number of meteorological variables have to be measured and processed.

As with precipitation data also evaporation data are needed in many hydrological studies. Some examples on the usage of evaporation data are:

- Rainfall-runoff modelling; especially in continuous stream flow models is the modelling of the actual evapo(transpi)ration important. The evapotranspiration data used in such models are often related to the evaporation data by simple formulae. Especially the accurate modelling of water flow in the unsaturated zone depends heavily on
evapotranspiration data.
- Water balance studies; in many studies is information needed about the amount of water available for predefined objectives. An example forms the efficient water use at the plot scale in irrigation projects; the design of an irrigation schedule at plot scale depends heavily on the calculation of water loss in the unsaturated zone by evaporation and transpiration.
- Reservoir design and management; evaporation data forms a loss function for any open water body. Accurate information on such a loss function during the different time periods of operation can have major influence on the operational aspects of water management. In arid climatological zones, the water demand is highest during the dry season. In such regions is water, besides groundwater, often subtracted from reservoirs in dry periods. The reservoir management during such periods must take into account these evaporation losses since the losses can be very high (1-5 cm/day).

The design process of evaporation networks is closely related to the design process of precipitation networks. Aspects of precipitation network design as to site accessibility, availability of observers, etc. are also to be considered in evaporation network design. A major difference however are the costs of network operation. These costs are much lower, since, very often, the societal benefits are of a different impact. The measuring of extreme (high or low) evaporation rates, or the inaccurate gauging of evaporation (within margins) has only minor impact on the society compared to improper precipitation gaugings. An example here with forms the measurement of precipitation and evaporation in case of high water discharges (i.e. floodings). For evaporation networks this has a consequence for the network density which, in general, much lower is than for precipitation networks. The WMO [1974] gave some guidelines to establish a minimum base network, based on the rate of aridity (i.e. dryness):

- In arid regions is the recommended minimum network density 1 evaporation station per 30,000 km².
- In humid temperate regions is 1 station for every 50,000 km² considered to be sufficient.
- In cold regions is 1 station per 100,000 km² the recommended minimum.

By these recommendations one can conclude that the need for evaporation data increases with the rate of aridity. In economic terms one can say that evaporation measurements become more important in case the (economic) value of water increases.

Evaporation networks are designed to serve a variety of objectives. For planning purposes are often monthly mean evaporation data used. For operational water management, as in irrigation projects, are mean data of short periods (1 - 10 days) required. The design criteria of observation frequency and gauging equipment are, as with precipitation networks, also closely related to the socio-economic benefits. One could say that "the network density is inherent to the economic value of the network".

When designing an evaporation network one has to consider the much more homogeneous spatial and temporal distribution of the evaporation processes compared to the precipitation processes. Regarding the spatial scale, the changes in evaporation data may not be substantial over large distances. A change in evaporation data is often only subject to the change of the climate over distance. These gradual climatic changes can be effected by local influences due to a change in topography and/or elevation or the existence of a river and/or lake. The large and small scale temporal variability is dependent on the season, the spatially variable meteorological conditions, and the meteorological differences in day or night.
general one can say that daily evaporation rates have low values on rainy, humid, cloudy and calm days, and high values on dry, sunny, windy days. A major difference between the precipitation and the evaporation processes is that evaporation is a continuous process while precipitation forms a discontinuous process; precipitation, in particular rainfall, always exhibits as an event.

As with precipitation, also the local variations in evaporation depend on climatic and physiographic conditions. The process variabilities are subject to these conditions but are of a different (i.e. lower) magnitude in terms of water depth.

The low temporal and spatial variabilities of evaporation are also reflected in the design criteria of WMO towards network density.

The techniques for optimizing evaporation networks are closely related to the optimization techniques applied in precipitation networks. Optimization is often achieved by the Kriging technique and the MIT studies. Many stations however cannot be included in the optimization process, since these stations only serve a specific, small scale objective. An example is the calculation of water demands of an irrigation schedule which is very much dependent on the accurate calculation of evaporation rates in a small area. In a large number of cases such stations are operated independent from any base network.
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