THE WORLD METEOROLOGICAL ORGANIZATION

The World Meteorological Organization (WMO), of which 187* States and Territories are Members, is a specialized agency of the United Nations. The purposes of the Organization are:

(a) To facilitate worldwide cooperation in the establishment of networks of stations for the making of meteorological observations as well as hydrological and other geophysical observations related to meteorology, and to promote the establishment and maintenance of centres charged with the provision of meteorological and related services;

(b) To promote the establishment and maintenance of systems for the rapid exchange of meteorological and related information;

(c) To promote standardization of meteorological and related observations and to ensure the uniform publication of observations and statistics;

(d) To further the application of meteorology to aviation, shipping, water problems, agriculture and other human activities;

(e) To promote activities in operational hydrology and to further close cooperation between Meteorological and Hydrological Services; and

(f) To encourage research and training in meteorology and, as appropriate, in related fields and to assist in coordinating the international aspects of such research and training.

(Convention of the World Meteorological Organization, Article 2)

The Organization consists of the following:

The World Meteorological Congress, the supreme body of the Organization, brings together the delegates of Members once every four years to determine general policies for the fulfillment of the purposes of the Organization, to approve long-term plans, to authorize maximum expenditures for the following financial period, to adopt Technical Regulations relating to international meteorological and operational hydrological practice, to elect the President and Vice-Presidents of the Organization and members of the Executive Council and to appoint the Secretary-General;

The Executive Council, composed of 36 directors of national Meteorological or Hydrometeorological Services, meets at least once a year to review the activities of the Organization and to implement the programmes approved by Congress;

The six regional associations (Africa, Asia, South America, North and Central America, South-West Pacific and Europe), composed of Members, coordinate meteorological and related activities within their respective Regions;

The eight technical commissions, composed of experts designated by Members, study matters within their specific areas of competence (technical commissions have been established for basic systems, instruments and methods of observation, atmospheric sciences, aeronautical meteorology, agricultural meteorology, marine meteorology, hydrology, and climatology);

The Secretariat, headed by the Secretary-General, serves as the administrative, documentation and information centre of the Organization. It prepares, edits, produces and distributes the publications of the Organization, carries out the duties specified in the Convention and other Basic Documents and provides secretariat support to the work of the constituent bodies of WMO described above.

Cover photo: Australian Bureau of Meteorology; WMO.
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FOREWORD

The World Meteorological Organization (WMO) coordinates global scientific activity to allow increasingly prompt and accurate weather information and other services for public, private and commercial use. Its activities contribute to the safety of life and property and provide support for developing international programmes related to global climate and other environmental issues, and to sustainable development.

The World Weather Watch, the core of the WMO Programmes, combines observing systems, telecommunication facilities and data-processing centres — operated by Members — to make available the meteorological, climatological and hydrological information needed to provide efficient services in all countries. Through this Programme, WMO Members coordinate the presentation of observed data and processed information.

The Commission for Hydrology has long had an interest in the application of the World Weather Watch to hydrology and in the application of climatological data and climate information in water resources projects.

In 1993, a report was published in German on the subject of meteorological systems for hydrological applications. The Commission for Hydrology suggested that this report should also be published in English. The report has therefore been brought up to date in keeping with technical developments and translated into English for wider distribution.

It is with great pleasure that I express the gratitude of WMO to the persons who contributed to the preparation of this report and gave advice and suggestions in finalizing it. These include Ms H. Bartels, Messrs H. Dunke, D. Frühwald, E. Heise and U. Wacker of the German Weather Service (Offenbach), Mr A. Herrmann and Mr F.J. Löpmeier from the University of Braunschweig, Messrs H.J. Liebscher, G. Strigel and H.G. Mendel from the Federal Institute of Hydrology (Koblenz), Messrs G. Haase, A. Hense, C. Simmer and Ms S. Theis of the Meteorological Institute of the University of Bonn and Prof. H. Fleer of the Geographisches Institut Ruhr of the University of Bochum.

G.O.P. Obasi
Secretary-General
SUMMARY

To ensure the successful implementation of hydrological services and to provide adequate support for research and planning purposes, there is a need for hydrological and meteorological data on various timescales. This report consists of seven chapters covering a wide range of issues on the relationship between meteorological systems and their applications for hydrological purposes. The objective of this report is to present the need for meteorological systems for hydrological purposes. The National Meteorological Services (NMSs) operate different types of measuring networks for the assessment of meteorological data. Depending on the type of network, data are available for hydrological purposes in the form of lists, in databases or in publications. The direct measurement of hydrologically relevant climate data (model input data) yields point values. The extent to which these are representative of the neighbouring region depends on the spatial homogeneity of the influencing factors. These always present the challenge of deriving, from point data, estimates of areal values which are valid for all cases other than very small catchment areas or special cases.

Chapter 1 presents in detail the use of meteorological data in hydrology and water resource management. Chapter 2 discusses meteorological measuring and observing systems, while Chapter 3 presents data derived from meteorological measurements. Chapter 4 discusses the estimation of areal precipitation and areal evaporation, and Chapter 5 is devoted to quantitative precipitation forecasting. Chapter 6 focuses on the World Weather Watch (WWW), which is a global system for the collection, analysis, processing and dissemination of weather and environmental information and thus represents the very core of meteorological services. Chapter 7 concentrates on the WMO Hydrology and Water Resources Programme (HWRP).

RÉSUMÉ

Pour assurer l’efficacité des services hydrologiques et être en mesure de fournir l’appui nécessaire dans les domaines de la recherche et de la planification, il faut disposer de données hydrologiques et météorologiques à diverses échelles temporelles.

Le présent rapport contient sept chapitres traitant de toute une série de questions ayant trait aux relations entre les systèmes météorologiques et leurs applications à des fins hydrologiques. L’objectif visé est d’exposer la nécessité de systèmes météorologiques permettant de répondre aux besoins hydrologiques.

Les Services météorologiques nationaux (SMN) exploitent différents types de réseaux de mesure pour les paramètres météorologiques. Selon le type de réseau, des données sont disponibles à des fins hydrologiques soit sous forme de liste soit dans des bases de données ou des publications. La mesure directe de paramètres climatologiques utilisables dans le domaine hydrologique (comme données d’entrée de modèles) permet d’obtenir des valeurs ponctuelles, qui ne pourront être représentatives de leurs régions avoisinantes qu’en fonction de l’homogénéité spatiale des facteurs déterminants. A cet égard, il est toujours difficile d’obtenir, à partir de données ponctuelles, des estimations de valeurs zonales qui soient valables pour tous les cas autres que ceux qui concernent de très petits bassins hydrographiques ou les cas spéciaux.

Le chapitre 1 traite de façon détaillée de l’utilisation de données météorologiques dans le domaine de l’hydrologie et de la gestion des ressources en eau. Le chapitre 2 concerne le mesurage météorologique et les systèmes d’observation, et le chapitre 3 présente des données obtenues à partir de mesures météorologiques. Le chapitre 4 porte sur l’estimation des précipitations et de l’évaporation pour une zone donnée, et le chapitre 5 est consacré à la prévision quantitative des précipitations. Le chapitre 6 met l’accent sur la Veille météorologique mondiale (VMM), qui, en tant que système mondial de collecte, d’analyse, de traitement et de diffusion d’informations météorologiques et environnementales, est la véritable pierre angulaire des services météorologiques. Enfin, dans le chapitre 7 il est question essentiellement du Programme d’hydrologie et de mise en valeur des ressources en eau (PHRE) de l’OMM.
Для успешного обеспечения гидрологического обслуживания и предоставления адекватной поддержки для проведения исследований и планирования необходимо иметь гидрологические и метеорологические данные различных временных масштабов. Настоящий доклад состоит из семи глав, охватывающих широкий диапазон вопросов, касающихся взаимосвязи между метеорологическими системами и их применением для гидрологических целей. Задачей настоящего доклада является предоставление информации о потребностях в метеорологических системах для гидрологических целей. Национальные метеорологические службы (НМС) эксплуатируют различные типы сетей наблюдений для оценки метеорологических данных. В зависимости от типа сети, данные для гидрологических целей имеются в виде перечней, баз данных или в виде публикаций. Непосредственные измерения актуальных с точки зрения гидрологии климатических данных (входные данные для моделей) содержат точечные значения. Степень, в которой они являются репрезентативными для территории, на которой они находятся, зависит от пространственной однородности воздействующих факторов. Всегда существует проблема расчета по данным в точке оценок значений по площадям, которые являются достоверными для всех случаев, за исключением территорий небольших водосборов или особых случаев.

В главе 1 приводится подробная информация по использованию метеорологических данных в гидрологии и для водохозяйственной деятельности. В главе 2 излагаются вопросы, касающиеся систем метеорологических измерений и наблюдений, в то время как в главе 3 приводятся данные в отношении расчетных величин, полученных по метеорологическим измерениям. В главе 4 излагаются вопросы оценки осадков по площадям и испарения по площадям, а глава 5 посвящена количественному прогнозу осадков. В главе 6 внимание концентрируется на Всемирной службе погоды (ВСП), которая является глобальной системой для сбора, анализа, обработки и распространения метеорологической и другой информации об окружающей среде и является основой для метеорологического обслуживания. В главе 7 говорится о Программе ВМО по гидрологии и водным ресурсам (ПГВР).
To implement their tasks, Hydrological Services, as well as research and planning institutes (consultancies), need, not only hydrological data, but also meteorological data based on different timescales. For planning purposes, the need is mainly for non-real-time meteorological data, usually in the form of climatological data sets. However, forecasts and warnings, as well as the operation and control of water projects, require real-time data, usually in the form of synoptic data sets.

Climatological data are made available by Meteorological Services in the form of point values for stations. These are then used to calculate various time-based means — such as daily, monthly or annual averages, frequency or extreme-value distributions and areal analyses — in the form of maps derived from point measurements. However, hydrological and water resource management often need areal values for use in calculations involving runoff. Only in a few cases are such values directly assessed, e.g. radar-measured precipitation (Chapter 2). For this reason, a conversion of point values into areal values is usually required (Chapter 4).

In developing hydrological models, less and less river catchment basins are considered directly. It is preferable to concentrate on deriving result representations in the form of grid points, the value assigned to the grid point being representative of a corresponding area within the grid. This method has the advantage that, with the aid of the grid, any areal divisions can be produced. The meteorological data should, therefore, be available as input data in the form of a grid point data set.

That requirement is met with meteorological data of numerical prediction models. However, the use of hydrological models for planning also requires the derivation of climatological data sets determined over many years for grid fields. The meteorological values of conventional measuring networks determined by derived point measurements must be converted into grid points in the light of orography, exposure, vegetation cover, form of settlement, etc.

Hydrology relies on precipitation values provided by Meteorological Services. Usually, such values are needed in the form of areal values with different temporal resolutions. For the plausibility control of measured hydrological data (e.g. for discharges), precipitation data are often required. Many Services carry out a comparison of all the values of the area to test their discharge values. A balance along a river stretch covering all measured discharges of the main stream, as well as those of its tributaries, is established using mathematical models. If there are no measurement data of the inflow from tributaries, then they are simulated through precipitation-discharge relationships. The same procedure is used to fill gaps in series of observations.

Surveys of water resources must be made for many water resource plans and for master plans. In most cases, this is done by assessing directly areal runoffs, by areal precipitation amounts or by establishing complete water balances. Since a complete areal coverage of evaporation measurements is not possible to this day, it is usually calculated from climatological data — e.g. radiation, air temperature, air moisture, sunshine duration, wind, etc. (Chapter 3).

In hydrology and water resource management, a large number of mathematical simulation models are used for the planning and operation of water resource systems. While for planning purposes non-real-time values are needed, for operational purposes real-time data are required. The simulation models used are precipitation-discharge models. In the case of models simulating exclusively flood discharge, only precipitation data are included. In areas in which a snow cover forms for a longer time period during winter, snow cover and temperature data are also used. In models for the simulation of low-flow discharge or discharge hydrographs over a longer time period, evaporation has to be taken into account. In this case, the meteorological data required for the calculation of evaporation are needed. The same data are required for models simulating groundwater recharge. All of the above-mentioned applications require areal data (Chapter 4).

The models for the simulation of the water quality in lakes and rivers require data on radiation, air temperature and atmospheric humidity. These data are also used for simulating the temperature behaviour of surface water. For models simulating ice formation on lakes and rivers, data on atmospheric temperature are also needed. Unlike in the above-mentioned cases, the applications refer only to the immediate river course. The river course itself is usually located in a valley having its own moisture regime. In most countries, the meteorological networks are located in places that are as representative of a region as possible. For this reason, there are hardly any meteorological stations in the immediate vicinities of a river course. It is also for this reason that the data from the climate stations of Meteorological Services are usually not simply transferable to the river courses and their immediate surroundings. The Hydrological Services, therefore, often have to perform their own meteorological measurements along the river course in order to obtain the required data.

For the design of structures such as dams, dikes, reservoirs, sewage treatment plants and urban drainage systems, data on the occurrence probability of extreme events are required. This is possible with the aid of extreme-value considerations (Subchapter 3.2). For the computation of flood probabilities, apart from discharge data, measurement data and estimations of extreme rainfall are also used. Probable maximum flood (PMF) is often computed from probable maximum precipitation (PMP) using simulation models (Subchapter 3.4).

For certain designs (e.g. urban drainage structures), the required data can be obtained directly from extreme-value statistics such as storm statistics. For the computation of low-flow probabilities, except for precipitation depths, data on the duration of dry periods (periods without rainfall or with abundant rainfall) are also needed.

In the case of all the above-mentioned applications where non-real-time data are concerned, a maximum of measured data can be made available for the required computations. This does not apply in the case of operational forecasting (e.g. flood forecasting). In that case, mathematical models are used only with data available at that time for forecasting. Only a small number of stations of the meteorological observation networks (synoptic measuring network) are equipped to provide direct access to that data. This is true, in
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Hydrological time series, parameters, methods and procedures needed in water management planning activities

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Water management plans

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<tr>
<th>Water level</th>
<th>Means, minimum, maximum, frequency, duration, lowest 30-day mean, forecasting techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended load</td>
<td></td>
</tr>
<tr>
<td>Sediment transport</td>
<td></td>
</tr>
</tbody>
</table>

Irrigation

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>Evaporation</th>
<th>Infiltration</th>
<th>Soil moisture</th>
<th>Runoff</th>
<th>Plant properties</th>
<th>Infiltration</th>
<th>Capacity</th>
<th>Field capacity</th>
<th>Wilting point</th>
<th>Frequency, duration, extreme value statistics, complete water balance</th>
</tr>
</thead>
</table>

Drainage

<table>
<thead>
<tr>
<th>Groundwater level</th>
<th>Soil moisture</th>
<th>Precipitation</th>
<th>Evaporation</th>
<th>Precipitation</th>
<th>Transmissivity</th>
<th>Field capacity</th>
<th>Wilting point</th>
<th>Means, maximum, frequency, duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban drainage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Intensity, duration, maximum, extreme value statistics, PMP</td>
</tr>
</tbody>
</table>

Water pollution control

<table>
<thead>
<tr>
<th>Dissolved matter</th>
<th>Means, maximum, minimum, frequency, intensity, duration, extreme value statistics, lowest mean of several days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge</td>
<td></td>
</tr>
<tr>
<td>Radiation</td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td></td>
</tr>
<tr>
<td>Precipitation</td>
<td></td>
</tr>
</tbody>
</table>

Fishing

<table>
<thead>
<tr>
<th>Dissolved matter</th>
<th>Means, minimum, maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended load</td>
<td></td>
</tr>
</tbody>
</table>

Recreation, leisure, sports

<table>
<thead>
<tr>
<th>Dissolved matter</th>
<th>Means, minimum, maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge</td>
<td></td>
</tr>
</tbody>
</table>
particular, for precipitation stations. As areal data are needed, precipitation data measured by radar or derived from satellite measurements are desired (Subchapters 2.2 and 2.3). Moreover, quantitative precipitation forecasting (QPF) values are required as input data for hydrological forecasts used for warnings issued to the population and for the operation of water plants (Chapter 5).

Tables 1.1 and 1.2 list the various application areas of hydrology and water resource management and their demands on meteorological data. Today, hydrological models are not yet available with all time and space scales. Figure 1.1 shows the time and space scales of mathematical models.

**CHAPTER 1 — USE OF METEOROLOGICAL DATA IN HYDROLOGY AND WATER RESOURCE MANAGEMENT**

**Table 1.2**

<table>
<thead>
<tr>
<th>Field of application</th>
<th>Hydrological element needed</th>
<th>Meteorological element needed</th>
<th>Type of meteorological input data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TimescaleSpacescale</td>
</tr>
<tr>
<td>Data processing, plausibility check of</td>
<td>Runoff</td>
<td>Precipitation</td>
<td>d, m s, a</td>
</tr>
<tr>
<td>hydrological data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water balance (non-real-time)</td>
<td>Runoff, Evaporation, Soil</td>
<td>Precipitation, Radiation, Sun</td>
<td>y, m, d a</td>
</tr>
<tr>
<td></td>
<td>moisture, Groundwater</td>
<td>shine duration, Air temperature</td>
<td>d, m s, g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Air humidity, Windspeed</td>
<td>d, m s, g</td>
</tr>
<tr>
<td>Simulation of time series (non-real-</td>
<td>Runoff, Groundwater,</td>
<td>Precipitation, Radiation</td>
<td>y, m, a</td>
</tr>
<tr>
<td>time) (non-real-time)</td>
<td>Water temperature</td>
<td>Water level</td>
<td>d, m s, g</td>
</tr>
<tr>
<td></td>
<td>Dissolved matter</td>
<td>Air humidity</td>
<td>h, d, m s, g</td>
</tr>
<tr>
<td>Extreme value statistics of floods</td>
<td>Runoff, Water level</td>
<td>Precipitation</td>
<td>y, m, d s</td>
</tr>
<tr>
<td>and low flow (non-real-time)</td>
<td></td>
<td>min, max</td>
<td></td>
</tr>
<tr>
<td>Forecasting (real-time)</td>
<td>Runoff, Water level,</td>
<td>Precipitation</td>
<td>h, d s, a</td>
</tr>
<tr>
<td></td>
<td>Snow cover, Equivalent of</td>
<td>d s, a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>snow, Snowmelt, Soil</td>
<td>Radiation</td>
<td>h, d s</td>
</tr>
<tr>
<td></td>
<td>moisture</td>
<td>Air temperature</td>
<td></td>
</tr>
</tbody>
</table>

1 – Meteorological elements needed for the calculation of evaporation.
2 – Averages of selected weather situations (dry and wet weather conditions).

**Figure 1.1 — Time and space scales of mathematical models.**
CHAPTER 2

METEOROLOGICAL MEASURING AND OBSERVING SYSTEMS

The National Meteorological Services (NMSs) operate different types of measuring networks for the assessment of meteorological data. Depending on the type of measuring network, the data are available for hydrological purposes immediately (real-time) or only after a certain period has expired (non-real-time) in the form of lists, in a database or in publications.

Depending on the meteorological objectives set and on the description of phenomena, synchronous observation (synoptical method) — or the observation at the same position of the sun (climatological method) — is predominant globally. However, following the progressive automation of measuring equipment, these differences are becoming partly indistinct. Physical descriptions of meteorological phenomena fall within different categories of data. Figure 2.1 shows a schematic representation of the characteristic length and timescales for different important forms of motion and processes in the atmosphere (Fortak, 1971).

The shading indicates the inherent energetics. The small circles represent in each case the characteristic speed of 10 m sec\(^{-1}\) to be observed on the convective, meso, and partly large scale. The field delimited at the top right approximately outlines the processes covered explicitly by circulation models. The relationships between size of area, meteorological phenomenon, prediction model and prediction period must be taken separately for extratropical and tropical systems from Table 2.1. In this table, convective and small scales have been combined. The result is almost unavoidably a subdivision into global, regional and national measuring and observing systems, which are distinguishable according to their measuring network. It should be added that many global meteorological phenomena can be encountered on the planetary as well as the regional and national scales.

**Table 2.1**

<table>
<thead>
<tr>
<th>Extratropical systems and relevant prediction models in the 1990s</th>
<th>Tropical systems and relevant prediction models in the 1990s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scale</strong></td>
<td><strong>System</strong></td>
</tr>
<tr>
<td>Planetary scale (&gt; 5 000 km)</td>
<td>Rossby waves</td>
</tr>
<tr>
<td>Large scale (1 000–5 000 km)</td>
<td>Anti-cyclones/ extratropical cyclones</td>
</tr>
<tr>
<td>Mesoscale– (100–1 000 km)</td>
<td>Squall lines Fronts Polar lows (vorticity maxima)</td>
</tr>
<tr>
<td>Small scale (&lt; 100 km)</td>
<td>Thunderstorms Sea breeze Cumulus</td>
</tr>
</tbody>
</table>

Figure 2.1 — Characteristic length and timescales for forms of motion and processes in the atmosphere (Fortak, 1971).
well as the large scale, just as regional meteorological phenomena develop on the large scale and mesoscale, while dynamic feedbacks between the phenomena of the various scales are taking place. Moreover, as the meteorological values show a different variability in space and time, there are further differences within the individual measuring networks as a result of the temporal spacing of observations and the areal distribution of the stations.

The increasingly applied remote-sensing techniques represent a good addition to the point measurements in conventional measuring networks, because of their direct areal assessment.

### 2.1 CONVENTIONAL MEASURING NETWORKS

#### 2.1.1 Synoptic measuring networks

The actual situation of atmospheric conditions required for weather forecasting is usually carried out globally at the same time, according to universal time coordinated (UTC), with the assistance of:

(a) Aerological-synoptic measuring networks;

(b) Synoptic measuring networks;

(c) Other synoptic measuring networks (ship, buoy and aircraft stations);

(d) Weather radar networks;

(e) Satellite observation.

Since the weather processes in the free atmosphere develop on a considerably larger scale than those in the ground-close atmosphere, considerably fewer measuring stations are required for the aerological measuring network than for the synoptic measuring network. Thus, about 1 000 aerologic stations and about 10 000 synoptic stations are in operation globally. Within the global real-time data exchange, however, at present not all these stations reach the respective regional centres (Figures 2.2 and 2.3).

At the aerological stations, the vertical profile (up to about 30 km) of the following meteorological data is determined and fed into a global telecommunication system in coded form:

---

**Table 2.2**

<table>
<thead>
<tr>
<th>Horizontal resolution</th>
<th>Vertical resolution</th>
<th>Observational error (rms)</th>
<th>Frequency of observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper-air temperature</td>
<td>50 km (A)</td>
<td>10 layers in troposphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 layers in stratosphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5–1°C in troposphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1–2°C in stratosphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2–4 per day</td>
<td></td>
</tr>
<tr>
<td>Upper-air wind vector (V)</td>
<td>250 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 layers in troposphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 layers in stratosphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1–2 m s(^{-1}) in troposphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2–3 m s(^{-1}) in stratosphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2–4 per day</td>
<td></td>
</tr>
<tr>
<td>Upper-air relative humidity (RH)</td>
<td>250 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 layers</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5°C with systematic difference</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>wrong observing systems eliminated on 3 days average</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Instantaneous measurements averaged over 3 days</td>
<td></td>
</tr>
<tr>
<td>Sea surface</td>
<td>250 km</td>
<td>10 per cent</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Instantaneous measurements averaged over 3 days</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface pressure (P) temperature (T, Td)</td>
<td>250 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>+/- 1 hPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>+/- 0.5°C temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>+/- 1–2 m s(^{-1})</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 per day</td>
<td></td>
</tr>
<tr>
<td>State of surface</td>
<td>**</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td></td>
<td>**</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>Satellite imagery (B)</td>
<td>At least 3 km horizontal resolution of imagery</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>At least 3 layers-low, middle, high and cloud top height</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>To be determined; will be function of latitude for geostationary satellites</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 per day</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(A) Tropics: 500 km resolution sufficient temperature.
(B) Satellite imagery included here because of its use in computing vertical motion and divergence fields, as well as for determination of synoptic distribution of water vapour, precipitable water and cloudiness.

* This table defines a basic set of the global observational data requirements which generally can be met by the GOS and, therefore, should be used in the design and implementation of the GOS.

** Includes precipitation, soil moisture, soil temperature, emissivity, albedo, snow and ice coverage. Resolution, accuracy and frequency not yet determined; information required from other commissions.

---

**Table 2.3**

<table>
<thead>
<tr>
<th>Type of observation</th>
<th>Density</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adequate</td>
<td>Minimum for sparsely populated and oceanic areas</td>
</tr>
<tr>
<td>Land surface</td>
<td>250 km</td>
<td>300 km</td>
</tr>
<tr>
<td>Oceanic surface</td>
<td>250 km</td>
<td>500 km</td>
</tr>
<tr>
<td>Surface-based upper-air</td>
<td>250 km</td>
<td>1 000 km</td>
</tr>
</tbody>
</table>
(a) Atmospheric pressure;  
(b) Air temperature and atmospheric humidity;  
(c) Wind direction and speed.

The measurements and observations made at synoptic ground stations are likewise exchanged through internationally-agreed codes and include global, regional and national key groups for various meteorological data as exemplified by Germany. They are listed in Table 2.4.

The general requirements to be met by a meteorological station, be it on land, on water or in the atmosphere, as well as the requirements to be met by the measurement of various meteorological elements are laid down in the following WMO documents:  
(a) *Technical Regulations* (WMO-No. 49);  
(b) *Guide on the Global Observing System* (WMO-No. 488);  
(c) *Manual on the Global Observing System* (WMO-No. 544).
<table>
<thead>
<tr>
<th>Paragraph 1 (additional climatological data)</th>
<th>Paragraph 2 (maritime global-, regional code groups)</th>
<th>Paragraph 3 (global, regional and national key groups with additional national climate data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tables 2.4 — Global, regional and national key groups with additional national climate data; Paragraph 5 (additional climatological data) Paragraph 4 (national code groups) Paragraph 5</td>
<td>Paragraph 2 (maritime global-, regional code groups)</td>
<td>Table 2.4 — Global, regional and national key groups with additional national climate data; Paragraph 5 (additional climatological data) Paragraph 4 (national code groups) Paragraph 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.1.2 Climatological measuring networks and hydrometeorological networks

As a result of the reaction of ground-near atmospheric layers to incoming and outgoing radiation conditions, these stations — established to supplement the global synoptic measuring network — often have measuring dates at the same position of the sun or are equipped with recording measuring instruments. In this connection, climate and precipitation stations should be mentioned as well as special measuring networks important for hydrological problems, such as:

- Global radiation (direct and diffuse radiation);
- Soil moisture;
- Wind direction and speed;
- Precipitation (recorder);
- Snow cover depth;
- Water equivalent of snow cover;
- Sunshine duration;
- Phenological observations.

The general requirements to be met by the climatological observation network as well as the requirements for location, data and measuring accuracy, operation and maintenance of climate stations are described in the *Guide to Climatological Practices* (WMO-No. 100), in the *Technical Regulations* (WMO-No. 49) and in the *Guide to Hydrological Practices* (WMO-No. 168). Recommendations for the establishment and operation of agrometeorological stations can be taken from the *Guide to Agricultural Meteorological Practices* (WMO-No. 134).

At present, no survey exists stating how many climate stations are in operation globally. However, the Regional Associations are preparing a survey under the World Climate Data Information Referral Service (INFOCLIMA) (WMO, 1985a). Joined to the global data exchange are the monthly CLIMAT messages supplying recent monthly data of atmospheric pressure, air temperature and humidity, precipitation depth and sunshine duration as well as the related long-term monthly reference values (WMO, 1971). Globally, there is a total of 2 200 stations from which at the utmost 1 500 messages are regularly received by the meteorological regional centres (Figures 2.4 and 2.5).

A large number of rain gauge stations are operated in national hydrometeorological or hydrological networks.

There is little information on the national special measuring systems available to WMO Member countries. The number of precipitation stations (one daily measurement of the precipitation depth) pursuant to information from the Hydrological Information Referral System (INFOHYDRO) worldwide is 150 000, that of precipitation recording stations (continuous recording of precipitation events) about 41 000, and that of evaporation stations 10 600.

The measuring systems of the *Deutscher Wetterdienst* have been compiled in Table 2.5 to give an idea of the respective network density, the observation frequencies and the data access time. As for various hydrological fields of application, the areal distribution of the real-time stations is often too coarse-meshed; special services are being established permitting a quasi real-time retrieval of data sets, e.g. water resources management reporting service, warnings in the case of snowmelt, etc.

Other special measuring systems include, for instance, weather radar stations, atmospherics detection stations (lightning counter), rocket stations, ozone-sounding stations, background air pollution stations, planetary boundary-layer stations and tide-gauge stations. The establishment and operation of stations are described in WMO, 1978; 1989 and 1996.

![Figure 2.4 — Survey of globally-agreed CLIMAT stations: Deutscher Wetterdienst (DWD), Global Precipitation Climatology Centre (GPCC). Observing stations (total 2 201) which are to transmit monthly climatological means from ground stations (Source: Weather Reporting, Volume A, WMO-No. 9).](image-url)
2.1.3 Error sources and measuring accuracy

The measuring accuracy and reporting interval for meteorological data required for hydrological purposes is given in Table 2.6. Since the number of requirements for precipitation measurements in the operational and in the research areas of meteorology, in surveying climate changes, in hydrology and in ecology is continuously increasing, and since precipitation represents the only input into the global water balance, problems arise in computing a global water balance. Apart from a large number of random errors occurring in precipitation measurements, the operation of measuring instruments installed above ground causes, in particular, the following errors:

(a) Wind field deformation;
(b) Suspected water losses;
(c) Evaporation losses;
(d) Splash water caused by rebounding raindrops.

Figure 2.5 — Survey of CLIMAT stations participating in global data exchange in 1987: Deutscher Wetterdienst (DWD); Global Precipitation Climatology Centre (GPCC). Observing stations which in 1967 regularly transmitted monthly CLIMAT messages (total 1 017 stations out of 2 201 official — CLIMAT observing stations) (Source: Weather Reporting, Volume A, WMO-No. 9).

Table 2.5
Frequency of observation, density of stations and availability of data of the different network of stations (Deutscher Wetterdienst)

<table>
<thead>
<tr>
<th>Measuring networks (number of stations)</th>
<th>Observation frequency</th>
<th>Station density</th>
<th>Data acces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerological stations 9</td>
<td>Six-hourly measurement according to UTC</td>
<td>1:40 000 km²</td>
<td>Real-time</td>
</tr>
<tr>
<td>Synoptic stations 176</td>
<td>One-hourly measurement according to UTC partly continuous</td>
<td>1:2 000 km²</td>
<td>Real-time</td>
</tr>
<tr>
<td>Climatological stations 595</td>
<td>Daily time 00, 06, 12, 18 partly continuous</td>
<td>1:600 km²</td>
<td>Non-real-time partly real-time</td>
</tr>
<tr>
<td>Precipitation stations 3 500</td>
<td>Daily time 07:30 partly continuous</td>
<td>1:100 km²</td>
<td>Non-real-time partly real-time</td>
</tr>
<tr>
<td>Special measuring networks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global radiation 59</td>
<td>Continuous</td>
<td>1:6 000 km²</td>
<td>Non-real-time, real-time</td>
</tr>
<tr>
<td>Wind 60</td>
<td>Continuous</td>
<td>1:6 000 km²</td>
<td>Non-real-time, partly real-time</td>
</tr>
<tr>
<td>Rainfall recorder 460</td>
<td>Continuous</td>
<td>1:780 km²</td>
<td>Non-real-time</td>
</tr>
<tr>
<td>Water equivalent 511</td>
<td>Three times a week at a fixed time</td>
<td>1:700 km²</td>
<td>Non-real-time partly real-time</td>
</tr>
<tr>
<td>Sunshine duration 164</td>
<td>Continuous</td>
<td>1:2 200 km²</td>
<td>Real-time partly non-real-time</td>
</tr>
<tr>
<td>Phenological observing network 2 020</td>
<td>Daily during vegetation period</td>
<td>1:180 km²</td>
<td>Non-real-time partly real-time</td>
</tr>
</tbody>
</table>
The first two errors are very important as they concern the loss of volume. As these physical processes depend on instrumental parameters, on the one hand, and on climate factors, on the other, the magnitude of the systematic error in precipitation measurements varies considerably depending on the type of raingauge used, the region and the season of the year (WMO, 1982b). About 150 different types of instruments are in use worldwide. The result is that jumps occur in the isohyets at the national borders of neighbouring countries which use different types of raingauges (Figure 2.6). At present, different methods for the correction of errors are being applied. Investigations show that such corrections may be used for the long-term mean, but that they cannot be generally used for individual events, in particular not for heavy rainfall (Subchapter 3.2).

It is recommended to apply corrections to the data used in budget studies and analyses, especially in high geographical latitudes. It is not necessary to correct heavy rainfall data. The correction of data and the method used should be indicated if corrected data or products are distributed.

## 2.2 REMOTE-SENSING PROCEDURES

Remote-sensing procedures — satellite and radar techniques which have become operational in the recent past — represent an addition to the already very old techniques of precipitation determination by means of weight and volume measurements. These remote-sensing procedures do not permit, it is true, direct precipitation measurement, but offer the advantages of areal coverage and real-time transmission. Satellite techniques at present are mainly drawn from the cloud-top temperatures (passive procedure). In using radar-based techniques, conclusions are drawn from the backscattering measured (active procedure). Considering their physics, both measuring methods are particularly suited for the interpretation of

---

### Table 2.6

<table>
<thead>
<tr>
<th>Element</th>
<th>Precision</th>
<th>Reporting interval for hydrological forecasting purposes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation: amount and form&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>± 2 mm below 40 mm, ± 5 per cent above 40 mm</td>
<td>Six hours&lt;sup&gt;(2)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Snow depth</td>
<td>± 2 cm below 20 cm, ± 10 per cent above 20 cm</td>
<td>Daily</td>
</tr>
<tr>
<td>Water equivalent of snow</td>
<td>± 2 mm below 20 mm, ± 10 per cent above 20 mm</td>
<td>Daily</td>
</tr>
<tr>
<td>Air temperature</td>
<td>± 0.1°C</td>
<td>Six hours</td>
</tr>
<tr>
<td>Wet-bulb temperature</td>
<td>± 0.1°C</td>
<td>Six hours</td>
</tr>
<tr>
<td>Net radiation</td>
<td>± 0.4 J m&lt;sup&gt;–2&lt;/sup&gt; d&lt;sup&gt;–1&lt;/sup&gt; below 8 M J m&lt;sup&gt;–2&lt;/sup&gt; d&lt;sup&gt;–1&lt;/sup&gt;, ± 5 per cent above 8 M J m&lt;sup&gt;–2&lt;/sup&gt; d&lt;sup&gt;–1&lt;/sup&gt;</td>
<td>Daily</td>
</tr>
<tr>
<td>Pan evaporation</td>
<td>± 0.5 mm</td>
<td>Daily</td>
</tr>
<tr>
<td>Surface temperature: snow</td>
<td>± 1°C</td>
<td>Daily</td>
</tr>
<tr>
<td>Temperature profiles: snow</td>
<td>± 1°C</td>
<td>Daily</td>
</tr>
<tr>
<td>Wind: speed</td>
<td>± 10 per cent</td>
<td>Six hours</td>
</tr>
<tr>
<td>Wind: direction</td>
<td>± 10°</td>
<td>Six hours</td>
</tr>
<tr>
<td>Sunshine duration</td>
<td>± 1 hour</td>
<td>Daily</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>± 1 per cent</td>
<td>Six hours</td>
</tr>
</tbody>
</table>

<sup>(1)</sup> In some locations, it will be necessary to distinguish the form of the precipitation (liquid or solid).

<sup>(2)</sup> The reporting interval in flash flood basins is often required to be two hours or less; in other locations, daily values may suffice.

---

Figure 2.6 — Map of basic and evaluation stations, with numbers 1–52 in rings and 53–59 in squares, respectively; one point means one or more nearby stations. Indicated are correction factors for the systematic error in precipitation measurement (WMO, 1982b).
the areal phenomena of precipitation (WMO, 1982a, 1985b). Both methods are already in operational use, satellite techniques being increasingly used for precipitation estimations over areas for which no data would otherwise be available. The parameters for atmospheric conditions derived from satellite data are, however, less accurate than the in situ measurements of conventional networks.

The determination of precipitation over large areas with the aid of remote-sensing procedures was first used only for application in minimum-term forecasts (up to a few hours after the time of assessment). Radar-based techniques are operational for hydrological uses, inter alia, in Europe, Japan and the United States (WMO, 1988a, 1988b), particularly for flood forecasting.

As already mentioned, precipitation measurements based on radar and satellite imagery are not to be considered as an alternative to conventional ground-based measurements but, rather, as complementary. Figure 2.7 gives a survey of comparison networks which are taken as a basis for the Global Precipitation Climatology Project of the World Climate Research Programme (WCRP) for the calibration of satellite-based data and consist of precipitation measuring networks and combined radar and precipitation measuring networks (WMO, 1988a).

2.2.1 Radar-based precipitation measurements

2.2.1.1 Measuring procedure

The determination of precipitation by means of a weather radar set is based on the location of precipitation areas with the aid of electromagnetic waves, analogous to the location of precipitation areas from aircraft or ships, on the one hand, and the measurement of that fraction of transmitting energy backscattered from the precipitation area, on the other hand. In physics, the MIE theory gives a general description of the scattering of electromagnetic waves on spherical particles in space. If, as in the case of a radar-based measurement, the wavelength is long enough (usually about 5 cm) compared to the diameter of the scattering particles (so-called hydrometeors), then the relationship between backscattered energy (meaning measured received energy), emitted energy (including antenna parameters) and the cross-section of backscattering of the particles can be represented in a simplified form by the so-called Rayleigh approximation. This area of backscattering covers the individual particles with their diameter raised to the power of 6. That term is usually designated as radar reflectivity factor $Z$. The radar equation consequently links the incoming energy ($PE$) with the instrumental constant ($C$), the goal distance ($r$) and the reflectivity factor ($Z$) as follows:

$$PE = C K^2 r^2 Z$$

(2.1)

The factor $K^2$ originates from the Rayleigh approximation and contains the complex refraction index. Consequently, it is different for the different states of aggregation (water: $K^2 = 0.93$; dry snow: $K^2 = 0.208$). The reflectivity factor $Z$ is computed via the radar equation from the measured incoming energy ($PK$).

The requested precipitation intensity ($R$) (mm h$^{-1}$) is linked via the so-called $Z/R$ relationship with the reflectivity ($Z$) (mm$^3$ m$^{-1}$) which has been determined. The general form of the $Z/R$ relationship reads as follows:

$$Z = AR^B$$

(2.2)

$A$ and $B$ are a function of the drop spectrum and may vary from one precipitation to another. In practice, mean $Z/R$ relationships depending on the respective precipitation type obtained from long-term drop spectra measurements are used. In the middle latitudes, however, it usually suffices to distinguish between two main precipitation types, e.g., precipitation occurring as a result of warm and cold air advection. A computer determines the instantaneous precipitation intensity via the $Z/R$ relationship fed in,
it extrapolates that relationship for the scanning time interval and finally obtains the resulting hourly or event precipitation depths for the respective area. In this case, the resolution is limited by the areal element over which the integration is made, usually 1 kilometre, 1 degree. At high rain rates (> 70 mm h⁻¹), differential phase techniques (Joe, 1996) are more accurate than a Z/R approach (Chandrasekar et al., 1990). It is insensitive to hail in a rain-hail mix, independent of system calibration, independent of rain attenuation, beam blockage and beam filling since these factors do not affect the differential phase shifts. To improve the result obtained by radar, some good ground stations are often compared with the related areal elements in the radar-based result in order to derive correction factors. The data output can be adjusted to the data user’s requirements via the peripheral instrumental equipment of the computer. Representation on a coloured monitor, isobylot plots, digital printouts, storage on magnetic tape and supply of data with the aid of remote data transmission are possible. Various possibilities of hydrological applications are described in Collinge and Kirby (1987). The contribution of radar data to hydrological forecasting is demonstrated in Collier (1996).

### 2.2.1.2 Error Sources and Measuring Accuracy

The main error sources in radar precipitation measurements are the various states of aggregation and the respective sizes of the precipitation particles (Figure 2.8):

(a) If the precipitation particles are very large in the radar volume, then the Rayleigh approximation no longer applies;

(b) If a Z/R relationship other than that adjusted to the type of precipitation is used, then the error rate in the conversion of the echo power into precipitation intensity can be up to 50 per cent;

(c) If the state of aggregation of hydrometers in the measuring volume with regard to time and with regard to space is partly different from the one assumed (e.g. sleet or snow storages), then the error through K² must be added to the Z/R error. Dual-polarization radars measure the reflectivity depolarization ratio, which is useful for indicating the presence of hail. Dual-wavelength radars, also designed for hail detection, usually use an S-band and an X-band radar together (i.e. 10 cm and 3 cm wavelengths, respectively);

(d) The error occurring as a result of the attenuation of the radar wave on its passage through areas of heavy rainfall is practically negligible in temperate latitudes and for the wavelengths (e.g. C-band) used;

(e) More serious are the cases in which the radar beam cuts the melting zone at a low or a decreased 0°C limit. Such bright-band effects lead, in the melting zone range, to considerable echo increases. Smith (1986) devised an analytic technique for reducing errors due to the bright-band, which proved very promising in tests. In routine operation, however, it was found to be susceptible to large errors, when significant variations in the freezing level occurred over the area covered by a radar. Rosenfeld, Amitai and Wolff (1995) derived a number of radar echo classification criteria which may be employed to recognize the occurrence of bright-band effects. Further work is needed to assess the operational reliability of this technique (Collier, 1996);

(f) Disturbing and unpleasant are the ground returns which are not immediately distinguished by the radar from precipitation echoes and are, therefore, likewise converted into precipitation intensities. The so-called clutter data sets which are stored in the computer can help for fixed target echoes (mountains and buildings). However, this procedure is no help in the case of temporary ground returns resulting from abnormal propagation conditions (extreme ranges). For ground clutter, the frequency spectrum shows a peak at zero frequency and becomes flat for frequencies higher than 20-30 Hz. By discriminating between these frequency spectra using a high-bandpass filter and estimates of the mean power of the rain echo, ground echoes may be separated from rain

---

**Figure 2.8** — Aggregate states of hydrometeors and microphysical processes in precipitation formation (WMO, 1988a).
Precipitation as a result of large-scale dynamic processes

Promising methods for the assessment of precipitation intensities from fronts or large-scale cloud fields are based on the fact that, for precipitation activity, the air must be subjected to a large-scale lifting process which is triggered off by convergence in low atmospheric layers and divergences in the upper atmosphere. The divergence in the upper atmosphere usually becomes apparent from the horizontal extension of the cloud surface in time, the change in the area being proportional to the vertical speed in an upward direction. Estimation of the precipitation intensity results from an evaluation of the development cycle of large-scale cloud structures (life history method). In this context, apart from the form of the clouds and its change in a horizontal direction, information on the synoptically-conditioned air mass character must be included (Neil and Spagnol, 1987). Most methods with visible or infrared data require an interactive subjective treatment of the satellite images and are therefore hardly suited for an automatic derivation of the precipitation depth under operational conditions. Since satellite images taken at frequent time intervals are needed, data from the geostationary satellites may be taken for the application of the “life-history” methods (Figure 2.9);

(b) Precipitation as a result of convective processes

Most methods for the assessment of precipitation from satellite data yield a relatively good application for convective clouds.

For convective precipitation events, the basic assumption is that precipitation probability is larger the colder the temperature at the cloud tops. The cloud surface temperature is determined from the radiation values in the atmospheric window channel (infrared channel).

In the United States, a procedure has been developed to estimate the intensity of precipitation from the cloud height via its surface temperature and from its vertical and horizontal changes.

This method supplies good results for large, convective cloud clusters in tropical air masses and is generally used in the United States for the forecasting of so-called “flash floods”, i.e. flood events setting in very suddenly (Scofield and Oliver, 1977).

It is more difficult for central Europe to use this method because the very rigorous boundary conditions are fulfilled only in a very few cases. It has nevertheless been possible to estimate approximately in individual cases the precipitation depth for southern Germany by means of that method (Krüger, 1983). However, estimations of precipitation depths from satellite data at present still have an error rate of 500 per cent in individual cases.

The European Space Operations Centre (ESOC) at Darmstadt regularly derives the so-called “precipitation index” from the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) series of meteorological geostationary satellites (METEOSAT) data. It is mainly based on the height of clouds calibrated by ground-based measurements via regression equations. The index is a mean over five days each and is derived for areas from 32 × 32 pixels. The evaluation area for the precipitation index is situated between 40 degrees north and 40 degrees south, and between 50 degrees west and 50 degrees east (Turpeinen, Abidi and Belhaouane, 1986). A similar method is applied by the National Oceanic and

CHAPTER 2 — METEOROLOGICAL MEASURING AND OBSERVING SYSTEMS

13

echoes (Collier, 1996). A compilation of standard clutter filters is presented by Meetschen (1999). However, clutter information can also be used for calibration, attenuation correction and determination of the refraction index.

The potential errors (a) to (d) above can, for the most part, be corrected by calibration procedures with the aid of ground-based measurements, while for errors (e) and (f), correction procedures are more complicated and still being developed.

Users again and again ask to what degree the precipitation measurements by radar are accurate. It is difficult to answer that question as there is no real reference value. Comparison of the value measured by radar with that measured by a ground-based raingauge always implies, in addition to potential errors in the ground-based value (Subchapter 2.1.3), the problem that a receiving area of 200 cm² is compared with a volume of about 0.5 km³. Such comparisons were routinely made in Great Britain with the result that, for calibrated radar values, the quotients of the hourly precipitation depths were for more than a year within factor 2 range.

A more important comparison in hydrological practice is the comparison of areal precipitation depths computed from point measurements with those derived from radar measurements. The areal precipitation depths routinely computed in Germany use the catchment basin procedure (Subchapter 4.4) — i.e. areal precipitation depths for hydrologically-fixed areas of basic areas (size: about 100 km²) are computed over catchment basins up to entire river basins. Radar-based precipitations for individual basic areas supply negative as well as positive differences during the summer months — between –30 and +35 per cent — as compared to the computed areal precipitation depths. If the reference area is enlarged, i.e. if several basic areas are combined to form a catchment basin of the size of 1 500 km², then the deviation is reduced to a negative difference of 5 per cent (Deutscher Wetterdienst, 1986).

At present, in many countries, radar networks are being established. The main objectives of such networks — quantitative measurements, qualitative images — are, however, very different. But it may be assumed that the assessment and determination of precipitation will be further improved and applied with the aid of radar techniques within the next few years. Globally, at present, about 600 radar stations are in operation (with an increasing tendency).

2.2.2 Satellite data for the estimation of precipitation

In principle, two methods for the assessment of precipitation depths from satellite data must be distinguished:

(a) Derivation of the precipitation intensity from cloud information with visible and/or infrared data; and

(b) Derivation of the precipitation intensity from microwave data.

In the visible wavelength range, information about cloud thickness, structure and composition can be taken from satellite images; in the infrared range, the cloud height is derived indirectly via the radiation temperature of the top layer of the cloud. The two wavelength ranges can normally be used separately, but a combination of both (bispectral method) leads to better results. Microwave data techniques use the characteristics of absorption/emission of raindrops and the spreading of ice particles.

2.2.2.1 Precipitation intensity from cloud information with visible and/or infrared data

Precipitation intensity from cloud information with visible and/or infrared data includes:

(a) Precipitation as a result of large-scale dynamic processes

Promising methods for the assessment of precipitation intensities from fronts or large-scale cloud fields are based on the fact that, for precipitation activity, the air must be subjected to a large-scale lifting process which is triggered off by convergence in low atmospheric layers and divergences in the upper atmosphere. The divergence in the upper atmosphere usually becomes apparent from the horizontal extension of the cloud surface in time, the change in the area being proportional to the vertical speed in an upward direction. Estimation of the precipitation intensity results from an evaluation of the development cycle of large-scale cloud structures (life history method). In this context, apart from the form of the clouds and its change in a horizontal direction, information on the synoptically-conditioned air mass character must be included (Neil and Spagnol, 1987). Most methods with visible or infrared data require an interactive subjective treatment of the satellite images and are therefore hardly suited for an automatic derivation of the precipitation depth under operational conditions. Since satellite images taken at frequent time intervals are needed, data from the geostationary satellites may be taken for the application of the “life-history” methods (Figure 2.9);

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It is more difficult for central Europe to use this method because the very rigorous boundary conditions are fulfilled only in a very few cases. It has nevertheless been possible to estimate approximately in individual cases the precipitation depth for southern Germany by means of that method (Krüger, 1983). However, estimations of precipitation depths from satellite data at present still have an error rate of 500 per cent in individual cases.

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Atmospheric Administration (NOAA) for the estimation of precipitation from geostationary operational environmental satellite (GOES) data.

2.2.2.2 PRECIPITATION INTENSITY FROM MICROWAVE DATA

Precipitation intensity from microwave data includes:

(a) Passive high-frequency microwaves
At frequencies above 60 GHz, the interaction intensity between radiation and precipitation has its maximum. Raining clouds are almost opaque; absorption scattering by both liquid and frozen precipitation-size particles is important. Accordingly, raining clouds appear cold compared to the environment. The radiance depression is dependent on the amount of scatterers in the upper part of the cloud. Since ice particles play a key role in precipitation generation, the precipitation intensity can be estimated from the observed radiance depression. The microwave reflection and emission of water surfaces is highly polarized in contrast to emission and scattering by atmospheric constituents. As a result, in addition to the radiance depression, the polarization reduction serves as another piece of information over ocean areas. The main advantage of the high-frequency method is its relative independence of the signal of the surface below the cloud. Thus, the signal can be observed over both land and ocean surfaces (Simmer, 1996);

(b) Passive mid- to low-frequency microwaves
Below 40 GHz, raining clouds become increasingly transparent for microwave radiation; below 10 GHz, emission dominates and the emitted radiation is almost proportional to the rain water content in the atmospheric column. If the height of the water column and its profile structure is known, then the precipitation intensity can be retrieved. As above, additional information is provided by polarization reduction. Over land, the polarization of the background radiation is low and the signal of the rain cloud can barely be distinguished from its surroundings. This is the main disadvantage of the low-frequency approach. At higher frequencies, absorption/emission and scattering by precipitation particles increase. This leads to a strong non-linear signal dependence on the precipitation intensity and to saturation at decreasing precipitation intensity with increasing frequency. This non-linear relation is a serious problem, because rain cells are typically smaller than the resolution of satellite radiometers (e.g. 30 to 50 km for SSM/Imager). Compared to the methods described above, the low-frequency approach is based on a more direct relation between signal and precipitation intensity. This method is, however, restricted to oceanic areas (Simmer, 1996);

(c) Rain radar
Active microwave techniques are designed to be used by the equipment of a satellite with a precipitation radar (Subchapter 2.2.1) in the Tropical Rainfall Measuring Mission (TRMM) together with various microwave radiometers, as well as a radiometer operating in the visible and infrared band. In TRMM, the vertical distribution of precipitation will be measured over the tropics in a band between ±35 degrees in latitude. Such information will greatly enhance the understanding of the interactions between the sea, air and land masses which produce changes in global rainfall and climate. TRMM observations will also help improve modelling of tropical rainfall processes and their influence on global circulation leading to better predictions of rainfall and its variability at various timescales. Although this, too, promises further progress in precipitation estimation from satellite data, it will be possible to meet only part of the global requirements for precipitation data.

In the microwave spectral region, the radiances are directly related to the hydrometeors in the satellite field of view.

Figure 2.9 — Planned global geostationary weather satellite system (ESA, 1981).
Contrary to the visible and infrared spectral region, the whole state of the atmosphere described by the vertical profiles of temperature, water vapour, cloud and rain liquid and ice profiles, and the shape of the particles determine the outgoing radiances at the top of the atmosphere. So any parameter retrieval is at least partially an inversion of the radiative transfer equation. Concerning rain, basically three paths have been followed to construct rain retrieval algorithms (complete inversion, statistical inversion and indexing) (Simmer, 1996).

2.2.2.3 Measuring accuracy

As the methods presently available for the estimation of precipitation from satellite data cover a large range of the electromagnetic spectrum, it is of particular importance to collect investigations on measuring accuracy and possibilities of application. This has been done in Table 2.7 on the basis of the literature published (EUMETSAT, 1988). Two essential points are revealed by this table and should be noted:

(a) The majority of the errors indicated are referred to an integral area of more than 1 000 km², although some of the methods are also suited for areas of a size of up to about 50 km². The major part of the investigations deals with the determination of convective rainfall and permits no conclusion as to frontal rainfall;

(b) It should further be taken into account that the ground-based measurements of the precipitation depth used for comparison are not performed with uniform accuracy (Subchapter 2.1.3), that the point measurements must be transferred to the area and that some instruments are equipped only for the recording of heavy rainfall.

2.3 Combined measuring systems

Over data-rich areas of the Earth, the total timescale of the precipitation measurement (from minutes to years) and the space scale (from one point to an area of about 500 000 km²) can be covered by the various measuring systems of the conventional measuring network, the ground-based radar measurements and satellite data. Thus, in Europe a comprehensive set of data is available through the dense measuring networks of conventional stations, ground-based weather radar and METEOSTAT satellites. It is possible to use the more accurate system for the calibration of the next higher system, i.e. point measurements can be used for the determination of radar-based precipitation depths, which, in turn, can be used for the derivation of satellite estimations.

In some countries, combined systems are already operational, e.g. the Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite (FRONTIERS) system in Great Britain (CEC, 1988). In this system, visible and infrared images from METEOSTAT are combined with data from the weather radar network and data of the conventional measuring network. Figure 2.10 gives an example of this combined measuring system. However, it was found that, particularly when heavy rainfall systems occurred, the forecaster was unable to step through the system procedures rapidly enough. Hence, a new fully automatic system, Nimrod, was proposed (Collier, 1991). This system, in which radar and satellite data are blended with mesoscale model data, has recently been implemented (Golding, 1995). Further details of the analysis procedures being developed are described by Kitchen, Brown and Davis (1994).

A graphical representation of the presumed accuracy of precipitation measurements from radar and satellite systems as a function of their respective reference areas is given in Figure 2.11. First, it is striking that the two measuring systems are quite complementary. The upper limit of area sizes for the assessment of quantitative radar data is about 10 000 km² and the lower limit of the area sizes for the use of satellite data is about 1 000 km². It can further be noted that the differences of error rates from calibrated radar-based precipitation measurements within and outside the melting zone range are, on average, from about 20 to 30 per cent.

### Table 2.7

List of measuring accuracies of precipitation estimations from satellite data as a function of reference area and period of integration (Collier, 1996)

<table>
<thead>
<tr>
<th>Technique</th>
<th>Areas over which estimates are assessed (km²)</th>
<th>Period of integration (h)</th>
<th>Approximate percentage accuracy (%)</th>
<th>Sample references describing techniques (rainfall types)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud indexing (with cloud model)</td>
<td>10⁵</td>
<td>24</td>
<td>122</td>
<td>Follonsbee and Oliver (1975); Adler and Negri (1988) (convective/stratiform)</td>
</tr>
<tr>
<td></td>
<td>10⁴</td>
<td>1/₂</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>Area average</td>
<td>10⁵</td>
<td>Inst- 30 x 24</td>
<td>15</td>
<td>Atlas and Bell (1992) (convective)</td>
</tr>
<tr>
<td>Life history</td>
<td>10⁴</td>
<td>1</td>
<td>85</td>
<td>Griffith et al. (1978) (convective); Arkin and Meisner (1987) (convective); Wylie (1979) (convective)</td>
</tr>
<tr>
<td></td>
<td>10³</td>
<td>24</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10²</td>
<td>1/₂</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 x 10¹</td>
<td>1/₂</td>
<td>65</td>
<td>Stout et al. (1979) (convective)</td>
</tr>
<tr>
<td></td>
<td>10¹</td>
<td>30 x 24</td>
<td>10</td>
<td>Xie and Arkin (1995) (convective)</td>
</tr>
<tr>
<td>Bi-spectral</td>
<td>10¹</td>
<td>1/₂−2</td>
<td>49</td>
<td>Lovejoy and Austin (1979a,b); convective/frontal</td>
</tr>
<tr>
<td>Passive microwave</td>
<td>10³</td>
<td>24</td>
<td>70</td>
<td>Lovejoy and Austin (1980) (convective/frontal); Wilheit et al. (1973); Spencer et al. (1983)</td>
</tr>
<tr>
<td></td>
<td>10²</td>
<td>30 x 24</td>
<td>10</td>
<td>Xie and Arkin (1995) (convective)</td>
</tr>
<tr>
<td>Active</td>
<td>10³</td>
<td>12</td>
<td>20 (when combined with bi-spectral technique)</td>
<td>The accuracy of this technique is unknown but Lovejoy (1981) suggests the figures given may be possible (see also Atlas and Bell (1992))</td>
</tr>
<tr>
<td></td>
<td>10²</td>
<td>30 x 24 monthly</td>
<td>10</td>
<td>Simpson et al. (1988) (convective)</td>
</tr>
</tbody>
</table>

Summary of the performance of satellite estimation techniques (from Collier, 1985 partly based upon Lovejoy and Austin 1979, 1980)
In other areas of the world, limitations in the assessment of precipitation events are due to the absence of one or several of these measuring systems. In this context, precipitation measurements with a time resolution of less than one day should be mentioned. In particular, over tropical oceans, no ground-based measurements are available. In such areas, only satellite-based estimations can be used to obtain derivations of daily or monthly precipitation values.

Figure 2.10 — European composite from METEOSAT and radar-based data (COST 73) (CEC, 1988).

Figure 2.11 — Areal coverage of radar- and satellite-based systems for the determination of areal precipitation depths and respective measuring accuracy (EUMETSAT, 1988).
CHAPTER 3

DATA DERIVED FROM METEOROLOGICAL MEASUREMENTS

3.1 EVAPORATION

3.1.1 Introduction

Evaporation is the transition of water from the soil or ground surface, from the vegetation cover and from open areas of water into the atmosphere. The evaporation losses of the Earth’s surface occur as a consequence of various processes in which, apart from meteorological conditions, the specific characteristics of the different surfaces play a part.

Evaporation is a component not only of the energy balance equation (Equation 3.1) but also of the water balance equation (Equation 3.2). This means that the connection between the heat balance and the water balance of the Earth’s surface is made through evaporation. With a high energy supply, the amount of evaporation is limited by the water supply available for the evaporation process, and vice versa: if a high water supply is available, then the maximum amount of water that can evaporate is restricted by the amount of energy available.

The energy balance equation (in W m\(^{-2}\)) is:

\[ R_n + G + H + LE = 0 \] (3.1)

with:

- \( R_n \): radiation balance;
- \( G \): Soil heat flux, or for bodies of water; change in heat content;
- \( H \): Sensible heat flux;
- \( LE \): Latent (evaporation) heat flux with:
  - \( L \): Evaporation heat in W m\(^{-2}\) mm\(^{-1}\);
  - \( E \): Depth of evaporated water in mm.

All four components can be shown as positive or negative values; the evaporation heat flux is usually negative. Further balance components such as, for example, heat flux from the biomass, energy transformation due to chemical processes are, for hydrological considerations, generally so small to be negligible. However, under certain weather conditions, the advective energy input reaches a relevant order of magnitude in local energy balances.

Depending on the time of year and weather situation, a considerable part of the radiation energy reaching the surface of the Earth, up to 100 per cent of the net radiation, can be expended on evaporation. The evaporation process on the Earth’s surface is, therefore, an important energy supplier for the atmospheric processes and it is necessary to take this into account in numerical forecasting models and climate models.

The water balance equation (in mm) is:

\[ P + E + Q + \Delta W = 0 \] (3.2)

with:

- \( P \): Precipitation (including correction of the systematical measurement error of the instrument);
- \( E \): Evaporation;
- \( Q \): Runoff (surface and groundwater runoff);
- \( \Delta W \): Change in water supply in the period under consideration.

Note concerning the water balance equation: The use of measured data for the amount of precipitation in Equation 3.2 necessitates the correction of the systematic error of the precipitation measurement, because a smaller amount of precipitation is measured by the measuring instruments than reaches the surface of the ground at the site under observation. The amount of correction depends on the type and exposure of the instrument and on the climatic conditions at the site. The evident annual run of the corrected values is important for the water balance.

At the Deutscher Wetterdienst, precipitation correction is routinely carried out according to the Richter (1995) procedure for hydrological and water management problems.

Evaporation represents a quantity of loss in the water balance. On average, 75 per cent of the precipitation water evaporates from the Earth’s land masses. In Central Europe, this figure is 60 to 80 per cent (62 per cent in Germany). Even in the light of considerable regional and seasonal differences, these figures show the extraordinary significance of evaporation in the hydrological cycle.

In the Hydrolonical Atlas of Germany (BMU, 2000) the water balance components for the climatological normal value period of 1961–1990 and further additional information on hydrography, soil, land use, etc. relevant to hydrological and water management problems are charted. In DVWK (1996) a summary of the procedures used in Germany to measure and compute evaporation with special consideration given to the requirements arising from hydrological and water management practice is presented.

The following descriptions of methods of measuring and computing evaporation concentrate on the procedures used in Germany.

3.1.2 Definitions

The total evaporation consists of the following elements:

(a) Evaporation (physical processes):

Evaporation from the Earth’s surface not covered with vegetation (bare soil, snow and ice areas), from precipitation retained on plants, buildings, roads, etc. (interception evaporation) and from open water surfaces;

(b) Transpiration (plant-physiological processes):

Evaporation from plants.

The term evapotranspiration, i.e. the sum of evaporation and transpiration, combines the partial processes of evaporation normally taking place simultaneously on a certain area of the Earth’s surface. In hydrology and water resources management, the areal evaporation — the average value, for example — over the area of a catchment basin with its different kinds of land use, is of special interest (see Subchapter 3.5).

In the scientific literature on evaporation modelling, the terms potential evaporation and actual evaporation are frequently used. However, the terms are not always used clearly or consistently. In this report, the following definitions are used (DIN 4049, 1994; DVWK, 1996):

(a) Potential evapotranspiration: evaporation from an area of natural vegetation with given meteorological conditions and an unlimited supply of water in the soil. On account of this
prerequisite, the potential evaporation is a fictitious value computed from meteorological data that evaluates sites, regions and periods of time according to their evaporation-climatic conditions.

For an unlimited supply of soil moisture, the (maximum) amounts of evaporation from plants more or less deviate from potential evapotranspiration. The extent and signs of the deviations depend on the kinds of plants and their phenological stage of development. In order to differentiate exactly the quantities used in evaporation modelling, it seems appropriate to introduce the term maximum evapotranspiration, a parameter that is characteristic of plants, as an additional term alongside potential evapotranspiration, the meteorological parameter.

(b) Actual evapotranspiration: evaporation from an area of natural vegetation with given meteorological conditions without the above restriction of an adequate supply of water to the plants, i.e. with the actual soil water supply.

3.1.3 Determination of evaporation on the basis of the water balance equation

Because the evaporation process depends on the specific characteristics of the individual kinds of surface, a direct measurement of evaporation from a heterogeneously used area is not possible. Only an estimation of the areal evaporation average of many years can be obtained fairly easily from the difference between the areal precipitation and runoff, if the storage element ∆W in the water balance equation (Equation 3.2) becomes negligible and if there are reliable runoff data from the catchment area (Subchapter 3.5). All direct measuring procedures determine the amount of evaporation from individual, defined kinds of surfaces and are exact only for these.

Listed below are some of the most common measuring instruments and procedures that are used for solving hydrological and water resources problems or for the verification and validation of evaporation models.

Atmometers/atmographs (Piche atmometer, Czeratzki disc)
The atmometers/atmographs use filter paper or porous ceramic discs as transducers. Therefore, a realistic link to evaporation processes on natural surfaces does not exist. The evaporation losses from these surfaces, which are constantly kept humid, correspond neither to the evaporation from natural surfaces nor to the potential evaporation. Because of their relatively simple measuring techniques, such instruments are used to record relative values of evaporation. When using the required correction procedures it should be taken into account that these are only valid for the site and climate conditions for which they have been derived.

Evaporation pan (Class A pan, land and raft evaporation pan, GGI-3000)
The evaporation pans mostly used worldwide also on a network scale differ in construction (size, material) and method of installation (standing on the ground surface, embedded in the soil or set up on an anchored raft on a lake). The evaporation losses are determined by measuring the changes in water level or in weight, or by measuring the quantity of water refilled, taking precipitation into consideration (separate measurement with a precipitation gauge) (DVWK, 1990; WMO, 1994a).

The construction and installation of the pan influence considerably the heat balance of the body of water in the pan as well as the advective component of the heat balance. Therefore, differences in the temporal course (daily pattern, annual pattern) as well as in the amount of evaporation losses can be noted between the various types of pans. Pan evaporation is used as a relative value for estimating the evaporation from natural waters or the potential evaporation adapted to the characteristics of the instruments and the evaporation climate. With raft evaporation pans, there is an approximation between the heat balance of the pan water and that of the lake. These evaporation values are used for the derivation and the parameterization of evaporation formulas for the evaporation from bodies of water (Richter, 1969).

Lysimeter (non-weighing and weighing of the most different construction types) (DVWK, 1980; WMO, 1994a)
These instruments measure the actual or, in the case of water-saturated soil, the maximal evapotranspiration (including interception evaporation) of the plant crop and the soil substrate. In addition, the precipitation should be measured in a precipitation gauge.

Non-weighing lysimeters (percolation lysimeters) are used as small instruments (grass-covered) with comparatively simple measuring techniques as relative instruments. Another important field of application for non-weighing instruments is the use of large lysimeters for water balance investigations of forest sites for which, due to the depth of the root zone, the installation of a weighing lysimeter poses a problem. The evaporation is determined from measured values of the amount of precipitation and the percolation as a long-term mean value assuming a negligible change in water supply ∆W in the soil (see Equation 3.2).

The installation, running and maintenance costs of weighing lysimeters are very high and are therefore only used for research purposes, e.g. for the derivation and parameterization of computation procedures for evaporation for hydrological practice. Modern precision scales allow a high-time resolution including data on the daily pattern of the evaporation.

The vegetation around the lysimeter should corresponds to that of the lysimeter over the largest possible area. This requires, for example, a homogenous agricultural or forestry cultivation.

The most important causes of errors in lysimeter measurements lie in the accumulation of seepage water on the floor of the lysimeter, the vertical flow of water along the wall of the lysimeter, disturbance of the soil structure and growth disturbances of the plant crop. These problems can be controlled by taking great care in designing, installing and maintaining the lysimeters (Lützke, 1965; Olbrisch, 1975).

At stations with weighing lysimeters and large comprehensive lysimeter measurements, observation programmes are normally carried out to record meteorological data, soil characteristics and plant crop characteristics (phenological phases, crop density, cultivation methods, yields, etc.). These complementary observation programmes are of prime importance for the generalization of lysimeter measurements as the evaporation data are only valid for given meteorological, soil and plant conditions.

Determination of evaporation with hydrographs of the soil water content
This is a method generally used for scientific investigations that can be carried out at changing sites (unlike weighing lysimeters). Tensiometers, neutron probes or time-domain-reflectometry
(TDR) probes are used to measure the vertical profiles of the soil water content. On the basis of the water content profiles, the upward-moving (evaporation) water flow in the soil is separated from the downward-moving (percolation) (Malicki et al., 1992). This method also gives evaporation values for individual sites. For a generalization of the results, additional comprehensive observations of the meteorological, soil and vegetation conditions are required.

3.1.4 Determination of evaporation on the basis of the energy balance equation and the water vapour transport

The methods described below for the determination of evaporation from meteorological data are mainly used for research purposes because they require a great deal of technical measurements and place heavy demands on the instruments and the processing of the measured values. The results are used, inter alia, for parameterizations of the evaporation processes on the basis of meteorological data from the standard measuring network.

Turbulence correlation method (eddy-flux, eddy-correlation) (Swinbank, 1951)

The evaporation is determined from the turbulent vertical water vapour flow in the layer of air near the ground. The method requires synchronous measurements of the air density, vertical wind velocity and specific humidity of the air at only one altitude. The considerable efforts required for measurement can be reduced by the evaporotron first presented by Dyer and Maher (1965). Nevertheless, the eddy-flux method is not one of the standard methods for measuring evaporation. Roth (1989) recommends using this method from a low-flying aeroplane to determine areal means for selected hours.

Gradient methods

The exchange procedures according to Sverdrup (1936) and Thornthwaite and Holzmann (1942) require measurements of the vertical profiles of meteorological data. According to Sverdrup, the energy balance equation (Equation 3.1) is modified by way of the so-called Bowen ratio \( \beta \) (Bowen ratio method):

\[
\beta = \frac{H}{LE} = \frac{\gamma(T_2 - T_1)}{\beta e_2 - e_1}
\]  

(3.3)

with \( \gamma = 0.65 \) hPa K\(^{-1} \) (psychrometer constant).

This ratio is derived from the vertical temperature and humidity exchange with equal diffusion coefficients and requires measured values of the air temperature \( T \) and of the vapour pressure \( e \) in two altitudes (index 1 and 2) over the evaporating area. The lower measuring altitude should be as low over the plant crop as possible. For areas of water, the water surface temperature and/or the saturation vapour pressure is used with index 1.

The well-known Sverdrup formula for the evaporation heat flux (Equation 3.4) is derived from Equation 3.1 together with Equation 3.3:

\[
LE = \left( Rn + G \right) / \beta \left( T_1 + \gamma x (\Delta T / \Delta e) \right)
\]  

(3.4)

\( \Delta T \) and \( \Delta e \) here are the air temperature and vapour pressure differences of both altitudes derived from the above-described gradient measurements.

The procedure according to Thornthwaite and Holzmann is based on exchange equations for the vertical turbulent transport of water vapour (Equation 3.5) or heat and of impulse in the corresponding formulation:

\[
E = - \rho \frac{q}{e} \frac{\partial e}{\partial z}
\]  

(3.5)

Here the evaporation \( E \) is given as water vapour flow (per area and time); according to the measuring of the specific humidity \( q \) (temporal mean value) at two altitudes the differential quotient \( \partial q / \partial z \) is replaced by the difference quotient. What makes the evaluation of this equation problematic is the determination of the diffusion coefficient like \( \beta \) (Equation 3.5), which depends on subsoil characteristics, on altitude \( z \), on wind velocity and on the stability of the atmospheric stratification. The influence of the ground requires a sufficiently large, homogeneous area as a suitable measurement site. The results of extensive experimental tests into the impact of subsoil roughness and into atmospheric stratification have been presented in the last decades (Monteith, 1976; Foken, 1990).

Energy balance method

Evaporation is calculated as the remainder of the energy balance (Equation 3.1) after all the other components have been determined by measurement or computation.

There are special measuring instruments (e.g. balance meter, pyranometer, etc.) and computation methods (e.g. Ångström equation for global radiation) for the determination of the radiation balance \( Rn \) or its long-wave or short-wave components. Because of the empirically-derived factors, the use of such computation methods has to be limited to the conditions of the radiation climate for which they have been specially developed. DVWK 1996 contains a list of the radiation formulae suitable for special application in evaporation models in Germany.

The soil heat flux \( G \) is measured with the help of heat flux plates or is computed from measured values, possibly available on a network scale, of the soil temperature at various depths with the help of the heat conductivity equation. For certain problematic positions and site conditions the soil heat flux can be considered negligible. Some equations estimate the soil heat flux as a percentage of the radiation balance values (see Høying-Huene, 1983a; DVWK, 1996).

For bodies of water, the change in heat content, i.e. the temporal change in the amount of heat stored in the body of water, comparable to the soil heat flux of the ground, is determined by measuring the vertical distribution of the water temperatures. In order to obtain reliable data, the annual course of the thermic stratification has to be recorded for deeper water. Owing to the high heat capacity of water and the generally large mass of water in lakes, significant amounts of energy are stored in the body of water and then released during the course of the year’s seasonal cycle. As a result of this, evaporation losses from the water surface can differ considerably from the evaporation from the surrounding land areas depending on the depth of the lake and on the meteorological conditions at the site.

The two methods described above are available for the separation of the evaporation heat flux from the sensible heat flux:

(a) Direct measurement of the sensible heat flux with the help of the turbulence correlation method (eddy-flux);

(b) Separation of both heat fluxes with the help of the Bowen ratio \( \beta \) (Sverdrup method).

Other heat fluxes involved in the energy balance (e.g. heat storage in plant crop, heat exchange on the bottom of bodies of
water) do not usually have to be taken into consideration. However, lateral energy advections which on land are recorded only with a great deal of technical measurements can reach a significant order of magnitude (Werner, 1987). The energy advection in a body of water (e.g. dammed reservoirs with deep water outlets) is, in comparison, easily and accurately determined by measuring the amounts of inflowing and outflowing water and the corresponding water temperatures.

**Use of remote-sensing data**

The radiation balance \( R_n \) and the temperature \( T_0 \) of the Earth’s surface are determined by satellite measurements. With these data, the evaporation heat flux can be established on the basis of the energy balance equation (Equation 3.1), whereby the soil heat flux \( G \) is, as described above, normally estimated from the radiation balance and the sensible heat flux \( H \) is determined from the measured values of the land-surface temperature \( T_0 \) and the temperature \( T \) of the air near the ground (site measurements) according to \( H = c_p/\rho a(T_0 - T) \). Here, \( c_p \) is the specific heat of the air and \( a \) is the so-called bulk surface resistance of the land surface from the Penman-Monteith formula (see Subchapter 3.1.5.3). With the use of standard values for \( a \) the conditional equation for the sensible heat flux \( L \) (Löpmeier, 1991) is reduced to \( H = at(T_0 - T) \). The coefficient \( a \) is empirically determined on the basis of satellite measurements (Jackson, Reginato and Idso, 1977; Seguin and Itier, 1983; Seguin, 1989).

According to the above formulations, the energy balance equation (Equation 3.1) assumes the following form for the computation of the evaporation heat flux LE:

\[
R_n + b R_n + a (T_0 - T) + LE = 0 \tag{3.6}
\]

**3.1.5 Estimation of evaporation on the basis of data from the meteorological standard measuring network**

Practical applications usually require procedures that can estimate rapidly and reliably the evaporation from land and/or water without special measurements and measuring networks. In the following paragraphs, not only are theoretical procedures described, but also those with empirical and semi-empirical equations that essentially rely on data from the meteorological standard measuring network and on non-meteorological data available, for instance, from tabular compilations and maps. Thus, long time series for the water balance component evaporation, that are of interest for many hydrological and water resources problems, can also be established on the basis of meteorological standard data.

**3.1.5.1 Computation procedures for evaporation from water bodies**

The aerodynamic or Dalton procedure is an empirical-statistical procedure that in the form of the Equation 3.7 has found wide acceptance, even internationally, for the estimation of evaporation losses \( E_w \) from areas of water (WMO, 1966b; Schrödter, 1985):

\[
E_w = f(v) (e_f(T_w) - e) \tag{3.6}
\]

Here \( e_f(T_w) \) is the saturation vapour pressure, with \( T_w \) being the temperature of the water surface and \( e \) the vapour pressure of the air, measured at a suitable weather station.

For the wind function, \( f(v) \), the following equations are usual:

\[
f(v) = a + b v^c \tag{3.8}
\]

or

\[
f(v) = m v \tag{3.9}
\]

The parameters \( a, b, c \) or \( m \) (mass transport coefficient) are derived empirically; \( v \) usually refers to a height of 2 m that is effective in the evaporation process, so that a reduction in the height of the measurement of the data available from weather stations has to be made.

The parameters of the wind function found in the literature understandably differ considerably one from the other since they are strongly influenced by the climatic and physiographic conditions under which they were derived. By using locally suitable parameters for the wind function, Equation 3.7 gives sufficiently accurate results for the daily values of the amount of evaporation.

If an adjusted wind function and/or wind data of a suitable weather station are not available, evaporation formulae can be used that do not take account of the influence of the wind and produce empirically a relation between the evaporation losses of the body of water and the vapour pressure gradients at the water surface \((e_f(T_w) - e)\) (Equation 3.10). Furthermore, evaporation formulae have been empirically developed which include the global radiation \( G \) as well as the vapour pressure gradients, and which can be regarded as a simplified version of the combination procedure described below (Richter, 1977):

\[
E_w = a' (e_f(T_w) - e) + b' \tag{3.10}
\]

\[
E_w = a'' (e_f(T_w) - e) + b'' G + c'' \tag{3.11}
\]

In the practical application of computing Equations 3.7 to 3.11 as well as of the combination procedure described below, the problem is often the unavailability of measured data for the water surface temperature \( T_{wo} \). Richter (1977) developed a procedure with which the water surface temperature of lakes can be computed from measured values of air temperature. In the annual course of these two values, a phase lag can be observed which is dependent on the water volume of the lake and parameterized by the average depth of water.

With a corresponding equation, the mean vertical water temperature in the lake can be calculated and this is required for the computation of the change in heat content in the energy balance procedure.

**Energy balance and combination procedure**

The computation of the evaporation from the energy balance equation with the help of the Sverdrupt procedure has already been described in Subchapter 3.1.4. The application of this method is indicated whenever there are no suitable empirical equations according to Equations 3.7 to 3.11 due to evaporation climate and site conditions. These conditions include, for example, a significant horizon superelevation that restricts the transport of atmospheric humidity or energy advection in the body of water (thermal pollution). The energy balance method is also recommended when a high degree of accuracy and a time resolution of the evaporation values are required. Measured values of the water surface temperature are not needed for this procedure because the balance equation is iteratively solved using an initial value of the surface temperature.
The demands made of meteorological input data are greater than with the aerodynamic procedure. However, the energy balance method is also useful for practical purposes if simplified empirical equations can be used for the computation of the individual balance components. The adaptation of such empirical components to the actual site conditions has to be checked for the case of application.

**Penman procedure**

The combination equation (Equation 3.12) derived from the energy balance and the mass transport — as described by Penman, 1948 — with energy balance term \(E_R\) and ventilation humidity term \(E_A\) represents, on the basis of its purely physical approach, the theoretically most mature evaporation formula:

\[
E_{\text{PENMAN}} = \frac{s}{s + \gamma} E_R + \left(\frac{\gamma s}{s + \gamma}\right) E_A \tag{3.12}
\]

where \(s\) represents the gradient of the curve of the saturation vapour pressure and thus a temperature function, and \(\gamma\) is the psychrometer constant.

With the simplifications and estimations introduced by Penman, e.g. concerning the aerodynamic roughness of the surfaces observed of water or short-cut grass, and with the application of the Dalton equation (compare Equation 3.7), there results from the original theoretical equation a formula which makes do with generally available meteorological measurement data.

For the computation of evaporation from an open area of water, the Penman equation (Equation 3.12) assumes the following form:

\[
E_w = \left(\frac{s}{s + \gamma}\right) R_nL + \left(\frac{\gamma s + \gamma f(v)}{s + \gamma}\right) (e_S(T_w) - e) \tag{3.13}
\]

\(R_nL\) is the radiation balance of the water surface, expressed as the equivalent of evaporation, and \((e_S(T_w) - e)\) is the vapour pressure gradient at the water surface.

Equation 3.13 requires that heat storage and energy advection do not take place in the water body under consideration. This requirement is not satisfied in natural waters since they store considerable amounts of energy in the warming-up phase in spring and summer which are then released again into the atmosphere during the cooling phase in autumn and winter.

The Penman formula is therefore not suitable for a direct calculation of the evaporation losses from natural waters. Its main field of application is the use as potential evaporation, described in the following section.

### 3.1.5.2 Computation procedures for potential evaporation

Potential evaporation is widely applied in hydrological and water resources practice as well as in agricultural consultation practice (e.g. sprinkler irrigation control). It is an initial quantity in models for the computation of the actual evaporation or in models for areal water balances. In addition, together with precipitation data, it is used to characterize the hydroclimate of areas and/or periods of time. The climatic water balance — the difference between the amounts of precipitation and potential evaporation — provides information on the climatically-dependent excess or deficits in the water regime situation and in their regional distribution. The actual evaporation or the balance from the amounts of precipitation and actual evaporation is determined by these hydroclimatic conditions and, furthermore, by the land use and soil type.

Penman’s combination equation (Equation 3.12) discussed in the previous section is a procedure for the computation of potential evaporation; it is founded on theory and simplified by empirical equations, and thus is also suitable for practical application. The Penman equation reads as follows when related to wet, low grass cover:

\[
ETP = \frac{s}{s + \gamma} (R_n + G)/L + \left(\frac{\gamma s + \gamma f(v)}{s + \gamma}\right) (e_S(T_L) - e) \tag{3.14}
\]

\(R_n\) is the radiation balance of the grass cover and \(G\) is the mostly negligible soil heat flux. Dividing these by the latent heat of evaporation \(L\) results in the evaporation depth in millimetres. The temperature of the evaporating surface and, thus, also its saturation vapour pressure can only be determined by complicated procedures (e.g. remote sensing) and are not usually known. For the computation of radiation values dependent on temperature or on the vapour pressure gradients in terms of ventilation, the temperature \(T_L\) from the meteorological standard network and the saturation deficit of the near-ground air \((e_S(T_L) - e)\) is used in approximation.

When using the Penman equation, the adaptation of its empirical components to the site conditions should be checked. Various procedures and equations are given in the literature for the computation of the radiation balance components in \(E_R\) and for the wind function \(f(v)\). In order to use the Penman equation worldwide, Doorenbos and Pruitt (1977) developed a correction factor which takes into account the different climatic conditions. Bultot and Dupriez (1985) generalized the Penman equation with the help of a transfer factor which depends on the type of vegetation (i.e. albedo). Jaworski (1985) introduced the roughness length of the crop into the Penman equation and tested it up to a time period of one hour.

Apart from the comparatively exacting versions (Equations 3.13 and 3.14) of the combination equation, a number of simpler estimation procedures for potential evaporation are used worldwide in water balance models. The computation procedures in use for potential evaporation ETP can be divided into:

(a) Simple, empirical-statistical procedures which have mostly been derived on the basis of measured values of evaporation (Subchapter 3.1.3) and one or several of the meteorological standard quantities. This type of procedure includes, for example, the evaporation equations of Thornthwaite (1948), Blaney and Criddle (1950), Haude (1952; 1958) and Turc (1961) as well as those of Turc and Ivanov presented in Wendling, Müller and Schwede (1984);

(b) Physical semi-empirical procedures on the basis of Penman’s combination equation with the inclusion of empirical formulæ for quantities not available in the meteorological standard measurement programme (see, for example, Makkink (1957) and Priestley and Taylor (1972) as well as Turc and Wendling in Wendling, Schellin and Thoma (1991)).

Detailed descriptions of these procedures are given in WMO (1966b) as well as in Schröder (1985) and DVWK (1996) taking into account further developments of some of the above procedures.

The water balance models and models for actual evaporation used in Germany mainly apply a Turc or Haude formulation for the model input potential evaporation. For both
procedures, so-called crop coefficients, that record the influence of
the plant crop and its phenological development within a year on
the maximal evaporation, have been developed. In order to take into
account the soil evaporation of areas only partly covered with
agricultural crops, Löpmeier (1987) divides the factors in the Haude
equation into a soil and a plant factor.

The empirical derivation of the factors in the
computation procedures for potential evaporation and the inclusion of
different meteorological measurement values leads to a
considerable disparity in the computation results of these
equations when applied to one and the same site. Comparative
computations for climatic conditions in Germany are presented in
Schröder (1985) and DVWK (1996). Choisnel de Villele and
Lacroze (1990) carry out comparative calculations with numerous
equations and equation variants for 20 stations in Europe and
arrive at an evaporation-climatic valuation of these equations.

Because of the great number of procedures used and the
differences in their computation results, data on potential
evaporation must be accompanied by a description of the
computation procedure used. For practical applications in water
balance models, care has to be taken that the input of the potential
evaporation is calculated according to the same procedure as for the
derivation of the water balance model.

### 3.1.5.3 Computation Procedures for Actual Evaporation

From Areas of Land

The amount of actual evaporation depends, on the one hand, on the
hydroclimatic site conditions that are described by the depths of
precipitation and potential evaporation and, on the other hand, to a
great extent by the specific characteristics of the soil and the plant
crop. In order to be able to take account of these influences
emanating from soil and vegetation, the actual evaporation has to
be calculated on the basis of areal units, so-called hydrotopes, which
can be considered more or less homogeneous as to soil and
vegetation.

A much applied formulation which is used both in simpler
methods for estimating actual evaporation as well as in complex
evaporation models can be expressed in a general form by the
following equation:

\[ \text{ETA} = k \times \text{ETP} \]  

(3.15)

For example, the annual development of quotients from
actual evaporation and of potential evaporation for the most
important agricultural land uses — according to Haude — as a
function of soil water content were empirically determined and
given in tabular form by Sponagel (1980). These tables allow a
rapid, rough estimation of monthly values of the actual evaporation of
the field crops in question. Owing to the empirical derivation, a
generalization is not necessarily obvious.

Instead of the quotient \( k \), complex evaporation models use
functional relations \( R \) between actual and potential evaporation
which are usually referred to as reduction functions (of the potential
evaporation). The relation between actual and potential evaporation
in an observed time interval depends essentially on the soil water
content \( W \) in the root zone, which is actually available for the
evaporation process and which is balanced for the time steps of the
evaporation model. Especially with a high potential evaporation, the
reduction of the potential evaporation also shows a dependence on
the value of the potential evaporation itself (Morton, 1983;
Hoyningen-Heune, Braden and Löpmeier, 1986). The following
equation then becomes:

\[ \text{ETA} = R(W, \text{ETP}) \times \text{ETP} \]  

(3.16)

with \( R(W, \text{ETP}) \) being the reduction function of the potential
evaporation. The maximal evaporation that results from the
inclusion of the plant coefficients for the computation procedure of
the potential evaporation should be substituted as ETP in Equation
3.16 (see Subchapters 3.1.2 and 3.1.5.2).

The dependence of the reduction function on the soil
moisture is described by various authors with step functions
(Renger, Strebel and Giesel, 1974), hyperbolic (Wendling, Müller
and Schwede, 1984; Klämt, 1988) or exponential functions (Disse,
1995). These functions are, as a rule, function systems whose
coefficients depend on the parameters of the water binding in the
soil. With these function types, the characteristic of the plants to
continue evaporating potentially even when the soil moisture drops
to below the value at field capacity is recorded. Only when the soil
water content drops below a certain limit which, depending on the
kind of soil, can sink to about 70 per cent of the available field
capacity, there is a greater reduction in the actual evaporation than
in the potential evaporation.

In order to record the complex influences stemming from
soil and crop characteristics on the actual evaporation, water balance
models are required that balance in time steps the water content in
the root zone from precipitation input and evaporation loss and take
into consideration the partial components of the evaporation
process — transpiration of the plants, evaporation of the intercepted
precipitation, evaporation from bare soil, etc. With increasing time
resolution of the target parameter actual evaporation, the required
number of necessary parameters and partial models to be included
increase, because the nonlinearities of, for example, the
phenological phase of plants, the plant physiological processes and
the transport process of water in the soil should not be described by
simplified empirical formulae.

**Interception evaporation**

When the mean values of the actual evaporation are computed, the
part of the interception evaporation is usually implicitly included in
the model. For time steps of less than one month, the use of a partial
model to take into account the evaporation of the intercepted
precipitation (or irrigation water) is recommended.

The water clinging to the plant surface following a
precipitation event forms the interception storage which evaporates
directly into the atmosphere without having benefited the soil water
reserves. As long as the plant surface is dampened, no stomatal
transpiration takes place. However, under the same weather
conditions, transpiration and interception evaporation have different
intensities (Szeicz, 1970). The evaporation from agricultural crops
(maize, grain) in the maturity phase consists mainly of the
component interception evaporation while the transpiration tends to
zero.

Complex interception models record the processes of
filling and emptying the interception storage with reference to the
capacity of this storage and the actual weather conditions, i.e. the
frequency and abundance of the precipitation events and the
potential evaporation (Rutter, Morton and Robins, 1975; Braden,
1985). The capacity of the interception storage depends on the
structural arrangement of the plant crop — height of growth, crop
density, roughness of the plant surface, geometry and arrangement of the foliage, etc. Especially with forests of multi-storey structure, the interception processes can be estimated only with the aid of complicated models. If the interception evaporation is considered only as a partial process of the total crop evaporation in a soil water balance model, then simplified regression models are usually applied. Such formulae compute the interception evaporation with reference to the storage capacity (leaf area index) and the amounts of precipitation and potential evaporation, which are already used as input in the soil water balance model (Hoyningen-Heune, 1983b; Thompson, Barrie and Ayles, 1981).

Evaporation from sealed urban areas
The evaporation from sealed areas is analogous with the process of the evaporation of intercepted water on plants. The interception evaporation model used for plant covers can be utilized for the computation of evaporation losses from sealed areas if their storage capacity for precipitation water is inserted.

While numerous usable measurement results for the interception capacity of agricultural and forestry crops are found in the literature, little experience has been gained in the storage capacity of sealing material used in towns and industrial areas. The interception capacity of many sealing materials is probably very small (e.g. asphalt); less than 0.5 mm can be taken as an approximate value. For porous material (e.g. bricks), the capacity is considerably larger. Apart from the characteristics of the material, the state of the sealing (existence of gaps and hollows, angle of inclination in the case of roofs) is important for the storage capacity or evaporation losses. Wessolek et al. (1990) gives some empirically-determined data of storage capacity.

Taken together, it can be assumed that the amount of evaporation from sealed areas is very small compared to that from areas covered with vegetation. This difference in the depths of evaporation is, however, of particular interest for certain tasks, e.g. the evaluation of changes in runoff as a result of increasing sealing, or the calculation of storage basins.

Bagrov procedure
With the help of the Bagrov procedure, the mean annual values of the actual evaporation from land areas, which are required for many fields of application in hydrological and water resources practice, can be calculated taking the type of soil and land use into consideration:

\[ \frac{d \ ETA}{d \ P} = 1 - (ETA/ETP)^n \]  

(3.17)

The data required to determine the mean annual amount of evaporation ETA from a hydrotope characterized by the type of soil and crop are the mean annual depths of precipitation P (including correction of the systematical measurement error) and of the potential evaporation ETP which describe the hydroclimatic conditions of the site. Furthermore, a Bagrov or effectivity parameter n valid for the unit of area is included in the computation. This records summarily the influences of the soil and plant crop on the evaporation.

The differential equation (Equation 3.17), which can only be solved numerically, was further developed for practical application by Glugla (see Dyck and Peschke, 1983). Apart from the numerical method of solution, nomograms were set up. With these, it is possible to determine the effectivity parameter n from the type of soil and land use and, subsequently, to determine the actual evaporation from the amount of precipitation, amount of potential evaporation and effectivity parameter.

On the basis of extensive evaluations of lysimeter measurements, the authors derived effectivity parameters for a great number of possible land uses in a test area or for non-meteorological site factors. For example, with the parameter n, the sealing of the land surface in populated areas, the age of forest stock or the yields of agriculturally-used areas can be taken into account when considering their impact on the amount of evaporation. Furthermore, there are instructions for the application of the Bagrov model with regard to the irrigation of arable land and for sites affected by groundwater. The Bagrov model forms the methodical basis (Glugla et al., 1999) for the preparation of the maps “actual evaporation” and “runoff” in the Hydrological Atlas of Germany.

Penman-Monteith formula
The further development of the Penman combination equation (Equation 3.12) by Monteith (Thom, 1975; Monteith, 1976) includes the specific influences of the plant crop on the humidity exchange with the help of the so-called crop resistances ra and rs. The prerequisite of a constantly wet surface as for the Penman equation is no longer necessary, so the actual evaporation ETA of a plant crop is computed as follows:

\[ ETA = \frac{s(Rn + G)/L + \rho c_p (e_s - e)/ra}{s + \gamma (1 + rs/ra)} \]  

(3.18)

Apart from the quantities of the Penman equation, Equation 3.18 contains the crop resistances ra and rs and the density \( \rho \) and specific heat \( c_p \) of the air.

The bulk surface resistance ra states more precisely the empirical wind function of the Penman equation. ra depends on the height, density and structure of the plant crop and is determined from measurements of the vertical wind profile. The bulk stomata resistance rs includes the total water transfer from the pores of the soil through the intercellular spaces and stomata of the plants into the atmosphere and depends for one on the soil water content and for the other on the physiological control processes that are specific to each kind of plant. rs becomes 0 when only the film of water on the leaves, the interception water, evaporates. In this case, a stomatal transpiration does not take place and the Penman-Monteith formula changes into the Penman equation for the evaporation from an open body of water (Equation 3.13). With sufficient soil water supply in the root zone (prerequisite of the potential evaporation), the bulk stomata resistance assumes a value specific for plants of \( rs_{min} > 0 \).

The empirical determination of rs as a function of soil and plant conditions requires complicated tests with weighing lysimeters. Monteith (1965) refers to the clear diurnal pattern of rs during the vegetation phase. For this reason, the actual evaporation should be calculated in time steps of less than one day. A distinct annual pattern of mean rs values for England are revealed by Wales-Smith and Arnott (1985). Available data for rs in the literature vary immensely and indicate the necessity of further research on this quantity.

Equations for the parameterization of ra and rs are found, for example, in Thompson, Barrie and Ayles, 1981; Brutsaert, 1982; Hoyningen-Heune, 1983a; Bultot and Dupriez, 1985; Wicke, 1988.
Grass reference evapotranspiration

A special application of the Penman-Monteith equation (Equation 3.18) is the so-called grass reference evapotranspiration developed by Allen et al., 1994. This is defined as evaporation from a permanently homogeneous grass crop, 0.12 m high, with no water stress (soil water content greater or equal to 70 per cent of the available field capacity). With this prerequisite, the grass reference evapotranspiration is equal in importance to potential evaporation. Following extensive research, the authors determined the values for the crop resistances in the Penman-Monteith equation with the said conditions as follows:

\[ r_{s_{\text{min}}} = 70 \text{ s m}^{-1}; \, r_{a} = 208 \text{ s m}^{-1} \text{ at a wind velocity of } 1 \text{ m s}^{-1}. \]

The maximal amounts of evaporation (i.e. occurring with sufficient soil water content) of other kinds of plants normally deviate from the amount of the grass reference evapotranspiration. The application of the grass reference evapotranspiration as a hydrometeorological reference quantity for the estimation of the maximal plant evaporation requires a crop coefficient which, for agricultural crops, has a distinct annual pattern corresponding to the phenological crop development.

The practical importance of the grass reference evapotranspiration lies in the fact that the potential evaporation, which is defined only qualitatively and is therefore indistinct, is replaced by a quantity which is exactly defined by means of set crop resistances. The problem described above of differing results produced by using different computation procedures for potential evaporation is thus eliminated. As opposed to the advantage of a defined potential evaporation, the data requirements of the Penman-Monteith formula for practical applications (evaporation mappings, long time series of evaporation, etc.) are excessive. Wendling (1995) tried to calibrate simpler empirical procedures for potential evaporation (Subchapter 3.1.5.2) with the help of the grass reference evapotranspiration. Such a calibrated formula was used to prepare the evaporation maps in the Hydrological Atlas of Germany (BMU, 2000).

3.2 HEAVY RAINFALL POINT STATISTICS

Many hydrological problems can be solved only with the aid of climatological fundamentals. This means the concerted statistical evaluation of series of meteorological data as long as possible. The statistical evaluation of extreme values of heavy rainfall events, for instance, is required for the entire sector of planning and design for the construction or redevelopment of hydraulic structures, such as the dimensioning of urban sewage networks or sewage treatment plants but also for the construction of retention basins as flood alleviation structures in small and large catchment areas. Heavy rainfall is a form of precipitation events which, compared to their alleviation structures in small and large catchment areas. Heavy rainfall is a form of precipitation events which, compared to their occasional and short duration (showers) with usually high, sometimes rapidly changing, intensity and a narrowly limited precipitation field and as long-lasting precipitation events (continuous rain) with low, usually hardly changing, intensity and an extended precipitation field. The mechanisms causing the development of precipitation fields vary accordingly (Chapter 5).

A statistical evaluation of the extreme values of such rainfall events is made following the selection of annual or partial series and is adjusted through mathematical distribution functions (WMO, 1981c). Such evaluation permits the computation of the statistical mean of the heavy precipitation amount to be expected as a function of the rainfall duration (minutes to days) and the recurrence interval (annuity). No certain conclusion can be made for recurrence intervals (in years) more than three times the number of measured years. For this, a 30-year series of precipitation amounts must be available to determine a recurrence interval of almost a hundred years. The heavy precipitation point statistics gleaned from a station are valid in the case of short-duration precipitations, mostly only for areas of 1 km², and in the case of long-duration precipitations for areas of approximately 20 km² around the station.

These point results can be transferred to other locations by various regionalization methods; however, knowledge about existing relationships between extreme value distributions and available climate analyses as well as correlations orography should be taken into account (Subchapter 3.3.3). This applies, for example, to the relationship between heavy daily precipitations and the isohyetal analysis of average annual precipitation amounts or to the derivation of showery precipitations with the aid of the exposure of a location (altitude gradient of orography as well as windward and lee-side influences).

In hydrological practice, however, a relationship must be established between the precipitation amounts from the point determinations of heavy rainfall statistics and the runoff from the catchment basin. Consequently, in this case too, the areal precipitation amount must be known. Thus, the question arises as to the conditions under which areal precipitation amounts can be obtained from point statistics. The main problem in estimating areal precipitation amounts through the extrapolation of point results lies in the spatially limited extent of the homogeneous or quasi-homogeneous precipitation fields for showery or continuous rainfall as described above.

In comparison to the point heavy rainfall statistics, the spatially averaged intensity of the precipitation events decreases with increasing areal extension. In order to take that areal effect into account, many depth-area-duration relationships of the precipitation were developed in the form of areal reduction curves (Table 3.1 and Figure 3.1). In this context, the factor by which the amount of the statistically-determined point precipitation of a given duration and recurrence interval is to be multiplied to obtain the areal precipitation depth for a given area for the same duration and recurrence interval is designated as a reduction factor. As some investigations show, for certain regions, characteristic reduction factors exist which vary mainly only in relation to the size of the area and the duration of the precipitation. A synopsis of the results of the individual investigations compiled in the two figures for regions in which the climates are not at all uniform shows altogether a relatively good agreement (Deutscher Wetterdienst, 1986).

However, in dealing with practical hydrological problems, it must be taken into account that the size of the area and the precipitation duration are not independent of each other. Thus, the reduction factor mostly has a value of around 0.9 to 1.0. Considering the systematic errors in precipitation measurements as well as the uncertainty of statistically determined point precipitation amounts, a reduction can usually be dispensed with.
3.3 REGIONALIZATION IN HYDROMETEOROLOGY

3.3.1 Introduction

In conventional measuring networks, climatic values are obtained only at points of irregularly distributed individual stations. For each determination of areal values, these point results are to be transferred to the area by means of areal analysis. Since the beginning of meteorological measurement, attempts have been made to represent these climatic elements in the form of maps. The first Climate Atlas of Germany appeared in 1921 (Hellmann et al., 1921). Although its database was very poor, it nevertheless contained a high proportion of empirical values and physical considerations concerning atmospheric processes. The aim of objective regionalization methods with the aids available today must therefore be to convert subjective methods of transferring point results to the area based on empirical methods as far as possible to objective computational methods with the development of an expert system, taking into account physical processes and interdependencies.

Table 3.1

<table>
<thead>
<tr>
<th>Duration</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>30</th>
<th>100</th>
<th>300</th>
<th>1000</th>
<th>3000</th>
<th>10000</th>
<th>30000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 minute</td>
<td>0.76</td>
<td>0.61</td>
<td>0.52</td>
<td>0.40</td>
<td>0.27</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>—</td>
</tr>
<tr>
<td>2 minutes</td>
<td>0.84</td>
<td>0.72</td>
<td>0.65</td>
<td>0.53</td>
<td>0.39</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>5 minutes</td>
<td>0.90</td>
<td>0.82</td>
<td>0.76</td>
<td>0.65</td>
<td>0.51</td>
<td>0.38</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>10 minutes</td>
<td>0.93</td>
<td>0.87</td>
<td>0.83</td>
<td>0.73</td>
<td>0.59</td>
<td>0.47</td>
<td>0.32</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>15 minutes</td>
<td>0.94</td>
<td>0.89</td>
<td>0.85</td>
<td>0.77</td>
<td>0.64</td>
<td>0.53</td>
<td>0.39</td>
<td>0.29</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>30 minutes</td>
<td>0.95</td>
<td>0.91</td>
<td>0.89</td>
<td>0.82</td>
<td>0.72</td>
<td>0.62</td>
<td>0.51</td>
<td>0.41</td>
<td>0.31</td>
<td>—</td>
</tr>
<tr>
<td>60 minutes</td>
<td>0.96</td>
<td>0.93</td>
<td>0.91</td>
<td>0.86</td>
<td>0.79</td>
<td>0.71</td>
<td>0.62</td>
<td>0.53</td>
<td>0.44</td>
<td>0.35</td>
</tr>
<tr>
<td>2 hours</td>
<td>0.97</td>
<td>0.95</td>
<td>0.93</td>
<td>0.90</td>
<td>0.84</td>
<td>0.79</td>
<td>0.73</td>
<td>0.65</td>
<td>0.55</td>
<td>0.47</td>
</tr>
<tr>
<td>3 hours</td>
<td>0.97</td>
<td>0.96</td>
<td>0.94</td>
<td>0.91</td>
<td>0.87</td>
<td>0.83</td>
<td>0.78</td>
<td>0.71</td>
<td>0.62</td>
<td>0.54</td>
</tr>
<tr>
<td>6 hours</td>
<td>0.98</td>
<td>0.97</td>
<td>0.96</td>
<td>0.93</td>
<td>0.90</td>
<td>0.87</td>
<td>0.83</td>
<td>0.79</td>
<td>0.73</td>
<td>0.67</td>
</tr>
<tr>
<td>24 hours</td>
<td>0.99</td>
<td>0.98</td>
<td>0.97</td>
<td>0.96</td>
<td>0.94</td>
<td>0.92</td>
<td>0.89</td>
<td>0.86</td>
<td>0.83</td>
<td>0.80</td>
</tr>
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<td>48 hours</td>
<td>—</td>
<td>0.99</td>
<td>0.98</td>
<td>0.97</td>
<td>0.96</td>
<td>0.94</td>
<td>0.91</td>
<td>0.88</td>
<td>0.86</td>
<td>0.82</td>
</tr>
<tr>
<td>96 hours</td>
<td>—</td>
<td>—</td>
<td>0.99</td>
<td>0.98</td>
<td>0.97</td>
<td>0.96</td>
<td>0.93</td>
<td>0.91</td>
<td>0.88</td>
<td>0.85</td>
</tr>
<tr>
<td>192 hours</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.99</td>
<td>0.98</td>
<td>0.97</td>
<td>0.95</td>
<td>0.92</td>
<td>0.90</td>
<td>0.87</td>
</tr>
<tr>
<td>25 days</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.99</td>
<td>0.98</td>
<td>0.97</td>
<td>0.95</td>
<td>0.93</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Figure 3.1 — Comparison of different reduction curves for duration and area (Verworn and Flender, 1986).
Figure 3.2a — Forms of representation of regionalized precipitation data: areal precipitations for hydrologically-limited areas.

Figure 3.2b — Forms of representation of regionalized precipitation data: Isohyetal analysis for mean annual precipitation amounts.

Figure 3.2c — Forms of representation of regionalized precipitation data: climatically similar regions with allocation of representative point statistics.

Figure 3.2d — Forms of representation of regionalized precipitation data: grid fields.
3.3.2 Cartographic representation of regionalized precipitation data

Depending on the regionalization method and purpose of application, different forms of spatial representation of the precipitation are usual (Figures 3.2a to 3.2d):

(a) The meteorological value which is directly related to the hydrological value of surface runoff is areal precipitation (Chapter 3), which is oriented on the hydrologically-limited areas of the topographic divides and gives a mean value for this reference area (Figure 3.2a);

(b) The most frequently used form of representation in meteorology, e.g. for the mean annual precipitation amount is the isohyetal map (Figure 3.2b). From the isohyetal lines, a conclusion is drawn about the behaviour or the distribution of precipitation amount between the measuring stations (Schirmer and Vent-Schmidt, 1979). The climatologist acquires knowledge about this not only through a thorough analysis of the measurement data but also extends his knowledge by continual observations of the precipitation events and possibly also by carrying out special measurements in dense measuring networks. This knowledge is transferred in the drawing of isolines; the variation range of the precipitation element is also taken into consideration so that each map contains a high proportion of subjectivity in the lines. The position of the isolines is therefore to be taken as an aid to orientation, delimiting from one another the areas in which the amount of precipitation fluctuates more or less around a mean value.

In Figure 3.2c, climatically similar regions are subjectively put together on the basis of the empirical data available, representative heavy rainfall statistics having been assigned to each region (LIU BW/DWD, 1975). Transitions between the regions are indistinct.

For a complete area coverage of the heavy rainfall evaluation, described in detail in Subchapter 3.3.3, coloured grid fields on a scale of 1:2.5 million are selected, the side lengths of the grid being 8.45 km and the area 71.5 km² (Figure 3.2d). Precipitation amounts of a certain range are assigned to each of these grid fields. Because of the range, it is possible to take into account uncertainties due to different disturbing influences (Bartels, Albrecht and Guttenberger, 1990; Bartels et al., 1997). Another example of the grid field representation of nationwide overviews of values derived from hydrological measurements are the maps in the Hydrological Atlas of Germany. The grid resolution of the Atlas tables is 1 km × 1 km (BMU, 2000).

The purely computational methods used to transfer the point values to the areas are based mainly on the fact that a distance-dependent weighting of the irregularly-distributed surrounding stations is carried out (see Chapter 5). The spatial distributions thus obtained, however, offer no guarantee that, with the given density of the measuring network, an area analysis true to nature can be obtained. Paul (1988) tried various computational interpolation methods and compared them with manually-analysed isohyetal distributions. These investigations show that none of the computational methods applied is an improvement on the cartographical representation enriched with the experience values of an analyst well-versed in climatology. Complementary to the computational methods, methodical regionalization investigations must first be made to check the effect of possible disturbing influences and thus the meaningfulness of spatial distributions (Bartels, 1992). Of special importance are observations on the temporal and spatial representativeness of the point results as well as the computational methods used for the description of the point results:

(a) Requirements for the testing of temporal representativeness are:
   (i) Investigations for statistically-sufficient long periods of evaluation;
   (ii) Standardized instrumentation during the period of evaluation;
   (iii) Standardized data processing;
   (iv) Guarantee of the stationary position and homogeneity of the time series (changes to the stations, relocation of the stations, etc.);

(b) Requirements for the testing of spatial representativeness are:
   (i) Investigations of the density and distribution of existing stations;
   (ii) Standardized instrumentation throughout the entire measuring network;
   (iii) Standardized measuring periods for all stations;
   (iv) Standardized statistical evaluation methods for all stations;

(c) In order to be able to describe and weigh the frequency of heavy rainfall events during a certain measurement period (outlier problem), as well as estimates for very rare events, it is necessary to apply extreme value evaluation methods. As a result, other tests are needed:
   (i) Usability of the computational statements applied to describe a partial data set;
   (ii) Deviations between the different computational procedures;
   (iii) Deviations between the measured and adjusted distributions.

Thus, the determination of an area of confidence (tolerance interval) for the validity of extreme value computations is possible.

3.3.3 Cartographic representation of regionalized heavy rainfall amounts

The aim of coordinated heavy rainfall regionalizations in Germany was not only to process heavy rainfall point statistics, but also to represent the spatial distribution of heavy rainfall amounts for selected durations (between five minutes and 72 hours) and relevant recurrence intervals (between once a year and once every 100 years) on maps with adequate spatial resolution for all durations and recurrence intervals (Bartels, Albrecht and Guttenberger, 1990; Bartels et al., 1997).

Therefore, an evaluation of randomly-occurring events within a 30-year measuring period and an extrapolation on very rare precipitation events was planned. The extreme values statistics statement starts for every duration $D$ (precipitation duration including interruptions) of a partial or annual series which is determined from a series of registered or measured precipitation amounts. Each series of heavy precipitation amounts $h(D;T)$ is adjusted to the theoretical distribution function by a regression calculation, where $T$ is the recurrence interval (annuality) (DVWK, 1985). The distribution function is represented on squared paper with $h(D;T)$ on the y-axis and In $T$ on the x-axis as a straight line. The parameter $u(D)$ is the ordinate section for In $T = 0$ and the parameter $w(D)$ gives the gradient of the straight line. In order to obtain clear precipitation amounts over all durations, a double logarithmic compensation of the parameters $u(D)$ and $w(D)$ in
duration range I (5 to 60 minutes) and duration range II (60 minutes to 12 hours) is carried out.

Building on these point evaluations, a regionalization of heavy rainfall events covering the area was then planned with the aid of a complex regionalization method which especially contains the orographically-modified variogram analysis. The results are recorded in grid representations with a resolution of 8.45 × 8.45 km per grid field. In this way, the KOSTRA values of the heavy precipitation amounts are obtained, with the help of which heavy rainfall point statistics can finally be derived, even for locations without precipitation measurement series (Table 3.2).

The evaluation of disturbing influences should follow from the KOSTRA investigation covering the area of Germany. The following remarks concentrate on the tests for temporal and spatial representativeness of heavy rainfall statistics using Gumbel and exponential distribution (DVWK, 1985).

Standardized instrumentation and data processing should be guaranteed in the measuring networks of the Meteorological Services. The application of statistical test procedures regarding the stationary position and homogeneity of the mean values and deviations of the time periods investigated yield as a rule satisfactory results in comparison with other disturbing influences.

Tests of temporal representativeness
The natural breadth of variation of rain is known to be very high, so that an evaluation period as long as possible should be laid down. The order of magnitude of the uncertainties caused by temporal variability (3 per cent) follow. The remaining error deviations with negative or positive signs. The addition of both effects, therefore, leads to a reinforcement of an over- or underestimation or to a compensation of both disturbing influences. If the methodical estimation error using the statement of computational method is now added and if the greatest error influence is investigated for each grid field, then an interesting picture is presented for Germany. The estimation error as a result of using a distribution function is decisive for 90 per cent of the total area of Germany. Later, the spatial (6 per cent) and then the temporal variability (3 per cent) follow. The remaining error influences are negligible. It should be taken into account that the choice of the distribution function is to be classified as rather conservative, i.e. as a rule, the estimation of precipitation amounts gives too high values.

Estimation errors by using extreme value computational methods
As a basis for the computation of the probability-dependent confidence intervals of the extreme value computations, a risk threshold of e.g. 10 per cent can be introduced i.e. 10 per cent of all disturbing influences are no longer covered by the confidence interval (WMO, 1981c).

The decisive criteria for a regionalization procedure result from the comparison of temporal and spatial variations for the available stations over a long time period. Both influences can cause deviations with negative or positive signs. The addition of both effects, therefore, leads to a reinforcement of an over- or underestimation or to a compensation of both disturbing influences. If the methodical estimation error using the statement of computational method is now added and if the greatest error influence is investigated for each grid field, then an interesting picture is presented for Germany. The estimation error as a result of using a distribution function is decisive for 90 per cent of the total area of Germany. Later, the spatial (6 per cent) and then the temporal variability (3 per cent) follow. The remaining error influences are negligible. It should be taken into account that the choice of the distribution function is to be classified as rather conservative, i.e. as a rule, the estimation of precipitation amounts gives too high values.

Tests of spatial representativeness
The spatial deviations can be investigated by reconstructing the extreme value statistics obtained station by station exclusively from the surrounding station values. The difference between the field distribution obtained by excluding individual station results and the field distribution with availability of station results can be recorded as a percentage of the over- or underestimation.

Table 3.2
Location-related KOSTRA heavy rainfall amounts $hN$ (mm) and precipitation yields $RN$ (l/(s·ha)) depending on the duration $D$ and the recurrence interval $T$ for an example grid field (RN = (166,6/D) hN with D in minutes)

<table>
<thead>
<tr>
<th>$T$ (years)</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$ (min)</td>
<td>hN</td>
<td>RN</td>
<td>hN</td>
<td>RN</td>
<td>hN</td>
<td>RN</td>
<td>hN</td>
<td>RN</td>
</tr>
<tr>
<td>5 min</td>
<td>5.5</td>
<td>185</td>
<td>7.0</td>
<td>233.8</td>
<td>8.5</td>
<td>283.0</td>
<td>10.4</td>
<td>347.9</td>
</tr>
<tr>
<td>10 min</td>
<td>6.6</td>
<td>110</td>
<td>8.6</td>
<td>143.4</td>
<td>10.6</td>
<td>177.3</td>
<td>13.3</td>
<td>222.1</td>
</tr>
<tr>
<td>15 min</td>
<td>7.2</td>
<td>80.5</td>
<td>9.7</td>
<td>107.8</td>
<td>12.2</td>
<td>135.0</td>
<td>15.4</td>
<td>171.1</td>
</tr>
<tr>
<td>20 min</td>
<td>7.8</td>
<td>64.6</td>
<td>10.6</td>
<td>88.0</td>
<td>13.4</td>
<td>111.4</td>
<td>17.1</td>
<td>142.2</td>
</tr>
<tr>
<td>30 min</td>
<td>8.5</td>
<td>47.3</td>
<td>11.9</td>
<td>84.9</td>
<td>15.3</td>
<td>84.9</td>
<td>19.8</td>
<td>109.8</td>
</tr>
<tr>
<td>45 min</td>
<td>9.3</td>
<td>34.6</td>
<td>13.4</td>
<td>49.7</td>
<td>17.5</td>
<td>64.8</td>
<td>22.9</td>
<td>84.8</td>
</tr>
<tr>
<td>60 min</td>
<td>9.9</td>
<td>27.6</td>
<td>14.6</td>
<td>40.6</td>
<td>19.3</td>
<td>53.5</td>
<td>25.4</td>
<td>70.7</td>
</tr>
<tr>
<td>90 min</td>
<td>11.1</td>
<td>20.5</td>
<td>16.0</td>
<td>29.7</td>
<td>21.0</td>
<td>38.8</td>
<td>27.5</td>
<td>51.0</td>
</tr>
<tr>
<td>2 h</td>
<td>11.9</td>
<td>16.6</td>
<td>17.1</td>
<td>23.8</td>
<td>22.3</td>
<td>30.9</td>
<td>29.1</td>
<td>40.4</td>
</tr>
<tr>
<td>3 h</td>
<td>13.3</td>
<td>12.3</td>
<td>18.8</td>
<td>17.4</td>
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<td>72 h</td>
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The procedure described is an iterative process which can lead to the following consequences:

(a) Limitation to a shorter evaluation period in favour of a higher density of stations and standardization of the time period;
(b) Limitation of the grid fields to a specified area size;
(c) Limitation of the class range of the precipitation amounts to a specified number of classes;
(d) Supplementary investigations for the derivation of other auxiliary functions.

Such auxiliary functions may result from extreme value statistics of predominantly advectively-determined long-term precipitations \((D \geq 24\, \text{h})\) through a relationship with the mean annual precipitation amount. With the aid of this relationship, existing maps of the mean annual precipitation amount, which were analysed by a climatological expert on the basis of a great number of empirical values concerning the effects of weather situations, can be referred back to.

The extreme value statistics of the mostly convectively formed short-term precipitations \((D \leq 60\, \text{min})\) do not show such a relationship with mean annual precipitation amounts. However, in this case, a good relationship with orography can be found in Germany. A measure for this is, for example, the exposure height in the low mountain region, which can be derived from the gradient and orientation of the slope to the prevailing weather situations.

A special regionalization procedure was developed to derive the spatial distribution of winter heavy rainfalls. This was done by establishing the spatial representativeness of the individual station values on the surrounding grid fields, whereby the deviations may not exceed a certain threshold. In addition, the determination can be used to show that because of the predominantly advectively-influenced precipitation events, the spatial similarities between winter short-term precipitations and long-term precipitations are much more strongly pronounced and cover greater distances than in the other seasons. Thus, various correlation partners from the much denser measuring stations which measure daily precipitation are available for the distribution of total areas in representative regions for stations with heat table recording precipitation gauges (so-called DIGI stations), which can be used to optimize limits in an iterative process.

The basic criteria including an orographic database are:

(a) Agreement between the point evaluations and the existing KOSTRA grid field occupancy (with maximum 20 per cent deviation between DIGI station values and grid values);
(b) Mean monthly values of the precipitation amount by regionally-typified monthly values of the precipitation;
(c) Mean annual precipitation amount as spatial analysis;
(d) Distance between each DIGI station and the assigned region.

**Conclusions**

For all regionalization methods, the various error influences (uncertainties) must first be weighed against each other in order to arrive at a given maximum possible spatial resolution with a certain meaningfulness (confidence range) on the basis of the density and distribution of the stations as well as the evaluation period and the computational method. Purely computational methods to transfer the point results to the areas (Chapter 3) can normally only deliver a very rough spatial distribution because, in this case, significant influences through the weather situation with differently operating

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**Figure 3.3 — Heavy rainfall amounts for the duration \(D \geq 24\, \text{h}\) and the recurrence intervals \(T = 5a\) to \(T = 100a\) for 30-year moving evaluations of the time period 1931–1980 from selected stations with daily values.**
precipitation mechanisms and orography with windward and lee-side effects remain ignored. Without such additional information, the station results, both for short-term and long-term precipitations, are valid only in a relatively small area around the station. If, on the other hand, the various influences with extensive error analysis and the combination of computational methods, existing empirically calculated documents and orographic concepts are included in the investigation, then distributions with a relatively high spatial resolution covering the area can be derived.

3.3.4 Cartographic representation of regionalized extreme values of precipitation supply
In the winter months, in addition to the precipitation, the precipitation supply — the sum of rain and melt water release — is of importance. If the breakdown of the snow cover and the precipitation stored in it come together with heavy rain, extreme values can appear which, in their amounts and intensities, influence the extreme value statistics in the snow-covered hydrologically relevant areas. This is especially true of areas in medium and high places in the mountains (higher than 400 m).

Precipitation values are obtained from measurements; values of precipitation supply are found with the aid of models. The snow cover model SNOW-K enables the daily calculation of melt water release out of the snow cover, taking into account the liquid precipitation, by continuous simulation of the development of the snow cover (Rachner, Matthäus and Schneider, 1997). The optimization of the model parameters and the verification of the derived results are obtained, relative to the location, by means of all available measured values of the water equivalent of the snow cover. The daily values of the precipitation supply arrived at in this way are subject to an extreme value statistical analysis (REWANUS) with the support of the KOSTRA investigations. Regionalization is obtained from station-related point results. Mean winter precipitation plays an important role in this regionalization procedure. Regional climatological influencing factors in the river basins of Germany were taken into account with very well confirmed regression relationships. On the basis of these regressions, the regionalization of station-related extreme values, calculated for all climate and precipitation stations, was obtained by distance-dependent interpolation on the middle point of the grid areas (resolution of 8.45 × 8.45 km per grid field). As a result of the REWANUS investigations, grid-oriented extreme values of the precipitation supply in the hydrological winter half year for durations of \(d = 0.5d\) to \(D = 10d\) are available with blanket coverage in the form of regionalized cartographical representations.

The KOSTRA heavy precipitation amounts for the winter period are based on measurements both of liquid as well as solid precipitations, whereby the precipitation fallen as snow is liquefied before the precipitation amount (in millimetres) is determined. Stored in the snow cover, the precipitation does not immediately have to turn into runoff, at least not completely. On the contrary, the values of the precipitation supply provide the hydrologically-effective contribution that is decisive for the formation of the runoff. Therefore, the REWANUS values, the information about the occurrence probability of extreme values of the precipitation supply, are of great significance, above all in the snow-covered hydrologically-relevant regions.

With regard to the extreme values of the precipitation supply for durations from \(D = 0.5d\), tabulated summaries similar to the heavy precipitation statistics (Table 3.2), can be derived with the aid of cartographical representations of regionalized extreme values of the precipitation supply (Günther et al., 2000).

3.4 Probable Maximum Precipitation (PMP)
3.4.1 General
Heavy rainfall statistics allow, given the normally available time periods of about 30 years, conclusions of, at the most, recurrence periods of up to 100 years. Flood structures, which are meant to be built with greater safety, cannot be based on these statistics. The probable maximum precipitation (PMP) is, therefore, defined conceptually as the theoretically greatest precipitation amount physically possible of a given duration for a specified catchment area at a specified season (without regard to climate changes). This definition represents the upper limit of a possible heavy precipitation event (WMO, 1986a).

In effect, there are three possibilities for quantifying PMP:
(a) By means of purely statistical methods (Hershfield, 1965);
(b) With the aid of deterministic physical models (Haiden et al., 1991);
(c) Empirically, by physically-based evaluation of meteorological data (DVWK, 1997).

Statistical methods are used for areas up to an area size of about 1 200 km²; physical methods can cover catchment areas up to 50 000 km². Surface areas beyond these measurements are very difficult to handle, both as models and empirically, because of the spatially different weather influences.

The resulting very high precipitation amounts, according to the definition of PMP, are therefore not directly used in dimensioning hydrological structures. The safety elements designed into barrages approach these values in their calculations. In this way, the use and the potential danger of the installation in the case of failure are weighed up against each other. Also taken into consideration is an estimation of the construction methods as well as the necessary building and running costs for a specified construction in a specified region. An optimization of these various needs, however, can only be arrived at through close co-operation among meteorologists, hydrologists and engineers. Parallel to this, relevant extreme values of precipitation in Germany are processed for subsequent use in hydrological practice. In addition — depending on the duration — the area between the KOSTRA heavy precipitation amount of the 100-year recurrence interval and the PMP is to be sounded out.

The procedures for the evaluation of PMP cannot be standardized. There is also no objective procedure to permit sure statements about the accuracy of the PMP estimates. Nevertheless, observations about accuracy can be made. In relation to this, the following factors should especially be taken into account:
(a) Excess of estimated PMP over the maximum observed precipitation amounts for the surrounding climatologically-homogeneous region;
(b) Number and severity of the available recorded precipitation events in the region in question for the longest possible time series;
(c) Number, character and interrelationship of the maximizing steps;
(d) Reliability of the model used in relation to the precipitation description and other meteorological variables;
(e) Probability of the individual meteorological variables used in the model being excessive in relation to the occurrence of very rare events.
3.4.2 Estimation of PMP using a physically-based evaluation of meteorological data

With maximization, an empirical path was taken by the Deutscher Wetterdienst to investigate the PMP amounts in Germany. To be able to estimate PMP, knowledge of the meteorological variables and processes which impose a limit on precipitation amount is necessary. Obviously, the water vapour content of the air plays an important part. By multiplying the precipitation amount measured in an extreme heavy precipitation event by the maximizing factor gives the maximized precipitation amount. The maximizing factor is the relation — depending on the region and the season — of the theoretically greatest water vapour content of the atmosphere to the water vapour content which is available over an investigated area during an observed extreme heavy precipitation event of a certain duration. By adopting an optimal degree of effect of the precipitation process, this maximizing factor already implicitly contains the appropriate wind influence.

Within the project entitled “Regionalization of maximized regional precipitation amounts in Germany” (MGN), the large number of computationally-evaluated probable maximum regional precipitation amounts for selected regions was regionalized, i.e. transferred to the other regions of Germany, and represented in maps of the maximized regional precipitation amounts (MGN) for durations from $D = 1 \text{ h}$ to $D = 72 \text{ h}$ (DVWK, 1997). The main focus was on relatively short precipitation durations of less than a day and relatively small regional areas. In the follow-up project entitled NIEFLUD, probable maximum regional precipitation amounts were processed for heavy precipitations of several days’ duration and covering a wide area ($> 1,000 \text{ km}^2$) in Germany’s river basins (Malitz and Günther, 2001). The precipitation database did not have to be restricted to the approximately 200 stations recording precipitation during the day and having high time resolution of around 30-year precipitation time series. Data could be obtained from the around 4,500 stations measuring precipitation once a day and having a longer observation period (often 60 years). The high spatial density of these stations permitted the regional precipitation amounts in Germany. To be able to estimate PMP, knowledge of the meteorological variables and processes which impose a limit on precipitation amount is necessary. Obviously, the water vapour content of the air plays an important part. By multiplying the precipitation amount measured in an extreme heavy precipitation event by the maximizing factor gives the maximized precipitation amount. The maximizing factor is the relation — depending on the region and the season — of the theoretically greatest water vapour content of the atmosphere to the water vapour content which is available over an investigated area during an observed extreme heavy precipitation event of a certain duration. By adopting an optimal degree of effect of the precipitation process, this maximizing factor already implicitly contains the appropriate wind influence.

Individual investigations using maximization calculations for a few stations have also been carried out by other authors in the past. Although these investigations were also carried out very meticulously, they always hold the danger that — because of the small number of stations and the comparably short length of the available precipitation series as well as the sometimes unrepresentative investigation period with regard to time — the values calculated are by a long way not the probable maximum precipitation amounts in the investigated regions (Haugk, 1983). As opposed to this, all individual results in a temporal and spatial context were evaluated at every step in both Deutscher Wetterdienst maximization projects in the search for the probable maximum regional precipitation amounts in Germany.

Figure 3.4 demonstrates the regionalized maximized areal precipitation amount for duration $D = 72 \text{ h}$ and an area size of about $1,000 \text{ km}^2$ in the summer season in Germany. The maximized regional precipitation amount for a region of interest — indeed in the middle of this region — can be read from this map. Figures 3.5 and 3.6 show the comparison of regional precipitation amounts with worldwide extreme precipitation amounts.

3.5 SNOWMELT

Snowmelt forecasting has top priority in short-term runoff forecasting (Kimbauer, 1993). Decisions on definite measures to be taken, such as operational planning and flood warnings, can be based on routinely established and regularly released forecasts. Forecasting models should, above all, produce good results in situations which are important for the user (Gutknecht, 1991). Experience in the use of snowmelt models for runoff forecasting has been gained for instance in Switzerland (Scheidler, 1992). Short-term forecasting takes into consideration changes in snow cover. Reliable forecasting of snow water runoff under extreme conditions (rainfall and strong wind) remains difficult. In Norway, by using remote-sensing data simultaneously, information concerning snow cover development is included in a flood early warning system (Haddeland, 1996). Continually-working models and event models can be differentiated according to their application. The former have important variables of state, e.g. the water equivalent (Rachner, Matthias and Schneider, 1997), and the latter need initial values in order to function (Kimbauer, 1993).

In order to quantify the estimations of runoffs from snow-covered catchment basins, information on the areal values of the water runoff from melting snow cover is required. In the station networks run by the Weather Services, the snow depth and, to some extent, the water equivalent of the snow cover are measured at the precipitation stations and the meteorological data at the synoptic-climatological stations. The snowmelt runoffs have to be derived from these data. Assessment and simulation of snowmelt runoffs therefore mainly require the following steps:

(a) Processing of meteorological input data for snowmelt models (e.g. precipitation, global radiation, air temperature, air humidity, wind velocity) in spatial-temporal resolution;

(b) Estimation of snowmelt rates and snow cover runoffs, taking into consideration the rain falling into the snow cover and the content of free water;

(c) Transformation of snow cover runoffs (snow and rain water) into areal runoffs.

Any step can be made with models of different complexity. The main problem with regard to the snowmelt and its modelling is that information obtained with point melt models must subsequently be transferred to the area. The related deficit in knowledge is made particularly clear in the study by Braun (1985), while in WMO (1986b) it has, to a large extent, been disregarded. However, in 1988, the WMO Rapporteur on Data Inputs for Hydrological Models, on the recommendation of the WMO Rapporteur on Meteorological Systems for Hydrological Purposes, was entrusted with the task of examining the methods for quantitative inputs from snowmelt.

The validity range of snowmelt models is, strictly speaking, limited to the location at which the required meteorological input data are recorded. The transfer of data and results recorded at individual locations to the surrounding area or larger regions has recently been the subject of intensive research (Blöschl, 1990; Kleeberg, 1992; Pfützen et al., 1992; Kirnbauer, Blöschl and Gutknecht, 1994). For most purposes, the generalization is at present carried out using empirical procedures, whereby the regional distribution of individual data is derived from an adequate amount of information from the stations.
action is a compromise. Despite its disadvantages due to unsatisfactory physical reasons it will continue to be a procedure that is taken seriously in the future (Becker, 1992; Braun and Rohrer, 1992).

The difficulty of simulating with a model the behaviour of runoff from snow cover is that the runoff from an extremely nonhomogeneous and anisotropic hydrological storage, such as the snow cover, constitutes a mathematically not clearly assessable and generally valid function of the input in the form of melt as well as rain water predominantly produced at the surface of the snow cover, of the thermal retention capacity and of the free water content of the snow cover, and its hydraulic properties varying considerably with time as compared to soils in conjunction with the mechanic (structural) retention capacity. In the absence of experience, a storage term determined by mathematical optimization is therefore often used for simulation models. However, no general statements can be derived since the coefficients used in the models cannot normally be clearly interpreted physically.

According to a state-of-the-art report on snow hydrology by Herrmann (1986), only specific experiments should be based on theoretical considerations concerning water storage, the movement of seepage water and thus the behaviour of runoffs from snow covers in the temporal resolution, e.g. Colbeck (1972), de Quervain (1973) and
Wankiewicz (1979). In particular, systematic analyses of runoff functions based on Denoth et al. (1979) — including information from snow profile studies and environmental isotopes as tracers (Herrmann, Martinec and Stichler, 1979) — are promising.

Meteorological-climatological requirements of point melt models estimating actual or potential melting rates or potential runoff rates for snow covers decrease in the following order:

(a) Energy balance method (Amorocho and Espildora, 1966; Anderson, 1976; Aguado, 1983);
(b) Combined energy-balance-index method (Anderson, 1973; Knauf, 1980);
(c) Index method;
(d) Temperature-wind index method (Martinec, 1960; Braun, 1985);
(e) Temperature (melt) index (factor) method (Zingg, 1951; U.S. Army Corps of Engineers, 1956).

The energy balance method has been more widely applied only since the late 1960s, i.e. following the development of electronic data processing, as it was then possible to represent adequately the complex physical processes of snow cover accumulation and, in particular, of ablation through mathematical relationships. Slight modifications of this approach take more or less full account of the heat fluxes supplying the available melting energy, including the changes in the latent heat content of the snow cover. Therefore, for the computation of the atmospheric heat fluxes, it is important to have the following parameters: net radiation, air temperature, air humidity or vapour pressure, wind velocity and, if necessary, the temperature of the rain water. In addition, for the determination of the latent heat content of the snow cover, the temperature and density of the snow are needed.

As meteorological input data for simulation models of snowmelt according to the energy budget approach, values for time intervals of up to one hour, depending on the respective application, are required. Above all, insufficient availability of data prevents the wider application of this method for operational purposes such as, for instance, runoff forecasts for snow-covered catchment basins.

Combined energy balance index methods prove to be more suitable. Taking into account the usual lack of data, with these methods energy terms determinable only with a considerable amount of measuring work are simplified or replaced by equivalent values which can be determined more easily. As examples, the approximation of net radiation via the global radiation reduced by empirical albedo values for characteristic snow cover surfaces or simplified estimations of the sensible and latent heat fluxes with parameter optimization should be mentioned. Unlike the index methods, mathematical relationships are to a large extent physically substantiated.

On the other hand, the temperature index methods — that give information on heat budget processes — include the air temperature and produced mostly unsatisfactory results, in particular with regard to melting due to radiation. In this context, the degree-day method is widely used; hereby, a relationship is established between positive daily mean temperatures of the air (degree days) and melt water losses supplying degree-day factors. Slight improvements can be achieved for prevailing advection melting, e.g. through the extension by wind or even vapour pressure terms.

While the index methods prove, to a large extent, to be unsuitable for hydrologically-usable simulations of point melting and for time resolutions of more than one day, they represent at present the only practicable approximation procedure for the estimation of melt water inputs to hydrological catchment basins. In this respect, no further decisive progress has been made in the field of realistic simulation of snowmelt runoffs since the introduction of degree-day factors, snow cover detection according to aerial or satellite images and analyses of the recession hydrographs.

Even valuable studies such as that by Braun (1985) do not alter this fact. What is lacking, in particular with regard to operational water level and runoff forecasts for snow-covered catchment basins, are improved grid-oriented and operational model systems with related meteorological input data as a prerequisite and more adequate transformation functions for melt water input, despite the relatively positive results of simulations of the meltwater runoff (WMO, 1986b).

Because of the large number of snowmelt models now available, a categorization is desirable. Classification is, however, only possible with “fuzziness”.

Generally, however, it can be said that the input data requirements for a model increase proportionally to how a physically-based model is planned. If the “process proximity” of the simulation is used as a differentiation criterion, then the following can be differentiated (Kirnbauer, 1993):

(a) Physically-based models;
(b) Conceptual models;
(c) Regression models.

The data requirements decrease in the given order, comparable to the above-mentioned examples.

Positive results with the operational analysis and forecast of snow cover development and melt water release from the snow cover were obtained, for example, in Germany with the model system SNOW-D (Rachner, Matthäus and Schneider, 1997). SNOW-D enables the daily calculation and forecast of grid point values of the water equivalent of the snow cover and its melt water release. The snow cover development is computed with the help of physically-based model components which describe accumulation (build-up, increase), metamorphosis (conversion, change) and ablation (decrease, melting of snow cover). Model input consists of data on:

(a) Six-hour interval averages of air temperature and vapour pressure;
(b) Global radiation/duration of sunshine and precipitation totals of the last 24 hours;
(c) Additional data three times a week from a part-time network (depth of snow cover, water equivalent of snow cover);
(d) The output data of the regional numerical weather prediction model of the Deutscher Wetterdienst is used as input for the calculation of forecasts.

In detail, the following information on model output is available:

(a) Current values of the snow cover (reference point 0600 UTC):
   (i) Snow depth (cm);
   (ii) Water equivalent (mm);
   (iii) Specific water equivalent (mm cm⁻¹);
(b) Forecast values of snow cover development (forecast interval maximum 48 hours, forecasting for six-hour intervals):
   (i) Water equivalent (mm);
   (ii) Precipitation supply, defined as the sum of meltwater release and rain (mm).

The results are provided grid-oriented and with a blanket coverage for Germany. A summary of the grid values can be made for any area required.
CHAPTER 4

ESTIMATION OF AREAL PRECIPITATION AND AREAL EVAPORATION

4.1 FUNDAMENTALS

The direct measurement of all hydrologically relevant climatic data (model input data) supplies point values. To what extent such point values are also representative of the neighbouring region depends on the spatial homogeneity of the influencing factors. An areal value for even a small catchment basin can be determined in this way at best only in special cases. Alone, remote sensing methods combined with ground measurements (point measurements as so-called ground truth) produce, due to their low spatial resolution, areal values, e.g. precipitation measurement by radar (quantitative assessment) and the estimation of the type of land use via satellite-measured radiation of the Earth’s surface in the visible and infrared spectral range (e.g. LANSAT). In this chapter, the most important methods and models for the conversion of point data into areal data have been compiled.

Although the methods described in Subchapter 4.2 are applied mainly to the target parameter areal precipitation, they can also, in principle, be applied to other climatic data such as potential evapotranspiration, air temperature and water vapour saturation. However, this matter is relatively seldom dealt with in the literature. For this reason, the general treatment of areal values in Subchapter 4.2 speaks only of target parameter. In the following discussion, the symbol Z is used for this parameter. This Z(N) value estimated for N spatially-distributed individual measurements Z(I), ..., Z(N) deviates from the true value of the target parameter to a degree so far unknown.

According to a definition, e.g. a DIN definition, the areal value is invariably a value of the target parameter averaged over a specified area. This area can be the catchment basin under consideration (e.g. input for block models) or an areal element of that catchment basin, e.g. isoline areas: areas between isolines as in the case of the isoline method (Equation 4.3) or quadratic areas as in the case of the grid interpolation procedure with equidistant grid points (Equation 4.5).

To avoid misunderstandings, it should be emphasized that the meteorologist understands the term areal evaporation as the transition having already been made from a point value to a relatively closely limited areal value related to a vegetation crop or a homogeneous sector. The hydrologist, on the other hand, imposes no limitation regarding homogeneity.

4.2 METHODS FOR THE COMPUTATION OF AREAL VALUES

Non-weighted arithmetic averaging

\[ Z = \frac{1}{N} \sum_{I=1}^{N} Z(I) \]  (4.1)

This simplest of all conceivable methods for the estimation of areal values should be used only if it is known that there is no considerable spatial scattering of the Z(I) values.

Weighted averaging

The method established by Thiessen (1911) is incorrect insofar as the weighting through polygons (polygon method, mid-vertical) originates from Horton (1923). Equation 4.1 is extended by weight factors K(I):

\[ Z = \frac{1}{N} \sum_{I=1}^{N} K(I) Z(I) \]  (4.2)

with the standardization:

\[ Z = \frac{1}{N} \sum_{I=1}^{N} K(I) = 1 \]  (4.3)

This graphic method is, however, difficult to programme when stations are changed.

Triangle method

This is a variation of the polygon method which is recommended for a concentration of stations in the boundary area (Giesecke and Meyer, 1984).

Isoline area method

Because of the inclusion of empirical values for the manual analysis of the isoline map, this method is considered relatively accurate. However, it requires considerable effort.

\[ Z = \sum_{J=1}^{M} K(J) ZZ(J) \]  (4.4)

M: Number of isoline areas;
W(J): Weight percentage of isoline area J;
ZZ(J): Z-value of isoline area J.

Grid interpolation procedure

In using the target parameter in a model with detailed areas, it is advisable to prepare beforehand a gridding of the area. Z is then, for instance, the arithmetic mean of the grid values of the total area or of a definite pixel set. Generally, the target parameter ZR(L) has to be estimated for grid point L of a grid placed over the area. In the equation:

\[ Z(L) = \sum_{I=1}^{N} A(L, I) Z(I) \]  (4.5)

A(L,I) means the weights of N = 8 measurement points (reference points) with regard to L, independent of Z(I).

These weights are so chosen that the expected value of the interpolation error equals zero and its variance with regard to A(L,I) is minimal. This leads to a system of equations, the solution to which is called optimal interpolation or the Kriging method. It has recently been described in detail and applied by Jensen (1989). The BONIE method (see Subchapter 4.4), operationally applied by the Deutscher Wetterdienst, is based, with a few supplementations, also on the method of optimal/statistical interpolation.
A simple variation of approximation consists in using, for characteristic events, empirical values of the target parameter for the reference point \( L \) and the measurement point \( I \) and to weight the measuring point \( I \) with the reciprocal square of distance \( D(I)^{-2} \). By dividing the area around \( L \) into four quadrants and selecting the closest measurement point (\( N = 4 \)) for each, Equation 4.5 changes into:

\[
ZR(L) = C(L) \frac{\sum_{I=1}^{N} D(I)^{-2} Z(I)}{\sum_{I=1}^{N} D(I)^{-2}} \tag{4.6}
\]

In this case, \( C(L) \) and \( Z(I) \) are the characteristic values of the target parameter for grid point \( L \) or the \( N \) measurement points \( I \), respectively. These may be typical (characteristic) precipitation distributions as in the case under consideration or long-term mean precipitation amounts.

The advantages of this method are:
(a) Relatively high accuracy of calculations;
(b) Simple automatic plotting;
(c) Simple programming.

The disadvantage is the considerable amount of mathematical work in the case of optimal interpolation.

**Mathematical method**

In this case, a given function is adjusted to the measurement data of the target value.

Applications are:
(a) Multiple regression;
(b) Bicubic spline function;
(c) Polynomials;
(d) Fourier’s estimations;
(e) Finite element methods.

Since the amount of mathematical work and the deviation of the mathematical function between the reference points can be considerable, mathematical procedures are not often applied in practice.

### 4.3 ERROR SOURCES IN AREAL COMPUTATION

Independent of the target parameter, for which an areal computation is to be carried out, several fundamental error sources can be indicated. Areal precipitation computation permits quantitative statements on this subject. However, in this field, and in particular in the field of areal evaporation computation, there is still an obvious need for research. The following error sources are known:

(a) Computation procedure:
Non-weighted arithmetic averaging (Equation 4.1) and approximation via mathematical functions (Subchapter 4.2) can lead to considerable errors. This applies where the distribution of measuring stations is not adjusted to the spatial gradient of the target parameter, or in the case of uncontrolled deviations of the mathematical function between the measurement points and in the boundary area;

(b) Density and spatial distribution of measuring points:
The computation error increases for an invariant spatial gradient of the target parameter with decreasing density of the measurement point network. Conversely, in the case of a fixed measurement point configuration, the computation error increases with an increasing spatial gradient of the target parameter. The use of relative values according to Equation 4.6 increases the accuracy of computation (Deisenhofer, Kumm and Wollkopf, 1982);

(c) Size of area:
The relative computation error decreases with increasing size of the area;

(d) Size of the target parameter (e.g. mm, cm³, °C, m s⁻¹):
The relative computation error decreases with increasing size of the target parameter;

(e) Time interval:
The relative computation error decreases with increasing time interval;

(f) Accuracy of point measurement:
This is affected by a systematic and a statistic (random) error. The error of an individual measurement becomes dominant with increasing density of the station network (Mendel, 1979).

### 4.4 COMPUTATION OF AREAL PRECIPITATION

The application of the methods for the computation of areal values mentioned in Subchapter 4.2 is relatively simple and reliable because:

(a) The methods have been developed expressly for the computation of areal precipitation or have already often been successfully applied;

(b) The network of precipitation stations, unlike that for the measurement of other climatic values (e.g. water vapour pressure, air temperature, wind velocity), is relatively dense;

(c) The spatial precipitation distribution, in particular in the case of flood-causing precipitation over an extended area, also unlike that relative to other climatic data, is subject to fewer variations;

(d) Point precipitation can be measured directly;

(e) The accuracy of areal precipitation computation can be estimated at least in a first approximation, e.g. by remote sensing.

As shown in Subchapter 4.2, the various methods of the grid interpolation procedure for the computation of areal precipitation can be recommended.

Concerning the accuracy of areal precipitation computation, reference is made to Subchapter 4.3. Figure 4.1 shows that the mean computational error for daily values in an area size of 600 km² for a normal density of the synoptical station network (one station per 1 000 km² in Germany) can exceed values of ± 30 per cent. Only for a density of one station per 80 km² (precipitation station network in Germany) is the mean error reduced to about ± 10 per cent.

Convective rainfalls (showers), however, require a higher station density because of their high spatial-temporal heterogeneity with the same mean error; in this case, an additional indirect measurement through remote sensing (radar) is advisable.

Inaccuracy in point measurement, however, has not been taken into account in this argumentation. As already pointed out in Subchapter 4.3, it becomes dominant when the station density exceeds a certain value. Consequently, a high station density is reasonable only if individual point measurements are carried out with a high degree of accuracy. The result of an investigation in the catchment basin of the Neckar River (13 800 km²) into the precipitation event of 22 May 1978 was that for a time interval of
one day, a non-exceedance of about 50 km² per station does not lead to any increase in computational accuracy; this is a total of 257 stations with a grid point distance of 10 km, altogether 141 grid points (Mendel, 1979).

The polygon method (Equation 4.2) has, in the past, frequently been improved for areal precipitation computation by taking into account the number and location of the stations as well as the season of the year (Diskin, 1969; Israelsen and Riley, 1972).

The isoline method by Meinardus (1900) is a combination of the isoline area method (Equation 4.4) and the grid interpolation procedure (Equation 4.5). With this method, a value is determined through interpolation from an isoline map for each grid point of a grid field. The arithmetic mean of the values then directly produces the areal value.

The grid interpolation procedure in the form of Equation 4.6 for the computation of areal precipitation was first developed and applied in the United States (NOAA, 1972) but subsequent positive experience is also available (Mendel, 1977). A special case of the grid interpolation procedure is the so-called catchment concentration procedure (Deisenhofer, Kumm and Wollkopf, 1982). It is routinely applied by the Deutscher Wetterdienst for hydrological purposes in calculating the amounts of monthly areal precipitation for about 4,000 catchment basins (base areas). For this, in a derived version of Equation 4.6, the reciprocal station distances from the main centre of the catchment and the monthly means are used.

At the Deutscher Wetterdienst, apart from the catchment concentration procedure, two further procedures have been developed. With these, the actual areal precipitation values of measurements made at intervals of up to one hour can also be made available in a user-friendly form for special hydrological applications.

The computation of amounts of areal precipitation according to the REGNIE method is based on the spatial equalization of the actual daily, monthly and annual precipitation distributions by using the regionalized precipitation values of a reference period. These are grid values on a geographical grid of 60 geographical seconds longitude and 30 geographical seconds latitude for Germany. The procedure presumes that with the regionalization of precipitation, reference values of a 30-year period depending on height, geographical longitude and latitude, exposure direction of the site and the amount of exposure, the significant climatological characteristics of the precipitation distribution are recorded. The remaining deviations in the actual precipitation measurements at the stations are classified as, due to the weather, non-climatological.

The actual amounts of precipitation at the stations can therefore be interpolated according to distance in the form of values relative to the precipitation reference value and transferred onto the grid (background area method). The relative values interpolated for each grid area are converted into data (in millimetres) by multiplying with the absolute amounts of precipitation of the reference area. The corresponding mean monthly precipitation reference areas for the period 1961 to 1990 are used as background areas for the computation of actual daily amounts of precipitation. The amounts of areal precipitation are obtained as the arithmetic mean of the grid values that are within the boundaries of the area.

BONIE is a procedure which can, on the one hand, be used operationally for flood forecasting and, on the other, for hydroclimatological investigations (Kremser and Reich, 1991; Reich, 1998). An arbitrary number of spatially-irregular measurement values are copied onto a regular network of grid points, the mesh size of which is at present 6’ in an east-west direction and 4’ in a north-south direction. The mesh size can be altered but this requires certain preparations.

BONIE is based on a learning algorithm derived from the theory of artificial intelligence. On the basis of sufficiently long series of daily precipitation values dependent on relief and weather, BONIE separates various characteristic spatial distribution patterns in a particular analysis region. It derives the various mathematical-statistical attributes of this pattern, above all the spatial correlation, but also the dependence on the relief and the geographical position, and ‘recognizes’, on the basis of the measurement values of one particular day, the corresponding pattern. These patterns are referred to as background area.

With the background information taken from this pattern it is possible to determine the spatial distribution of precipitation more accurately than with any other procedure, also when there are limited gaps in the data. Instead of the background areas derived from climatic data, radar measurements can also be used.

The analysis regions have an area of approximately 10,000 km² and are usually identical with the river catchment areas or parts thereof.

The grid point values are interpolated with the help of the statistical interpolation method similar to that of Kriging on the basis of all measurement values available in the area (and not just the nearest as in the quadrant method). The estimated value of the area size \( f \) (corresponding to \( z \) in Subchapter 4.2) is calculated for the grid point \( g \) from the measured values at the stations \( i \) according to the following equation:

\[
\hat{f}_g \approx f^b_g + \sum_i w_i (f_i - z^b_i)^2
\]

where the superscript \( b \) refers to the value of the background area and the superscript \( o \) to the measured size of the area. The aim of
CHAPTER 4 — ESTIMATION OF AREAL PRECIPITATION AND AREA EVAPORATION

37

the estimation of the interpolation weights \( w_i \) is to minimize the interpolation error in the average of all measurements:

\[
\epsilon_g^2 = \frac{1}{M} \sum_{i=1}^{M} (f_{gi} - \hat{f}_{gi})^2 = \text{Min} \quad (4.8)
\]

The calculation of the interpolation weights is based on the following equation:

\[
\sum_{i=1}^{N} (a_{ij} + o_{ij}) w_i = a_{ij}; j = 1, \ldots, N \quad (4.9)
\]

whereby \( a_{ij} \) and \( o_{ij} \) stand for the correlation coefficients of the anomalies \( f_{i} - f_{j} \) from the background area at the stations \( i \) and \( j \) or at the grid point \( g \) and at the station \( j \). \( a_{ij} \) refers to the correlation of the measured errors at the stations \( i \) and \( j \). Without any further discussion, it should be explained that those errors caused by measuring at stations \( i \) and/or \( j \), i.e. by their lack of representation compared with the surrounding area, are not correlated with each other, i.e. \( o_{ij} = O \) for \( i \neq j \) (errors due to faulty equipment have to be rectified using another method).

If the formulation of Equation 4.9 is generalized on a system with \( G \) grid points, i.e. \( G \) right sides, then the matrix is written:

\[
(A + O)W_G = A_G \quad (4.10)
\]

with \( (A + O) \) as a quadratic matrix with \( N \) lines. \( W_G \) and \( A_G \), on the other hand, are matrices with \( N \) lines and \( G \) columns. The \( w_i \) are included in Equation 4.7.

With this equation, interpolation errors in the statistics of averages are minimal. An example for the operational application of BONIE at the Deutscher Wetterdienst is shown in Figure 4.2.

The areal value is calculated by mathematically averaging the grid point values. If the distance between grid points is sufficiently small, this arithmetic mean will correspond to the spatial integral of the measurements — the actual areal value.

4.5 AREAL EVAPORATION

The areal evaporation of a catchment area can be calculated by balancing the regional mean values of all water balance elements of this area (see Subchapter 4.1):

\[
P_A + ET_A + Q + \Delta W = 0 \quad (4.11)
\]

where:

- \( P_A \): Areal precipitation (with correction of the systematic error in measurement);
- \( ET_A \): Areal evaporation;
- \( Q \): Discharge (above and under the ground);
- \( W \): Available water supply in the area, \( \Delta W \): Change in available water supply in the period of observation.

The evaluation of a possibly existent underground discharge component and especially the change in available water supply \( \Delta W \) for e.g. monthly periods requires complicated measuring in order to prepare soil moisture and ground water level hydrographs. The water balance equation is therefore essentially used for scientific investigations into regional water balance and areal evaporation (Ernstberger, 1987; Jaworski, 1985; Schädler, 1980; Szabo, 1985).

For a period of 20 years it can be assumed that the sum of the positive and negative storage changes \( \Delta W \) is about zero:

\[
\bar{ET}_A = \bar{P}_A - \bar{Q} \quad (4.12)
\]

In the selection of the year series, care should be taken that weather and soil water conditions are more or less average at the beginning and end of the period because, if the conditions differ too much from these, then \( \Delta W > 0 \) cannot be assumed. The calculation of areal evaporation according to Equation 4.12 presupposes a compact catchment area, the above-ground and under-ground watersheds of which correspond, which shows no diversion or feed of imported water. The given presuppositions and the long period of measurements limit the obvious practicability of the procedure for many hydrological tasks. The procedure is mainly used for the adaptation and evaluation of the results of areal evaporation models.

Already the older procedures presented in the literature calculate the areal evaporation from meteorological standard data with the help of regression equations. Kalweit (1953) correlated the amount of areal evaporation with the saturation deficit and prepared with this method a time series of the monthly areal evaporation for the Spree catchment area. The regression functions were based on lysimeter measurements and evaluations of the water balance Equations 4.11 and 4.12.

Regression equations are also used for determining areal evaporation with satellite-based data. The International Satellite Land-Surface Climatology Project (Becker, Bolle and Rowntree, 1988) computes, for example, the areal evaporation \( ETA \) over parts of Mali, south-east France and Libya according to the following equation:

\[
ET_A = b_1 + b_2 R + b_3 \Delta T \quad (4.13)
\]

Radiation balance \( R \) and the difference \( \Delta T = T_0 - T \) between surface and air temperatures were each measured for daily intervals and for a spatial scale that depends on the resolution of the satellite (NOAA, LANDSAT; MOS). Equation 4.13 can be interpreted as an abstraction of a Penman variation presented by Schröder (1985) and Petznick (1988): \( b_2 R \) is the energy term and \( b_3 \Delta T \) is the ventilation term. Satellite-based measurements for the computation of areal evaporation are used within the framework of scientific research. Worldwide, intensive work on the development of models for the quantitative, satellite-based computation of areal evaporation is being carried out.

![Figure 4.2 — Example of a BONIE operational routine plot precipitation depths from 03.09.2000 6 a.m. to 04.09.2000 6 a.m.](image)
In hydrological and water management practices, an inductive procedure is usual for the computation of areal evaporation. The region in question is not homogeneous, thus it is divided into hydrotopes with a quasi-homogeneous land use, on which the methods described in Subchapter 4.2 are used for the calculation of evaporation from vegetation-bearing areas (taking into consideration the kind of soil and vegetation), sealed areas and bodies of water. The evaporation mean for the area — the areal evaporation — results from the amounts of evaporation of the individual hydrotopes and from their proportion of the area. On the basis of this calculation method, areal evaporation time series, which are of interest for many tasks, are prepared, taking into consideration land use, land use changes, land use scenarios and the effects of these on areal evaporation and areal water balance.

Various methods can be used to calculate the mean value of areal evaporation:

(a) For small areas or for a small number of hydrotopes, the areal evaporation is usually easily calculated as the weighted mean value of the evaporation of the individual hydrotopes according to their areal proportions;

(b) For larger areas, within which regional changes of the meteorological data used in the models occur, a grid calculation is recommended. The areal evaporation is shown as an arithmetic mean of the amounts of evaporation from the grid areas. Furthermore, the regional distribution of the amounts of evaporation can be shown graphically. The size of the grid areas depends on the density of the available data and the accuracy of the meteorological and non-meteorological input data as well as the accuracy of the evaporation models used (model errors). This calculation can be carried out easily with the help of geographical information systems (GIS). In the GIS procedure, the grid values of the soil and land use data intersect with the — possibly regionally — interpolated meteorological model data.

The models BAGROV (Glugla et al., 1999) and VEKOS (Klämt, 1988) and the water balance model AKWA (Golf and Luckner, 1991) are examples of models that have been developed in Germany for the computation of areal evaporation. These models have been set up for routine and practical use. As input variables, they use data from the meteorological standard network and the data available for the whole of Germany for soil parameters and for land use (see BMU, 2000).
CHAPTER 5

QUANTITATIVE PRECIPITATION FORECASTING

5.1 PRECIPITATION

Precipitation reaching the ground is the final product of a number of processes in the atmosphere. Dynamic, thermodynamical and cloud-physical processes developing on various scales are involved. They extend from the synoptic scale with cyclones via the mesoscale, with frontal and convective systems up to the microscale, within which the cloud-physical processes occur (Figure 2.1). There are interactions between all these processes. Figure 2.8 shows the large variety of microphysical processes.

Precipitation worth noting normally falls from clouds of a certain depth. Clouds occur in many forms. They form when the air is supersaturated with respect to water or ice. Supersaturation occurs as a result of the cooling of the air following lifting or mixing processes, i.e. through vertical or horizontal transport processes as well as through contact with the radiating surface. A predominant influence on cloud formation and consequently on precipitation comes from moisture convergence in the lower layers of the atmosphere and from vertical motion. All three aggregate conditions of the water (phases) play a role in precipitation formation. In mid-latitudes, it is in particular the ice phase which contributes to the effectiveness of precipitation formation (Bergeron-Findeisen process).

In precipitation forecasting, a distinction is made between stable and convective precipitation depending on the mechanisms of formation.

Stable precipitation forms whenever there is a large-scale ascent of stably stratified and sufficiently humid air caused by dynamic processes, e.g. in warm fronts. The vertical velocity is only within the range of a few centimetres. If condensation occurs, then extended layer clouds of the type Cirrostratus, Altostratus and Nimbostratus are formed. Considering the spatial distribution of stable precipitation, it can be said that it covers areas with characteristic lengths of 1 000 km at low horizontal variability. For this reason, it is also designated as large-scale precipitation. The local duration of the rainfall is several hours. On the windward side of mountains, the ascending motion is intensified due to the orography, leading to higher precipitation depth.

Convective precipitation presupposes vertical mass overturnings with condensation in unstably stratified atmospheric layers (moist convection). Unstable temperature stratification occurs as a result of heating of lower and/or cooling of upper atmospheric layers due to radiation or advection. Convection clouds (Cumuli, Cumulonimbi) with varying vertical depth are the visible signs for mass overturnings related to moist convection. This occurs in cells with characteristic horizontal lengths of one to 10 km. The vertical velocity occurring in convective clouds is higher by two orders of magnitude as compared to that observed at large-scale lifting. The convective precipitation field is characterized by high temporal and spatial variability. The triggering of moist convection is also influenced by properties of the Earth’s surface (e.g. orography, soil water content).

In mid-latitudes, moist convection with showers is a typical phenomenon within the area of cold air, occurring in the rear of a cyclone. Convective clouds may organize to form major mesoscale systems (order of magnitude: 100 km), in lines along fronts and squall lines or in compact form as a cloud cluster. The most impressive phenomenon of organized convection is the tropical cyclone. Owing to the high water vapour content of the air, enormous precipitation depths are observed.

Convective overturnings may also occur in areas with ascending air on a large scale, e.g. in fronts. Convective clouds are then embedded in layer clouds and the stable precipitation is intensified convectively.

Figure 5.1 shows the high variety of precipitation patterns in the area of an extratropical cyclone. Different types of mesoscale precipitation bands described by Matjeka, Houze and Hobbs (1981) and Tetzlaff (1987) can be seen. Type 1a designates precipitation fields ahead of and type 1b precipitation fields along warm fronts. In the layer cloud, which consists predominantly of stably stratified layers, small pockets of cold air are observed. These lead to a small-scale cell formation with the formation of ice crystals which trigger off the Bergeron-Findeisen process in the cloud below and then lead to a locally intensified precipitation band. Type 2 represents a precipitation band ahead of the cold front in the warm sector and corresponds to a squall line. The precipitation bands along cold fronts are organized in accordance with circulation perpendicular to the front (type 3) and are associated with clouds of varying vertical depth. In this case, depending on the intensity of precipitation, two classes are distinguished (type 3a and type 3b). Relatively rarely cold air advances in upper levels ahead of the surface cold front. Then precipitation of high intensity is observed locally. Precipitation is arranged here in the form of bands or cells (type 4a and type 4b). Moreover, in the cold air following the cold front, precipitation bands may occur (type 5).

Figure 5.1 — Typical mesoscale precipitation patterns of extratropical cyclones (Matjeka, Houze and Hobbs, 1981).
5.2 QUANTITATIVE PRECIPITATION FORECASTING PROCEDURES

Quantitative precipitation forecasting includes the spatial and temporal distribution of precipitation (occurrence, onset, duration, intensity) in addition to the forecasting of the type of precipitation (e.g. rain, snow, hail). This requires the knowledge and description of atmospheric processes on various scales relevant to precipitation formation and taking into account their interactions.

First attempts to produce quantitative precipitation forecasts were based on synoptic or statistical methods. The problem of quantitative precipitation forecasting could be tackled in the past decades on a mathematical-physical basis. This is due to an enlarged knowledge in atmospheric dynamics, thermodynamics and microphysics as well as with the aid of the facilities provided by numerical weather prediction (NWP) (Chapter 5.2.3).

The procedures for quantitative precipitation forecasting presented hereafter reflect the historical development which involve an increase in complexity. Subdivision and designation of the various methods are oriented on Belloq (1980) and Grebner (1982). For an evaluation of the procedures, reference could be made to Grebner (1982), who has given a survey on procedures applied in Europe.

In this chapter, a distinction is made between the following:

(a) Synoptic-statistical procedures;
(b) Stochastic procedures;
(c) Dynamic models;
(d) Dynamic-statistical model interpretation; and
(e) Remote-sensing procedures.

The compilation was made mainly from a national point of view as at 1998 and presents the methods by means of prototypical examples. Although the first two methods (a) and (b) are now of lower importance in synoptic meteorology, they have gained renewed interest in climatology and global change analysis.

5.2.1 Synoptic-statistical procedures

The synoptic-statistical procedures are based on the assumption that precipitation on the ground is statistically interrelated with a combination of values characterizing atmospheric conditions as well as their variations up to the initial time of the forecast. These interrelations can be described by regression relationships or a collection of similar cases. The forecast procedures based on these methods produce estimations for precipitation classes and will be explained hereafter under the terms “regression procedure” and “similarity procedure”.

Regression procedure

This procedure establishes regression relationships between predictors (variables of the state of atmospheric fields such as pressure gradient, pressure tendency, moisture conditions at certain pressure levels) and the value to be predicted (predictand, e.g. precipitation depth). The forecast period is determined by the time period, for which significant relationships exist between measured and predicted data. Derivation of the regression equations is made separately for the individual annual seasons. According to Grebner (1982) the method can be evaluated as follows:

(a) Advantages:
   (i) Input data (predictors) are variables used in synoptics; and
   (ii) Minor requirement for computer capacity and computing time;

(b) Disadvantages:
   (i) Limitation mainly to weather situations with large-scale precipitation;
   (ii) Exclusively region-specific procedure;
   (iii) Great variance of results;
   (iv) Fixed forecast period of estimations;
   (v) Precipitation estimation possible only in the form of classes.

Example:

A regression procedure of the Swiss Meteorological Institute at Zurich produced quantitative precipitation forecasts exclusively for winter cyclonic weather situations on the northern side of the Swiss Alps up to about 1983. Basic meteorological assumptions for the pressure and wind field are that the forecast area is situated in a frontal zone and the advected air masses show a high absolute moisture.

The statistical basic material is composed of the following data: the measurements from 25 precipitation stations, the variables of state of the atmospheric fields (taken from the calendar of weather situations, tabular radiosonde values of Payerne, weather charts) and the four-day precipitation depths of 53 episodes for the years 1951 to 1967 of at least 10 mm areal precipitation on the northern side of the Swiss Alps.

Then follows an analysis of the relationship between precipitation depth and the values of atmospheric variables and the selection of the predictors. The four-day mean wind speed at the 500 hPa level and the four-day means of the dew points in 850, 700 and 500 hPa show the highest correlation coefficients with precipitation depth (predictand). Therefore, regression equations were set up for them (Figure 5.2).

That method produces four-day precipitation depths (areal means). Application to cases mostly in the winter months of 1967/1968/1969 showed good results. On days during which precipitation was to be expected, the predictor wind speed at 500 hPa was taken from the American NWP charts. The dewpoints were determined from observations of the Payerne radiosonde station and from two stations situated upstream.

Then the predictors were inserted in the derived regression equation. According to Table 5.1, the mean difference between the measured and the predicted precipitation depths is 8.7 mm.

Just as in the case of dynamic models, low precipitation depths are often overestimated and high amounts underestimated. The Swiss procedure cannot be directly transferred to other areas. A further disadvantage of the procedure is in particular its limitation to precipitation caused by dynamic and orographic effects and consequently to specified precipitation situations.

Similarity procedure

In this case, one proceeds on the hypothesis of similarity in a way that cases independent from one another but similar because of synoptic criteria of similarity develop similarly and show comparable precipitation depths. The procedure is based on
historical data sets (reference cases). For a concrete case, the most
synoptically similar weather situation is selected. The relevant
precipitation distribution is used as a forecast for the concrete case.
Unlike in the regression procedure, this method always resorts to
the original, historical data material. There is no regression equation
in between.

The advantages according to Grebner (1982) include:
(a) Information on the areal distribution of precipitation as
compared to the regression procedure; and
(b) Easily estimated precipitation amounts to be expected
provided that there are several similar reference cases.

The disadvantages according to Grebner (1982) include:
(a) Suited only for large-scale precipitation caused by dynamic
effects;
(b) Difficult determination of criteria of similarity;
(c) Similar initial conditions do not automatically entail corre-
sponding further developments;
(d) High storage requirement for reference cases;
(e) Valid for 24 to 48 hours, partial time periods of less than 24
hours being unpractical; and
(f) Rare cases with high precipitation amounts badly repre-
sented in the absence of any special selection procedures.

It is common to all synoptic-statistical procedures that the
quality of forecasts for convective precipitation is low.
Example:
A similarity procedure for the estimation of heavy rainfalls for
catchment basins in north-west England and north Wales is
described by Holgate (1973). Temperature and moisture
values, e.g. for the Langdale Valley, Cumberland (north-west
England) are 36 mm and 6 mm h⁻¹, respectively (Holgate, 1973).
Between 1954 and 1963 these criteria were met in 35 cases. Based
on this experience, the following criteria for continuous heavy
rainfalls were developed for that catchment basin (Figure 5.3):
(a) A low moves in an easterly or northerly direction along an
Iceland-Cornwall line before it is fully developed;
(b) The warm front of the low is being occluded when reaching
the catchment basin; and
(c) The relative humidity in the warm air is high and this
uniformly from the ground up to the 650 hPa level.

The procedure is not able to catch individual convection
cells and the resultant showers. In general, more precipitation was
predicted than actually occurred so that more flood warnings than
necessary were issued. Table 5.2 shows the number of precipitation
events which were above the critical threshold value and were
correctly estimated as compared to the number of events which
actually occurred.

Table 5.1
Comparison of measured and computed mean precipitation
depths from 25 stations on the northern side of the Swiss Alps
(Courvoisier, 1970)

<table>
<thead>
<tr>
<th>Output date of forecast</th>
<th>Computed 4-day precipitation depth (mm)</th>
<th>Measured 4-day precipitation depth (mm)</th>
<th>Difference computed — measured (mm)</th>
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<tbody>
<tr>
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<td>32.2</td>
<td>24.2</td>
<td>+ 8.0</td>
</tr>
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<td>16.10.67</td>
<td>34.2</td>
<td>20.0</td>
<td>+ 14.2</td>
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<td>29.8</td>
<td>+ 3.2</td>
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<td>15.0</td>
<td>+ 7.3</td>
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<td>33.4</td>
<td>38.6</td>
<td>−5.2</td>
</tr>
<tr>
<td>28.11.69</td>
<td>17.7</td>
<td>6.8</td>
<td>−10.9</td>
</tr>
<tr>
<td>03.12.69</td>
<td>24.6</td>
<td>27.4</td>
<td>−2.8</td>
</tr>
</tbody>
</table>

Figure 5.2 — Interdependence of four-day precipitation depth as areal
mean on the northern side of the Alps and four-day mean of the wind
velocity at 500 hPa (above) and of the dew points at 850, 700 and 500
hPa (below) (Courvoisier, 1970).
5.2.2 Stochastic procedures

Stochastic procedures were developed in conjunction with runoff models for catchment basins with a short system response time in order to provide runoff forecasts as early as possible to have as much time as possible for decisions on regulations between the time of the forecast and the arrival of the flood wave. Stochastic procedures proceed on the assumption that within a series of measurements, there exist mathematically describable statistical correlations which can be used for probabilistic estimation of the further development of measurement series. The statement whether precipitation will fall or not is not possible. A prerequisite for the estimation of precipitation with the aid of the stochastic procedure is that the precipitation event has already started. The physical conditions of the precipitation process are disregarded in this case. Input data are exclusively measured precipitation data (depth, duration, intensity).

A reason for using this procedure is the poor forecast quality of dynamic models for small catchment basins (up to 42 METEOROLOGICAL SYSTEMS FOR HYDROLOGICAL PURPOSES

Table 5.2

Results obtained with the similarity procedure according to Holgate for the Langdale region, Cumberland (Holgate, 1973 modified)

<table>
<thead>
<tr>
<th>Period</th>
<th>Critical threshold value</th>
<th>Number of observed events</th>
<th>Number of correct forecasts</th>
<th>Total number of forecasts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965–66</td>
<td>24 mm total</td>
<td>11</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>4 mm h⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1966–68</td>
<td>36 mm total</td>
<td>13</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>6 mm h⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1968–72</td>
<td>16 mm total</td>
<td>50</td>
<td>38</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>4 mm h⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.3 — Track and development of cyclones from 29–31 October 1965 (Holgate, 1973).

Figure 5.4 — Preparatory work for the establishment of a forecast algorithm of a stochastic model.
regressions between the logarithms of precipitation depth and duration is not so favourable (Klatt, 1983).

All in all, the deviations between estimated and measured precipitation in the direction of a too-high precipitation estimation show a skew distribution and considerable variance (Figure 5.6). Too-low precipitation estimations or underestimations of major events are relatively seldom. However, deviations are considerable. The selection of the adequate non-exceedance probability depends on the goal set. While for the operation of a multipurpose storage, a non-exceedance probability (Pu) of approximately 60 per cent appears reasonable, the total of all deviations considered over a longer time period equalling approximately zero; for flood forecasts, Pu > 60 per cent must be selected (Klatt, 1983).

For precipitation estimation, Markov-chain models can also be used. On the basis of empirically-determined conditional probability functions, they produce any occurrence probabilities for future precipitation depths and/or intensities.

For successful application of such stochastic procedures, it is indispensable to carry out a correlation analysis of already available precipitation events, including their potential linear transformations. For a temporal estimation, only data or their linear transformations should be used. They show a high degree of autocorrelations for as many successive estimation intervals as possible.

These procedures, which are described, for instance, by Lattermann (1983) and Schilling (1983a, 1983b), do not take into account the precipitation depths of events nor simple non-exceedance and exceedance probabilities, but probabilities of transition from one state into another in the course of an event.

Spatial precipitation variability can hardly be described by means of this model technique, even if there is a significant spatial correlation of stations. If spatial correlation is insignificant, the results are not usable.

5.2.3 Dynamic models

5.2.3.1 General characteristics and survey

Dynamic models are physical-mathematical models, so-called NWP models, which describe the spatial-temporal behaviour of precipitation in the direction of a too-high precipitation estimation show a skew distribution and considerable variance (Figure 5.6). Too-low precipitation estimations or underestimations of major events are relatively seldom. However, deviations are considerable. The selection of the adequate non-exceedance probability depends on the goal set. While for the operation of a multipurpose storage, a non-exceedance probability (Pu) of approximately 60 per cent appears reasonable, the total of all deviations considered over a longer time period equalling approximately zero; for flood forecasts, Pu > 60 per cent must be selected (Klatt, 1983).

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atmospheric processes in a deterministic way. In all NWP models which are at present being used operationally by the Meteorological Services, the formation of precipitation is simulated. This means that apart from other weather parameters, such as surface pressure, temperature, wind speed, etc., the weather parameter precipitation is computed at any time.

NWP models are based on the physical laws, such as conservation of momentum, mass and energy. These are reflected in the equations of motion, continuity and thermodynamics. Other important model equations are the equation of state and — for most models — the hydrostatic equation. Models considering moisture processes use, in addition, equations for moisture variables.

From a mathematical point of view, a weather prediction model consists of a discrete system of non-linear partial differential equations. After having set the initial and boundary conditions, the time development of the meteorological variables is computed approximately via the coupled equations (of a prognostic and diagnostic type) with the aid of special numerical procedures.

Depending on the numerical treatment of the differential equations, a distinction is made mainly between two groups of models, i.e. grid point models and spectral models. If the derivations with respect to time and space are approximated by finite differences, then the model concerned is a grid point model. The fields of the variables are given as discrete values at the grid points of a three-dimensional grid. In the case of spectral models, however, the fields of the variables with regard to the horizontal are represented as a linear combination of spherical harmonics with time-dependent coefficients. Horizontal derivatives in this case can be computed analytically (Haltiner and Williams, 1980).

Important characteristics of the numerical structure of a weather prediction model are:

(a) Number of vertical layers;
(b) For grid point models: size of horizontal mesh width;
(c) For spectral models: the highest possible number of waves which can be represented on a great circle (truncated wave number); and
(d) Time stepping scheme.

The rapid development of NWP models during recent decades has been closely linked to growing computer power. Increasing computational speed and storage capacity are associated with increasing horizontal and vertical resolution and an extended refinement of the parameterization of physical processes.

In operational weather prediction models, the following physical processes are taken into account in a parameterized form in addition to the simulation of horizontal and vertical advection and to the effect of pressure and Coriolis force:

(a) Turbulent transport of momentum, sensible and latent heat;
(b) Formation of stable and convective precipitation within the hydrological cycle;
(c) Radiation; and
(d) Soil processes.

Out of the large number of parameters describing the characteristics of the Earth’s surface, at least orography is taken into account in the models.

As far as the horizontal extension of the model domain is concerned, a distinction is made between global models (the model domain covers the whole surface of the Earth) and limited area models (LAMs) (the model domain covers only a partial area of the Earth’s surface). The majority of the global models belong to the group of spectral models; limited area models, however, are mostly grid point models.

Spectral global models used for weather forecasting have a truncated wave number of T126 to T319, i.e. the smallest wave length which can be represented is between 300 and 125 km. The models produce forecasts for a time period of at least four days; the European Centre for Medium-range Weather Forecasts (ECMWF) at Reading (United Kingdom) disseminates forecasts of its global models for a time period of seven days. The models can simulate satisfactorily the large-scale motion of the atmosphere for the first days of the forecast. The quality of the forecasts decreases with increasing forecast period.

In 1999, the Deutscher Wetterdienst introduced the global grid point model GME (31 layers, horizontal mesh width $\Delta s = 55$ km) for operational use replacing the global spectral model (19 layers, T106). The GME uses an icosahedral-hexagonal grid (i.e. a nearly uniform triangular grid).

The production of global ensemble forecasts of the state of the atmosphere has become commonplace at many of the world’s operational prediction centres during the past decade (Molteni et al., 1996; Tracton and Kalney, 1993; Harrison et al., 1995). These ensemble forecasts are predicated on the notion that the state of the atmosphere as derived from all available observations is not known precisely, but can be represented in terms of a probability distribution. Operational ensemble forecast systems attempt to sample this initial state probability distribution and then produce samples of the resulting forecast probability distribution by integrating each individual member of the sample independently in a forecast model, usually a model developed for use in producing more traditional single discrete forecasts. This is called a single-model ensemble prediction approach. In some ensemble prediction systems the uncertainty of model formulation is also taken into account by selecting different model options of parameterization of horizontal diffusion, deep convection, radiation, gravity drag, orography, etc. (Houtekamer et al., 1996).

In addition to the single-model approach there also exists a multi-model approach. This approach uses different models with different physics, numerics and truncations. Each model starts from its own analysis, thus differences in the initial conditions are also present. (Balzer and Eimmrich, 1997; Ziehmann, 2000).

Many operational prediction centres now routinely deliver a variety of ensemble-based products to forecasters. One example of such a product is a map of contours of the probability that precipitation amount exceeding 1 mm will fall during a given time interval.

A higher spatial resolution (vertical and horizontal) is achieved with the aid of limited area models. The objective of higher resolution over a limited area is to obtain higher accuracy of the near-surface weather parameters (temperature and moisture at 2 m, wind at 10 m, cloud cover and precipitation) due to a better representation, e.g. of the Earth surface characteristics.

Most of the limited area models are conceived for the meso-$\beta$ scale (processes with characteristic horizontal length between 20 and 200 km) (Figure 2.1). State of the art models are characterized by horizontal mesh widths of 5–55 km, 15–45 layers, five to 15 of which represent the lowest two km of the atmosphere (boundary layer). Depending on the computer capacity available, model domains with up to approximately 100 000 grid points at a
level are selected. The forecasts cover a period (forecast period) of one to three days. Limited area models with the above-mentioned or with a higher resolution are also called regional models because of the smaller model domain covered.

Examples of regional models for the meso-β scale which were in operational use for weather forecasting in 1999 are as follows:

Germany: LM (central and western Europe, 35 layers, \( \Delta s \approx 7 \) km);

United Kingdom: Mesoscale Unified Model (north-western Europe/north-eastern Atlantic, 38 layers, \( \Delta s \approx 11 \) km);

Norway: High-resolution limited area model (HIRLAM) (version 1: Europe/North Atlantic, Polar Basin, northern areas of Russia and America, 31 layers, \( \Delta s = 55 \) km; version 2: north-western Europe, Norwegian Sea, 31 layers, \( \Delta s = 27 \) km);

United States: Eta-32 model (northern America, north-eastern Pacific, north-western Atlantic, 45 layers, \( \Delta s = 32 \) km);

Canada: GEM model (northern America, 28 levels, \( \Delta s = 24 \) km).

The Deutscher Wetterdienst plans to increase the horizontal resolution of the operational model LM to \( \Delta s = 2.8 \) km in 2002. In this second-stage application, the LM model will also simulate processes on the meso-γ scale (processes with characteristic horizontal length between 2 and 20 km).

Limited area models require time-dependent boundary values from a global or meso-α model, whereas high-resolution regional models for the meso-γ scale take them from a meso-β model.

The production of ensemble forecasts with the aid of limited area models is still a very difficult task. It is presently confined to a few experimental systems.

Information on the state and development of operational weather prediction models of the individual Weather Services can be found in the annually published Numerical Weather Prediction Progress Report (WMO, 1999).

5.2.3.2 System of numerical weather prediction

NWP models are embedded in the NWP system. Within this system they represent the central component, but predictions are not possible without the entire NWP system. Other important components within the NWP system are meteorological observations obtained with the aid of the observing system, the initial state (analysis, initialization) as well as verification. In Figure 5.7, the NWP system of the Deutscher Wetterdienst has been schematically represented.

The meteorological observing systems described in Chapter 3 provide surface and upper-air observations as well as remote-sensing data. Via the GTS, observations (messages) must be rapidly and reliably transmitted to the individual Weather Service centres (Chapter 6). After having been decoded, sorted and checked for transmission errors and internal consistency, the messages are stored in a meteorological data bank. The observational data are needed for the description of the atmospheric state at a certain time, i.e. for the analysis and for the verification of predictions.

The starting point of any forecast is knowledge of the initial conditions, i.e. of the three-dimensional state of the
atmosphere at the initial time of the forecast. For this purpose, the meteorological variables must be determined with the aid of an extensive procedure at the points of a three-dimensional grid covering the atmosphere (numerical analysis). Within the analysis procedure, meteorological data from irregularly distributed stations are interpolated onto the given grid points.

At the Deutscher Wetterdienst, global analyses are made on the grid of the GME model ($\Delta \approx 55$ km) valid at 0000, 0600, 1200 and 1800 UTC. The following parameters are analysed: surface pressure, geopotential height and wind components at 31 pressure levels, relative humidity at the lower pressure levels, sea surface temperature (0000 UTC) and snow depth (0000, 0600, 1200 and 1800 UTC).

The commonly applied method of multivariate optimum interpolation is used to analyse surface pressure, geopotential height and wind components. The six-hour GME forecast valid at the analysis time serves as the initial approximation (initial guess) for the analysis.

With the sequence of GME analyses at six-hour intervals and six-hourly GME forecasts, the data assimilation is performed by adjusting the model atmosphere to the observations every six hours. The temporal and spatial aspect of this data assimilation is expressed in terms of four-dimensional data assimilation (Wergen, 1984).

For the LM, analyses of the horizontal wind vector, potential temperature, relative humidity and near-surface pressure are continuously made on the grid of the LM (central and western Europe, $\Delta \approx 7$ km) by nudging the model atmosphere towards observations. Besides synoptic observations (which are confined to a fixed time schedule) also continuous observations, such as aircraft observations, are used. The analyses are stored at hourly intervals.

Prior to any forecast run of the model, the initialization of the fields of variables must be carried out to remove initial noise from the forecast. This means fine tuning so that during forecasting, the amplitudes of gravity-inertia waves are not unrealistically large, thus impairing the meteorologically important processes (Wergen, 1984). The amplitudes of gravity-inertia waves must be kept small in order to allow a quality control of observations within the four-dimensional data assimilation with the aid of the forecasts over six hours. With the models of GME and LM of the Deutscher Wetterdienst, a digital filtering scheme is used in order to reduce the amplitudes of the gravity-inertia waves during the simulation (Lynch, Giard and Ivanovic, 1997).

The model results must be subjected to careful interpretation by a meteorologist, in particular for local applications. Only spatial systems which have a size of at least several grid points can be represented realistically, because the differing schemes usually cause errors in the smallest wavelengths of the forecast field. Furthermore, attention should be given to the fact that the values of the variables at the grid points are representative of the respective volume element. They must not be considered as local forecast values for the location of the grid point. This also applies to precipitation. Statistical procedures such as Perfect Prog and Model Output Statistics are an important aid for local interpretation (Subchapter 5.2.4).

The systematic daily verification of numerical forecasts serves for the control of success and further model improvement. At the Deutscher Wetterdienst, predicted fields of numerous variables are compared with the corresponding fields of analysis and/or with observations.

The schedule of global analyses and forecasts in the present NWP system of the Deutscher Wetterdienst distinguishes between early runs and main runs. Early runs start about 2.25 hours after analysis time, whereas main runs start about 4 hours after analysis time. The advantage of the early run is a quite early completion of the forecast. The forecast of the main run is expected to be more reliable, though, because more observational data are available when the main run is started.

The GME computes two main runs a day, which produce 174-hour forecasts and are based on the analyses of 0000 and 1200 UTC, respectively. Additionally, three early runs are computed for 0000, 1200 and 1800 UTC to provide lateral boundary values for the LM. Accordingly, the LM is run three times a day to produce 48-hour forecasts starting at 0000, 1200 and 1800 UTC.

The operational run time for a 174-hour GME forecast on the CRAY T3E 1200 distributed memory massively parallel processor (MPP) of the Deutscher Wetterdienst is about 2 hours 40 minutes. A 48-hour LM forecast run in conjunction with its corresponding GME run takes about 1 hour.

An operational NWP system which is to produce forecasts under operational constraints requires an efficient computer system: vector computer, possibility of parallel computations on several processors, computer performance of many GFlops (Giga floating point operations per second) and main storage for several Gigabytes. Such conditions can be met only at a central agency of the respective NMS so that only here can quantitative precipitation forecasts be produced with the aid of a routinely operated NWP system.

5.2.3.3 Precipitation Forecasting with the Aid of the Routine Models GME and LM

The present NWP system of the Deutscher Wetterdienst consists of the global model GME (global, horizontal mesh width $\Delta \approx 55$ km, forecast period 174 hours) for synoptic and meso-$\alpha$ scale simulations and the high-resolution meso-$\beta$ scale model LM (western and central Europe, $\Delta \approx 7$ km, forecast period 48 hours) to allow for short-range weather forecasting in central and western Europe. Both models are grid point models: GME uses an icosahedral-hexagonal grid and LM uses a rotated latitude/longitude grid. In the GME model, the atmosphere is represented by 31 layers, and in the LM, by 35 layers. The GME works with a comparably high vertical resolution in the stratosphere, whereas the LM resolves the lowest part of the troposphere best with 12 layers in the lowest 2 000 m. In both models, moisture is included in all layers. The values at the lateral boundaries of the LM forecast domain are interpolated from GME fields and are updated every hour.

The physical complexity of both models is similar. A survey of the numerical and physical structure of the GME and LM models is given in Tables 5.3 and 5.4.

Hydrological cycle

The hydrological cycles of the GME model and the LM model include the following processes: grid-scale, convective and turbulent transport of moisture and cloud water content; condensation of water vapour and evaporation of cloud water; formation of rain and snow through various processes; freezing and evaporation of falling rain in the atmosphere; sublimation and melting of falling snow in the atmosphere; deposit of rain and snow on the ground. Soil processes are parameterized with the aid of two soil moisture layers and a Penman-Monteith type transpiration parameterization (Chapter 4.1.3.1).
In the GME and LM models, as normally done in NWP models, the distinction between the two types of precipitation (Subchapter 5.1) is made quite formally. Stable (or large-scale) precipitation is coupled with clouds filling up at least one grid point volume. Mostly, large-scale precipitation areas extend over several grid points. This type of precipitation is determined in the model directly from the variables at the grid points and is therefore designated as grid-scale precipitation. The second type of precipitation (convective precipitation) is coupled with convective overturnings whose characteristic horizontal length is smaller than the mesh width of the model. This subscale process must therefore be parameterized, i.e. it must be described with the aid of the variables at the grid points.

**Treatment of grid-scale precipitation**

The grid-scale scheme allows four hydrological components: water vapour, cloud water, rain, and snow. Between them, a couple of interactions is possible. Precipitation formation is initiated by autoconversion and nucleation, both temperature-dependent. Rain is generated by autoconversion from cloud water droplets which have formed after supersaturation of water vapour in a grid volume...
element, initiated mostly by grid-scale dynamic uplifting. A stratified cloud exists in this case. Rain drops may grow through accretion from cloud droplets. Snow is formed from cloud droplets through a simplified nucleation process, and it may grow by the riming of supercooled cloud droplets. This latter process together with the depositing of water vapour on snow are very efficient for precipitation formation in mid-latitudes (Bergeron-Findeisen-process). Further cloud-microphysical processes which are parameterized are melting and sublimation of snow, freezing and evaporation of rain and evaporation of cloud droplets. Rain and snow fall in the same column where they have been generated, because horizontal advection of precipitation is neglected.

Treatment of convective precipitation
Convective precipitation results from moist convective processes which occur on scales not resolved by the model. The mass flux parameterization scheme after Tiedtke (Tiedtke, 1989) is used to describe the effects of subgrid-scale convective transports of momentum, heat and moisture on the grid variables. A stationary one-dimensional bulk cloud model is used to simulate the processes taking place in an ensemble of convective clouds, such as up- and downdrafts and lateral mixing (entrainment/detrainment). There are three different types of convection: penetrative, mid-level and shallow convection. However, at a certain grid point, only one type at a time is allowed. Penetrative (deep) convection is initiated if horizontal advection of moisture is large, shallow convection if evaporation at the surface is dominant. Convective cloud coverage is not associated consistently with convective rain but is defined independently from the results of parameterized convective processes and is set 0.2.

Provision of precipitation forecasts
Model output
The GME/LM model output of precipitation consists of four components: grid-scale rain, grid-scale snow, convective rain and convective snow. During the model run, each precipitation component is summed up at every grid point from the beginning of the forecast and is stored in a meteorological data bank at hourly intervals as accumulated values at the model grid points (Direct Model Output (DMO)).

Analyses of the GME are available daily for 0000, 0600, 1200 and 1800 UTC; for the LM, the analyses are stored at hourly intervals. Forecasts are available as follows (Deutscher Wetterdienst, 1999):

GME:
- full domain (163 × 842 grid points; 31 levels)
  - 1 h – 78 h: every 1 hour
  - 81 h – 174 h: every 3 hours
- full domain (0.75° × 0.75° – grid; 480 × 241 grid points; 14 pressure levels)
  - 3 h – 174 hour: every 3 hours

LM:
- full domain (325 × 325 grid points; 35 levels)
  - 1 h – 48 h: every 1 hour
  - The above-mentioned fields are found in the WMO GRIB code and stored in the meteorological data bank. Just after the model run, data are transferred to the meteorological data archive and kept there for at least one year. The data bank serves as an interface to all follow-up programmes such as visualization, physical and statistical interpretation of forecasted precipitation (DMO) and hydrologic applications using QPF as input.
  - The spatial distribution of DMO accumulated over specific intervals is visualized. In addition, the temporal evolution of precipitation amount at selected grid points over central Europe along with other weather elements is plotted at hourly intervals for the model runs of LM (Figure 5.8). These graphical products are used at the Regional Forecast Centres of the Deutscher Wetterdienst for estimating areal precipitation and for issuing warnings of heavy precipitation.

Dissemination
Precipitation data forecasted by the models are disseminated via the GTS in GRIB and GRID code to other NMSs. In addition, data and plotted maps are distributed via Internet, the DWD’s satellite distribution system FAX-Europe and telefax, and the precipitation forecasts are available on the DWD’s server. Several hydrologic institutions in Germany receive LM-forecasted grid-point values up to 48 hours ahead at hourly intervals. Individual information and advice on heavy precipitation and interpretation of QPF are given by forecasters to hydrologists on demand. The Regional Forecast Centre in Leipzig issues estimations of areal precipitation of the Mulde and Spree river basins in east Germany valid for periods 0600–1200, 1200–1800 and 1800-0600 UTC once a day. Threshold values which are exceeded with a probability of 90, 50 and 10 per cent are subjectively estimated by the forecasters using DMO and model output statistics (see Subchapter 5.2.4) products.

Figure 5.8 — Extract from the meteogram for the BKF grid point ‘Trier’. 96-hour BKF forecast starting on 10 June 2000, 0000 UTC.
Quality of precipitation forecasting

Statements as to the quality of precipitation forecasts by means of NWP models should be made only on the basis of the results of a comprehensive verification. Such verification is, however, difficult as compared to the verification of other weather parameters.

The weather parameter precipitation can be described by several characteristics: onset, duration, type of precipitation, intensity curve and precipitation depth. A full verification must cover all of these characteristics.

A basic problem is that the precipitation value predicted at a grid point is to be interpreted as a mean value over the area of the grid square, while observations provide point values. For this reason, an areal mean must be derived from the precipitation measurements made at irregularly distributed stations, which may be situated at different altitudes. Precipitation analysis appears to be particularly difficult in the case of convective precipitation, showing considerable areal variability. When making comparisons, attention should be given to the fact that for the models, the elevation of the area assigned to the grid point normally corresponds to the elevation averaged over the grid square.

The current precipitation verification at the Deutscher Wetterdienst is carried out in two modes (Damrath et al., 2000). In the first mode, all available information from synoptic stations in Germany and Switzerland is used to assess the quality of the 12-hour precipitation amount twice a day. This set of observations covers about 240 stations. The second mode uses about 4 200 stations in Germany only. These stations report only the 24-hour precipitation amount, but they do not give reports in real time.

The determination of statistical measures for the quality of QPF is based on the comparison of station measurements of precipitation amount with the forecasted precipitation amount at the model grid point nearest to the station. With these data, contingency tables (see Table 5.5) for different thresholds of precipitation height are evaluated. In the first (synoptic) mode, the thresholds 0.0, 2.0, and 10.0 mm/12 h are used. In the second (non real time) mode, the thresholds are 0.0, 1.0, 2.0, 4.0, 8.0, and 16.0 mm/24 h. From the results A, B, C and D in the contingency table (see Table 5.5) various scores can be derived for ‘per cent correct’, ‘false alarm rate’ and most importantly ‘true skill statistics’ (TSS):

\[ TSS = 100 \frac{(AD - BC)}{(A + B)(C + D)} \]  

The range of TSS is from −100 to 100 with the value being 100 being for a perfect forecast.

Unfortunately, long-term verification results of the operational GME and LM forecasts are not available yet. Therefore, verification results of EM and DM forecasts are additionally presented. The models EM and DM had been in operation for about seven years until they were replaced by GME and LM in December 1999. For hydrological applications, mainly the precipitation forecasts with the models DM and LM are relevant. The LM now supports hydrological applications in a similar way as the DM used to.

The main difference between LM and DM is an increase in horizontal resolution (DM: Δs = 14 km; LM: Δs = 7 km). The LM also aims at a better description of the initial state by employing the nudging technique. Furthermore, the physics of LM (e.g. soil model, turbulence scheme, convective parametrization) will be upgraded. The LM is expected to produce forecasts of a somewhat better quality than the DM model.

To see how well the models capture the regional distribution of precipitation height, observed and forecasted precipitation distributions for February 1999 over Germany and over Switzerland are shown in Figure 5.9. It is obvious that with the high resolution DM and, especially LM, specific patterns of the precipitation field can be simulated fairly well. This particularly applies to orographically-forced large precipitation amounts over the mountainous regions of southern Germany and Switzerland. However, both an increase in precipitation on the windward side of the mountains and a decrease on the lee side are exaggerated by the models. This effect is observed not only in winter, when problems in the measurement of falling snow might lead to wrong conclusions concerning the verification of precipitation, but also throughout the summer (Damrath et al., 2000).

The following statistics (Damrath et al., 2000) demonstrate the long-term trend of precipitation forecast quality, the differences in forecast quality of EM and DM and the forecast quality with regard to day/night. Figure 5.10 shows the 12-month moving average of TSS for the thresholds 0.0 mm/12 h and 10.0 mm/24 h, respectively, for the forecasts starting at 0000 UTC and 1200 UTC. As can be seen, both the EM and the DM have nearly the same quality for the threshold 0.0 mm (Figure 5.10a and Figure 5.10b). Therefore, the decision ‘precipitation yes or no’ will be issued by both models with the same accuracy. This holds until September 1997, when the former 20-level version of DM was replaced with a 30-level version. Moreover, the area of DM was enlarged significantly (163 × 163 grid points instead of 109 × 109 grid points, the resolution remaining unchanged). The model forecasts for precipitation during the day are in general better than

Table 5.5
Contingency table for different thresholds of precipitation height

<table>
<thead>
<tr>
<th>Forecast over a given threshold</th>
<th>Observation over a given threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>A</td>
</tr>
<tr>
<td>YES</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>D</td>
</tr>
</tbody>
</table>
those for nocturnal precipitation. The advantages of the high-resolution DM compared to EM are obvious for precipitation amounts of more than 10 mm/12 h (Figures 5.10 and 5.10). Only during the first year of the moving averages presented in Figure 5.10 can a positive trend in forecast quality be seen. This is somewhat surprising since for other weather elements, such as wind and temperature, an increasing forecast quality has been noted in recent years. Again, it is confirmed that ‘precipitation is notorious for being difficult to quantitatively predict accurately’ as stated by Gaudet and Cotton (1998).

In case of a threshold of at least 3.0 mm/12h, the EM forecasts of QPF are superior to the forecaster’s judgement (Balzer, 1998). Only for thresholds of 0.5 mm/12h and 0.0 mm/12 h is the forecaster able to provide better forecasts than the EM model. In the last five years, forecasters have not been able to improve further the EM/DM forecasts of rare precipitation events (Balzer, 2000).

The verification statistics generally show better model performance during the winter months as compared to the summer months (Damrath et al., 2000). This points to a general problem of correctly parameterizing convective precipitation. This may result in comparatively poor QPF input to hydrologic models in cases of summertime flash floods. The use of the new models GME and LM is expected to improve this situation.

Finally, it is demonstrated how the numerical QPF forecast quality varies with forecast period and threshold value. Figure 5.11 presents the TSS of DM and EM forecasts for different thresholds (‘class limits’) and forecast periods (1–3 days ahead). Additionally, the TSS of a persistence forecast (PE) is shown. A persistence forecast assumes that the observed precipitation amount will persist in the future. Such a forecast often serves as a baseline for minimum forecast quality. Figure 5.11 clearly shows a decrease of forecast quality with increasing forecast period. This is due to the chaotic nature of the atmosphere. Furthermore, the forecast quality decreases with increasing precipitation threshold. Thus, it is more difficult to forecast a severe precipitation event than to issue the decision ‘precipitation yes or no’.

A correct precipitation forecast is an important factor in the forecast of floods. Several examples of numerical precipitation forecasts relevant for flooding events are presented in Damrath et al. (2000). In most cases, the former operational models of the Deutscher Wetterdienst (EM and DM) achieved good results, and the potential of the models of the current operational system (GME and LM) to realistically simulate these situations is even higher, this being very important for hydrologic applications.

The temporal evolution of precipitation in situations which had led to flooding events in the federal state of Baden-Württemberg (Germany) was investigated by Cress (1997). There
was sufficient similarity between forecast and observations, if the precipitation heights were averaged over an area. The comparison of precipitation at individual stations, however, revealed major differences in terms of phase and intensity. Thus, the precipitation forecast at a model grid point must not be interpreted as a prognosis of precipitation at a single location and a single point in time. It is suggested to use rather a window in space and time to estimate the exceedance probability of a certain precipitation threshold at a specific location. It is expected that this view will become even more important when using the higher resolution meso-γ models in future.

The results of precipitation verification described so far give an impression of the average model behaviour with regard to season, day/night, model, threshold value and forecast period. This information can be used only to a limited extent for the estimation of the quality in a specific individual case. Minimization of the systematic error in precipitation forecasting by means of statistical model interpretation is useful (Subchapter 5.2.4). For interpretation, it is helpful to use the results of simulations starting from preceding initial dates, to consider the precipitation values at neighbouring grid points, to have a look at precipitation forecasts of other models or to use ensemble forecasts.

### 5.2.3.4 Outlook

The computer capacity at the Deutscher Wetterdienst will be further upgraded during the coming years. A sustained speed of 0.5 TeraFlops on the MPP system is expected to be reached in 2002. This will allow a further improvement of the horizontal and vertical resolution of the operational GME and LM models. The final stage of the GME/LM system will be achieved in 2002. The horizontal resolution of the models will then have reached 28 km and 40 layers for GME and 2.8 km and 50 layers for LM. Output fields of LM will be provided every 15 minutes resulting in an enormous demand for data storage (Frühwald, 1998).

By this substantial increase of resolution, the LM will resolve processes of the meso-γ scale (2–20 km) which aims to improve local weather forecasting. Large convective systems can be resolved explicitly. This offers the possibility to forecast the transient precipitation patterns associated with such systems. In particular, in areas of strong orographic forcing, realistic convection patterns may be produced even when the initial field is interpolated from a model with a coarser mesh. Also, the influence of the ground on the time evolution of weather systems will be simulated more accurately by LM.

Cloud ice will be a prognostic variable allowing the simulation of Cirrus clouds. In the medium term, rain and snow will be treated through prognostic equations. The three-dimensional transport of hydrometeors may modify the precipitation pattern on the lee side of mountain ranges.

The continuous data assimilation (nudging method) for LM will also exploit remote-sensing data such as radar and lightning data. LM is envisaged to run in ‘nowcasting on demand mode’ in case of convective weather. Radar information has to be converted to a modified initial state at hourly intervals. Thus, a simulation with a forecast period of two to eight hours can start every one hour for estimating the propagation and evolution of severe weather associated with deep convection on the meso-γ scale.

Results of LM test simulations on the meso-γ scale with 2.8 km mesh size indicate that dynamics of deep convective cells will be reproduced rather realistically. However, for 24-hour predictions, time and location of the development of deep convection cannot be expected to be realistically represented by LM due to the chaotic nature of convection (Frühwald, 1998), thus requiring a careful interpretation of these upcoming QPF products.

### 5.2.4 Dynamic-statistical model interpretation

NWP models produce precipitation values which are assigned to a grid point and are to be interpreted as a representative value for the respective grid square. In practical weather forecasting, however, forecast values for individual locations are also required. It is possible that the elevation of such locations deviates considerably from the elevation assigned to the grid point, which implies that the weather parameters computed at the grid point cannot be simply transferred to such a location. With the aid of statistical follow-up procedures, it is possible to interpret the model results with reference to the respective location. Two methods are distinguished in this context:

(a) Perfect Prog (PP (Klein, Lewis and Enger, 1959); and
(b) Model Output Statistics (MOS) (Glahn and Lowry, 1972).

Both methods are based on the fact that from the data set of the predictors and of the required parameter (predictand, e.g. observed precipitation at the respective location), a relationship between predictors and predictand can be derived in the form of a multiple linear regression equation by means of a statistical analysis. Using that equation, the local predictor can be estimated in the actual case. That method is also applicable to areal precipitation, provided the area is smaller than the area of the grid square (ΔS)².

In the case of the PP method, the predictors are measured or analysed meteorological parameters; in the case of the MOS method, the predictors are selected from the set of parameters predicted from the model (Pander, 1982). In both cases, particularly those parameters which have a causal link to precipitation are suited as predictors. In the case of the PP method, a more comprehensive database (long-term observations) is normally available than in the case with the MOS method; for MOS, only model data from a time period during which no changes were made to the model can be used. A change made to the model requires recalculation of the multiple linear regression equation; however, minor changes to the model either do not have or have only a minor effect on the interpretation results. For a prognostic application of the PP method, the predictors have to be replaced by predicted model values. However, no specific prediction model is binding.

At the Deutscher Wetterdienst, a statistical interpretation scheme on the basis of MOS is applied to the GME results. It has been developed in close cooperation with Knüpffer (1998) for general forecasts and for special application in aviation meteorology. The MOS system was originally designed for the application to EM results. The data set for the evaluation of the regression equations consisted of daily EM forecasts up to 78 hours lead time and of hourly synoptic observations of 120 German and 120 European stations. The data set covered the time period from January 1992 until December 1998. The MOS system was then transferred to GME by rederiving the regression equations using the seven-year data set mentioned above and additional GME forecasts recomputed for a two-year period. The GME-forecasts were given a weighting factor of 2 in this process. The results so far have justified this procedure.

The MOS system uses a set of about 150 potential predictors of different types. Basically, the DMO variables...
(geopotential height, temperature, ...) are used. A second set of predictors consists of derived model variables (e.g. temperature advection and vorticity advection). Persistency predictors such as the latest observation or the latest statistical forecast are used as well. A variety of other predictors complement the set. The predictands have been defined partly in categorical and partly in probabilistic form for general and special requirements. For QPF, both categorical and probabilistic results are evaluated, the latter providing probabilities for the precipitation height exceeding 0.0, 0.2, 1.0 and 5.0 mm for six and 12 hours (Damrath et al., 2000).

The regression algorithm has been optimized with respect to root-mean-square error minimization of the predictands on independent data, thus avoiding problems due to statistical overfitting (Knüppfer, 1996). Some of the predictands have to be transformed in order to adjust the sensitivity of the regression algorithm to specific ranges, as required. For QPF, a square-root transformation both for DMO and for the predictand prevents the few cases with very high precipitation amounts from dominating the regression equation. This allows a better forecasting of cases with lower precipitation amounts.

Even with the refinement of QPF by MOS, the predictability of precipitation is less than the predictability of other weather elements. This was revealed by a predictability study by Knüppfer (1966) on the basis of data from the European Centre for Medium-range Weather Forecasts. The MOS forecasts of different elements were compared to a reference forecast, which was an optimum combination of persistency and climate. The predictability was defined as the lead time of the MOS forecasts, for which the reduction of variance of the MOS forecasts, as compared to the reference forecasts, became less than 10 per cent. The predictability depends on the weather element. For this study, it was much more than eight days for temperature, about 5.5 days for wind and five days for QPF. The situation becomes much worse if the true skill statistics (TSS) method is used. The skill of a six-day temperature forecast is similar to the skill of a three-day wind forecast or of a one-day QPF.

The MOS-system runs several times per day on the basis of the operational model runs. The results are presented to the forecasters in numerical and graphical form. The MOS forecasts are also integrated into the operational verification scheme. Here only, an ensemble of 14 stations in Germany is considered. The MOS-system for EM forecasts (EMOS) leads to a degree of refinement similar to that of the MOS-system for GME forecasts (GMOS) (Balzer, 2000). The results for EMOS for the period from October 1998 to March 1999 are shown in Table 5.6. For temperatures and clouds, the MOS product for EM greatly enhances the quality of the EM forecasts. The improvement for QPF is, however, not as high and depends on the rainfall rate. Rainfall amounts of more than 10 mm/12 hours even show a degradation of the forecast quality by MOS. This seems to be a result of the square root transformation mentioned above (Damrath et al., 2000).

<table>
<thead>
<tr>
<th>EMOS results (October 1998–March 1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RMSE</strong></td>
</tr>
<tr>
<td>EM</td>
</tr>
<tr>
<td>DM</td>
</tr>
<tr>
<td>EMOS</td>
</tr>
</tbody>
</table>

Statistical model interpretation is applied for local precipitation forecasting at several Weather Services. Derivation of statistical relationships requires a single, comprehensive statistical analysis of large data sets, but little computing time is required when the method of statistical interpretation is applied daily. Interpretation can be carried out with reference to a location or to an area (smaller than the area of the grid square and forecast periods of less than 48 hours are recommended).

MOS corrects systematic model errors, with corrections being more successful for stable precipitation than for convective precipitation. In the case of the PP method, the systematic model error growing with increasing forecast period simultaneously entails a decrease in the quality of the interpreted values. According to Brunet, Verret and Yacowar (1988), for the first section of a 72-hour forecast period, the PP method is more suitable and for the second section, the MOS method is more suitable. For rare extreme precipitation events, only a slight improvement is achieved with both methods.

Apart from MOS and PP, a Kalman filter technique is often used to refine the DMO. The statistical correction by a Kalman filter aims to reduce systematic model errors which are often caused by a mismatch between model and station topography.

### 5.2.5 Remote-sensing procedures

Unlike conventional measuring networks, radar and satellite data provide areal information. Measuring methods and accuracy of radar-based precipitation measurements and satellite-based precipitation estimations are described in Subchapter 2.2. Irrespective of the primary purposes, such remote-sensing data can also be used for quantitative precipitation forecasting in different ways.

For so-called nowcasting (forecasts for periods up to 2 hours), the cloud and precipitation fields observed at 15–60 min intervals are moved together with the observed or predicted wind or in accordance with the travel direction of the precipitation area observed so far. Assuming that the prediction intensity observed is maintained, this extrapolation method is a practical method for quantitative precipitation prediction for time periods of up to 2 hours. In addition, estimates of changes in intensity can perhaps be made from the time development of the weather system as a whole.

In NWP, remote-sensing data serve the improved description of the initial state of the atmospheric parameters. This is particularly true for humidity over areas with only a few observations at the surface or in the free atmosphere. Vertical profiles of humidity derived from satellite-based measurements and/or information on clouds and precipitation from remote-sensing data are used to get information on the distribution of humidity.

Also, precipitation observations can be used to estimate roughly the latent heat release which is associated with the formation of precipitation. This latent heat then serves as a forcing agent during the first hours of the simulation. Thus, vertical motion, which influences precipitation to a decisive extent, can be simulated more realistically during the first hours of the model run, as far as structure and amount is concerned. Jones and Macpherson (1997) proposed a latent heat nudging technique which shortens the period of adjustment of the mesoscale model (up to 12 hours) and thereby improves precipitation forecasting.

There are worldwide efforts (in western and eastern Europe, Canada, Japan, the United States, and other countries) to
develop combined measuring systems from conventional and remote-sensing data, and to make them usable for quantitative weather forecasting through data exchange. The western European compound project COST 73 (Cooperation in science and technology) of the European Commission, supported by 16 countries, should be mentioned. The most developed system was the FRONTIERS plan of the United Kingdom which was presented already in Subchapter 2.3. The assimilation of radar data into operational NWP models is in its infancy, but there is much potential for growth in this field. The COST-717 Working Group on Using Radar Information for Assimilation into Atmospheric Models was established in autumn 1999. It offers a framework for European radar and NWP scientists to achieve this potential.

In order to make a global exchange of remote-sensing data via the GTS possible (Subchapter 6.1.3), the BUFR code was developed.

5.3 NEED FOR, AND REQUIREMENTS OF, QPF ON BEHALF OF HYDROLOGY AND WATER RESOURCE MANAGEMENT

Population growth in conjunction with increasing colonization of the alluvial plains signals an increasing need for water stage and discharge forecasting. Moreover, there is a varying intensification of floods caused by man, related with an acceleration and increase in flood waves. An unfavourable distribution of precipitation caused by a change in the climate, which is being discussed, could also have a negative effect on the discharge characteristics.

Precipitation forecasts are particularly needed by operational water stage and discharge forecasting, i.e. they are transmitted to the user. However, two restrictions should be mentioned in this context:

(a) A discharge forecast for a time period during which the discharge hydrograph is predominantly characterized by the water stored in the catchment basin can be computed according to experience made without using measured and predicted precipitation (e.g. 18-hour forecast for the Rhine gauge Worms; Bundesanstalt für Gewässerkunde, 1987); and

(b) Precipitation forecasts available at present and in the past for water stage and discharge forecasts have not always met the requested requirements for accuracy. This applies, for example, to the mesh width for grid point forecasts and the influence of the orography. Recalculations with subsequently observed instead of predicted precipitation amounts indicate the influence of the QPF error (Bundesanstalt für Gewässerkunde, 1987).

A high variety of applications of operational water stage and discharge forecasts is known. This is reflected in the evaluation of a global questionnaire. Out of 107 questionnaires sent to different agencies, 78 were returned. According to those questionnaires, flood protection is a main reason for application, but also navigation, energy and water supply (irrigation, drinking water, low flow augmentation, recreational value) and water quality are mentioned. The size of the catchment basin is between 100 km² and 100 000 km², the forecast period between two hours and six days. In 90 cases, precipitation data are also used, but unfortunately it remains unclear to what extent predicted precipitation is included.

In this case, just as in other literature, the question as to the reasons for a possible non-application of the QPF is not raised. It would therefore be interesting to know an answer to the questions whether such a QPF is available, where there is a lack of confidence in QPF or whether the runoff model is not suited for an application of QPF.

QPF of the operational NWP models at the Deutscher Wetterdienst are widely used to issue flood warnings and to provide input data for hydrologic models used by the water authorities of some of the federal states of Germany. At several flood forecast centres in Germany, QPF at model grid elements for specified periods is visualized for monitoring the meteorological situation with respect to a potential flood situation. During the flood event, the further development of the flood situation is assessed with QPF. In addition, forecasted areal precipitation for catchment areas computed from DM (now LM) grid-point values are employed (Fell and Prellberg, 1999). In mountainous areas, such as in the Bavarian portion of the Alps, fast catchment response to rainfall QPF is the only basis for pre-warning heavy precipitation. Task forces, such as the police and local fire brigades, can be put on alert for observing the potentially approaching flood situation.

At the Flood Forecast Centre in Karlsruhe (Baden-Württemberg, Germany), QPF of DM (now LM) is the input parameter to a regression algorithm estimating the water levels at about 30 gauging stations in Baden-Württemberg for 48 hours ahead (Homagk, 1996). If the forecasted water levels exceed a specified threshold value, this information can be used for switching the data transmission of the automatic ombrometer network to an hourly interval or for putting the flood forecasting system on alert (Homagk, 1999). Figure 5.12 shows observed and forecasted hydrographs at the Heidelberg gauge (River Neckar, Germany). Using DM-forecasted precipitation amount for the catchment area of River Neckar, the forecasted maximum and the timing of the maximum correspond better to the observed values.

The most important use of QPF is made for precipitation-runoff models where rainfall is the most sensitive parameter after snow. In Germany, precipitation amount forecasted by the former BKF model and statistically improved with the MOS approach was
successfully utilized for discharge forecasts at gauging stations in the Leine river basin within a pilot study more than 10 years ago (Holle, 1987). At present, precipitation-runoff models are widely applied in Germany where they are mostly combined with flood routing models (BMU, 1997).

A flood forecasting system based on these types of models has been in operation since 1995 for the catchments of River Neckar and for the eastern tributaries of the upper Rhine River. This system is the first one which employs both precipitation amount measured by ombrometers at 120 stations and forecasted by DM (now LM). By using forecasted precipitation amount, the accuracy of water level forecasts has been improved, the forecast range extended, e.g. at the gauging station Heidelberg from 12 to 24 hours, and forecasts at some additional gauging stations provided (Homagk and Schulz, 1999).

The River Moselle forecasting system was tested daily by using DM forecasts. This comprehensive three-model system developed and operated at the Bundesanstalt für Gewässerkunde in Koblenz comprises a hydrodynamical, a statistical, and a precipitation-runoff model (Krahe, 1998). The latter covers sub-basins of the River Saar, which is one of the larger tributaries of the River Moselle. It was coupled to DM data, such as precipitation, 2 m temperature and humidity, 10 m wind speed, and cloudiness, at 6-hour intervals. Evaluations of test runs show, on the one hand, good results concerning the forecasted onset/duration of the precipitation event. On the other hand, a tendency for overestimating the precipitation amount was found (Krahe, 1998). The precipitation-runoff model is now being used as a tool to verify the QPF forecasted by LM.

Reservoir management is another application of QPF. Controlled release is carried out, e.g. for the Bigge reservoir in the Lenne river catchment in Nordrhein-Westfalen (Germany) to ensure minimum discharge along the lower reaches of the River Ruhr and to protect the town of Altena from flooding (Ruhwerbernd, 1994). QPF of the Deutscher Wetterdienst is used for the precipitation-runoff model for the River Lenne (Göppert et al., 1998) which is the main tributary of the Ruhr River. In order to estimate the bandwidth of discharge, three runs with the precipitation-runoff model are performed based on original QPF values and precipitation amounts derived from the weather bulletins issued by the Regional Forecast Centre in Essen and the Agrometeorological Advisory Office in Bonn (Morgenschweis, 1999). This ensemble technique, which has been applied in medium-range weather forecasting for several years, seems to be a promising approach to get information on the reliability of the forecast results in hydrology.

In May 1999, the successive reservoir management of the Sylvenstein reservoir (Bayern, Germany) based on DM forecasts protected the town of Bad Tölz from inundation by the Isar River during the Bavarian flood event (Küstner, 1999). The catchment of the Sylvenstein reservoir covering an area of 1 100 km² was hit by an excessive rainfall of about 200 mm in 48 hours.

Last but not least, precipitation (6-hour totals) of the Deutscher Wetterdienst is an essential input parameter to the SNOW model (Rachner, Matthäus and Schneider, 1997). This model provides both diagnostic and forecasted water equivalent of snow cover and meltwater release. The model domain covers all of Germany, but a dense network of stations measuring the water equivalent of snow cover three times a week exists only in four of the sixteen federal states. Output values of snow are provided on a 7-km grid to be used as input to precipitation-runoff models operated by hydrologic institutions responsible for flood forecasting. The number of stations measuring the water equivalent of snow cover will have been enhanced to about 600 in Germany by 2004.

On the whole, operational quantitative precipitation forecasting is of high economic importance and not only through early warnings to flood-prone areas. Among those who profit are not only public utility companies responsible for irrigation, drinking water and electricity, but also agriculture, forestry and the building industries as well as traffic and tourism.

In recent times, short-term (up to 72 hours) precipitation forecasts have gained new importance in conjunction with water pollution through agriculture, industry, urban drainage and households. Thus, for instance, the bridging of low-flow periods predicted on the basis of high pollutant concentrations in the respective water and reduction of that concentration through low flow augmentation or the deliberate discharge of polluted waters during predicted flood periods are, though generally applied, dubious methods. In this context, the increasing pollution of shallow waters and bank storage should also be mentioned. The quantitative problems linked with the problems of quality therefore increasingly force drinking water works to make use of precipitation forecasts.

The requirements to be met by QPF for the purposes of operational water stage and discharge forecasting can therefore be reduced to the following:

(a) Forecast as early as possible of the beginning and duration of a precipitation event — While QPF is made continuously for various reasons, water stage and discharge forecasts are of interest only as regards extreme conditions, in particular floods. In this case, one speaks of event forecasts. Flood-causing precipitation must therefore be predicted early so that the data set can be updated and a forecast can be made of the rising water stage hydrograph. This leads to the second requirement;

(b) Validity of the forecast as long as possible — The term “as long as possible” in this context describes the forecast period using a QPF which shows sufficient accuracy for the user and exceeds the forecast period of forecasts produced according to other methods (e.g. empiric). Normally, the forecast is short term, i.e. two days ahead. Two-day forecasts even in major catchment basins draw fully on the retention in the catchment estimated on the basis of precipitation measurement and precipitation prediction. Because of a shorter concentration time (maximum flow period up to forecast, gauge) in the smaller catchment basins for the same period of forecast, emphasis is on QPF so that it has a stronger impact on the discharge curve. The period of the water stage and discharge forecast in smaller catchment basins with less than 1 000 km² therefore is relatively short, normally less than one day. But in this case, the question of the spatial distribution of the predicted precipitation becomes relevant, which leads to the third requirement;

(c) Spatial and temporal discretization as high as possible of the predicted amounts — This means that QPF screening sufficiently covers the area of the forecast as well as the spatial precipitation distribution.

5.4 EVALUATION OF PROCEDURES AND THEIR FURTHER DEVELOPMENT

Comparison of procedures for quantitative precipitation forecasting and their evaluation depends on the respective applications.
Table 5.7
Hydrological relevant characteristics of different QPF procedures

<table>
<thead>
<tr>
<th>Hydrological relevant characteristics of the different procedures</th>
<th>Regression procedures</th>
<th>Similarity procedures</th>
<th>Stochastic models</th>
<th>Dynamic models</th>
<th>Dynamic-statistical interpretation</th>
<th>Remote-sensing procedures (radar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial aspect</td>
<td>Forecast area (total area)</td>
<td>Area covered by the procedures' individual locations</td>
<td>~ 100 km²</td>
<td>(a) Global</td>
<td>Area covered by the model</td>
<td>Area of radar network</td>
</tr>
<tr>
<td></td>
<td>Smallest subarea</td>
<td>–</td>
<td></td>
<td>(b) ≤ 1/4 of hemisphere for limited area models</td>
<td>Individual places; also areas</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Grid square</td>
<td>≤ grid square</td>
<td>1 km × 1 km</td>
</tr>
<tr>
<td>Time aspect</td>
<td>Forecast period</td>
<td>Up to about 96 h</td>
<td>24–48 h</td>
<td>Hours</td>
<td>≤ 7 d (global models)</td>
<td>Mostly ≤ 48 h</td>
</tr>
<tr>
<td></td>
<td>Shortest forecast interval</td>
<td></td>
<td></td>
<td></td>
<td>≤ 78 h (limited area models)</td>
<td>12 or 24 h</td>
</tr>
<tr>
<td>Quality of precipitation forecast</td>
<td>Unsatisfactory. Only local interpretation for frequently occurring weather situations and large-scale precipitation</td>
<td>Suitable only for large-scale (advective) precipitation and a single event</td>
<td>Satisfactory for grid-scale; not yet satisfactory for convective precipitation (further details are designed to be assessed by general inquiry)</td>
<td>Local interpretation possible; systematic forecast error is reduced; rare extreme events cannot be captured</td>
<td>Accuracy about factor 2</td>
<td></td>
</tr>
<tr>
<td>Computing resources required</td>
<td>Computer/memory capacity</td>
<td>PC</td>
<td>Workstation</td>
<td>PC</td>
<td>Vector computer (several processors)/several Mwords</td>
<td>Workstation</td>
</tr>
<tr>
<td></td>
<td>Computing time</td>
<td>Some minutes</td>
<td>5–10 minutes</td>
<td>Some minutes</td>
<td>15–30 minutes for 24-h forecast</td>
<td>Several minutes</td>
</tr>
<tr>
<td>Availability of forecast values</td>
<td>After completion of calculations</td>
<td>Suitable only for large-scale (advective) precipitation and a single event</td>
<td>After completion of model simulation, about 3–5 h after main observation times: 0000, 1200 UTC</td>
<td>Some minutes after completion of model simulation which is a prior condition for the application of the dynamic-statistical interpretation</td>
<td>1 h after the beginning of the event</td>
<td></td>
</tr>
</tbody>
</table>
Answers to questions concerning the area affected by precipitation, the time of onset, the duration and depth of precipitation are all important. Attention should also be given to operational aspects such as the required computing resources and the time at which the predicted precipitation data are available.

In Table 5.7, the individual methods for quantitative precipitation forecasting are classified with the aid of hydrologically relevant characteristics, prototypes of which are described in Subchapter 5.2. The characteristic spatial aspect should be understood to mean the total area and the smallest subarea for which forecasts can be produced. The same applies, mutatis mutandis, to the characteristic time aspect. Statements on the quality of the forecast, on required computing resources and on the availability of results follow. It is left to the user from the hydrological field to select, with the aid of the survey, the method serving his purpose.

A description of the international state-of-the-art of operationally-used methods for quantitative precipitation forecasting is not possible at present. For this reason, a relevant WMO inquiry is proposed. Main emphasis should be placed on dynamical models (weather prediction models). Specified questions on the hydrological cycle and on verification should make a qualitative estimation of the quantitative precipitation forecasting possible.

Regression and similarity procedures are no longer of importance for Weather Services where operational NWP systems are operated. The results obtained through these two procedures can also be obtained with the aid of NWP models. These models describe the essential processes of thermodynamics and microphysics of clouds relevant for precipitation in a parameterized form and produce precipitation as an explicit forecast value. The models are being further developed with respect to higher resolution, improved modelling of physical processes and more accurate determination of the initial state. For initial moisture fields (specific humidity, cloud water content), observations based on remote-sensing systems will be increasingly used in the future.

Intercomparison tests are desirable for NWP models (Anthes, 1988). Within the European Working Group on Limited Area Modelling (EWGLAM), forecast results from limited area models of several European Weather Services are already exchanged each month (one forecast per month); the results include, inter alia, precipitation forecasts over two 12-hour intervals.

The results of the weather prediction models may be refined by applying the dynamic-statistical model interpretation (Perfect Prog, MOS) described in Subchapter 5.2.4. Local interpretation of the precipitation value at the grid point for a location or an area smaller than a grid square permits correction of the systematic model error and indirect consideration of local factors having a permanent effect on the precipitation value to be predicted. The user thus obtains improved precipitation forecasts on average, but not for each individual case.

On the whole, the methods of statistical interpretation have proved efficient. They are widely applied to forecasts by models with mesh widths Δs ≥ 50 km. There are also attempts to develop operational MOS systems for models with even smaller mesh widths (e.g. Collins, 2000).

Research and development are required for forecast intervals over 2–12 hours, i.e. for the part of very-short range (up to 12 hours) exceeding the range of nowcasting (up to 2 hours). In this case, a practicable linking of nowcasting methods with the deterministic method of NWP models is required. In this connection, it should be taken into account that the adjustment period (spin-up time) of the weather prediction models coincides with that time period.

Stochastic models are suited for small areas (20–500 km²) and short forecast periods (1–3 hours). Based on measurement data of a current precipitation event, such models produce the probability on its further development with respect to time. A further development through a synoptic orientated typification of the precipitation event taking relevant meteorological parameters into account could lead to further improvements (Fleer, Franke and Lecher, 1986).
6.1 DESCRIPTION
The World Weather Watch (WWW) is a global system for the collection, analysis, processing and dissemination of weather and environmental information, and thus represents the very core of the meteorological services. It was set up in 1963 (WMO, 1988d). The operation of WWW is based on the fundamental concept that each of the 160 Members of WMO undertakes, according to its means, to meet certain responsibilities in the agreed global scheme, so that all countries may benefit from the consolidated efforts.

The WWW has three main components:
(a) The Global Observing System (GOS) that uses all technical facilities on land, at sea, in the air and in higher atmospheric layers for the observation and measurement of meteorological elements;
(b) The Global Telecommunication System (GTS), a worldwide data communication system with special circuits for the rapid exchange of observation data, analysed and processed information including weather forecasts which are produced by the third main component; and
(c) The Global Data-processing System (GDPS), a network of world and regional centres for computerized data-processing including, for example, computer modelling for numerical weather prediction, statistical analyses and graphic processing.

A survey of the activities of WWW from the point of view of the National Meteorological Services (NMSs) is given in Figure 6.1.

The WWW, with its three main components, is active on three levels: national, regional and global, according to the various scales of meteorological processes. The integrated system concept of the WWW with GOS, GTS and GDPS, the World Meteorological Centres (WMCs), the Regional Specialized Meteorological Centres (RSMCs) and the National Meteorological Centres (NMCs), as well as the various fields of application, are shown in Figure 6.2.

Also closely linked with WWW activities are education and training as well as technical and scientific research. One of the first and most comprehensive research programmes was the Global Atmospheric Research Programme (GARP) with many subprogrammes aimed at studying essential fundamentals for the improvement of weather forecasting. To support those Members who are unable to make their own contribution to the global system as planned by WWW, the Voluntary Cooperation Programme (VCP) was established.

6.1.1 Global Observing System (GOS)
While progress in creating a larger density of the conventional network of ground stations and in improving GTS connections is relatively slow, a breakthrough in the bridging of spatial and temporal gaps in the observation of rapid weather formations due to the development and use of new meteorological satellites (Meteosat second generation — MSG) and automated observing systems (Measuring Network 2000) can be seen.

Thus GOS today is considerably influenced by satellites orbiting between the North and South Poles (800 to 1 000 km from the Earth) collecting and transmitting global data on cloud covering, vertical temperature and humidity profiles, sea and land surface temperatures, as well as snow and ice cover. The geostationary satellites are positioned at a distance of approximately 36 000 km from the Earth. The present situation of the geostationary satellites changes constantly. Thus, on the position GOES/E there is at present an older METEOSAT — INSAT has been replaced by a modified GOES and GOMS has not yet become a reality. Between 75°N and 75°S, these satellites provide continuous images of cloud cover and serve as a telecommunication system for the collection and transmission of data (Figure 6.3).

Global satellite update
(a) Europe:
Meteosat-5 arrived at 63°E, 36 000 km above the Indian Ocean on 19 May. Following successful imaging tests, it entered into service for the INDOEX experiment on 1 July. Meteosat-6 was relocated to a standby position at 10°W after Meteosat-7 took over as the operational satellite at 0° on 3 June;
(b) United States:
GOES-9 (West) began suffering serious problems in its attitude control system in July as it neared the end of its planned lifetime. The in-orbit back-up satellite, GOES-10, replaced it
on 28 July. Launched in 1994 and past its projected lifetime of three years, GOES-8 (East) continues to function with no significant changes in the past 28 months. GOES-11 was launched in May 1999. NOAA-K, the first in a new series of five polar-orbiting satellites was launched on 23 May. Renamed NOAA-25 in orbit, it is now in a commissioning phase and will replace NOAA-12 at a future date. NOAA-14, launched in December 1994, continues to function well;

(c) Russia:
The next Russian polar-orbiting meteorological satellites Meteor-3M-1 and 3M-2 were launched in 1999 and beyond 2000, respectively. The future GOMS Electro-geostationary meteorological satellite was launched in 2000;

(d) China:
The next FY-1C polar orbiting meteorological satellite was launched in 1999 and the next FY-2B geostationary meteorological satellite in 2000;

(e) Japan:
GMS-5, the current operational geostationary meteorological satellite, will continue until the next generation, MTSAT. This will be a dual-role (telecommunications and meteorology) geostationary satellite. MTSAT-1 was launched in 1999 and MTSAT-2 is scheduled for 2004;

(f) India:
INSAT-2B, the second generation satellite, positioned at 93.5°E and INSAT-1D of the first generation at 83°E, are the current operational satellites with INSAT-2A in standby mode at 74°E.

As already explained in Subchapter 2.2, at present, satellite-based measurements alone are not sufficiently accurate. Radar and conventional measurements have to be used for interpretation and computation. The GOS has thus developed into a composite system whereby not just one observational component or measuring technique is applied, but the whole set of data available is required (Table 6.1).

### 6.1.2 Global Data-processing System (GDPS)
GOS already existed in a similar form prior to the establishment of WWW, whereas the GDPS was created by WWW (Table 6.2). The introduction of supercomputers and highly sophisticated numerical analysis and prediction models has shown that a distribution of tasks is essential. The system of three WMCs was designed to ensure the processing of information on a global scale (Subchapter 2.1) for both real-time and non-real-time applications. These output products are used by the RSMCs which, as shown in Table 6.2, carry out either regional or problem-related functions. These include prediction products on the mesoscale or large scale. Relevant information is given in WMO, 1993.

The GDPS is being continually extended so that the number and quality of the output products increase from year to year. The WMCs now produce almost 350 analyses and forecasts and the RSMCs make available over 2,000 products every day. The improvement in quality can be measured in terms of forecast

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| Regional Specialized Meteorological Centre 
with geographic specialization | • short- and medium-range forecast products |
| Regional Specialized Meteorological Centre 
with activity specialization | • climate diagnostic products |
| Regional Specialized Meteorological Centre 
with climate diagnostic products | To prepare; |
| National Meteorological Centre 
with severe weather warnings | • regional fine-scale analyses |
| National Meteorological Centre 
with regional climate diagnosis | • regional fine-scale forecast products |
| National Meteorological Centre 
with other products as decided nationally | • adjustment of global products to regional conditions |

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Figure 6.3 — The presently existing polar-orbiting and geostationary satellites (Image 9, 1998).
The quality of weather forecasts in the northern hemisphere for the next seven days is as good as it was in 1960 for the next three or four days. Without the GDPS, WMO Members would not be able to maintain the variety, complexity and high standards of the meteorological services.

6.1.3 Global Telecommunications System (GTS)
The GTS components linking the GOS via the Regional Telecommunication Hubs (RTHs) with the WMCs, the RSMCs and the NMCs must function properly if the observations and derived products are to be collected, processed and disseminated to the NMSs in forms suitable for application. At present, the GTS conveys over 15 million bytes of data and 2,000 weather charts daily. Transmission is via satellites, cable or VHF/UHF radio.

The GTS itself is organized on three levels:
(a) The Main Telecommunication Network (MTN) that consists of 24 point-to-point circuits linking the three WMCs (with RTH) and the 15 RTHs on the MTN (Figure 6.4);
(b) In addition, a further 14 RTHs (not on the MTN) supplied via regional connections; and
(c) The 149 NMCs within the scope of the RTHs that are linked with the 32 RTHs via international connections.

Apart from the “official” GTS circuits, numerous connections with the “on-bilateral agreement” status have been set up where necessary, to transmit additional mainly national meteorological data (Resolution 40 (Cg-XII)).

The general guidelines of these systems are compiled in the Manual on the Global Telecommunication System (WMO-No. 386). Today, the normal data transmission speed for MTN circuits is 64 Kbps, but, where necessary, the regional and national connections are also increasingly being operated at 64 Kbps.

Two important conversion processes are taking place in the GTS:
(a) The transition from the X.25 transmission method that up until now used almost exclusively the procedure of message switching systems in store and forward to methods based on IP (TCP sockets, FTP). File distribution technologies have thus become increasingly important;
(b) The changeover from the use of rented telephone and digital transmission lines to Managed Data Networks (MDN) whereby the transmissions maintenance is left to a large extent to the MDN server. In Regional Association VI (Europe), the MDN is about to commence operations under the name of Regional Meteorological Data Communication Network. Other regions have started with preparations for the changeover. Hence, the transmission speeds have today become more a question of requirements and less of technical possibilities and costs.

6.1.4 Future developments
As WWW has to adapt itself to the progressive technical possibilities in all sectors, this system will always be open to improvements. Future developments will include:
(a) A continual increase in transmission speeds, as required;
(b) A gradual optimization of international data exchange by improving the organization of the data networks, by changing to modern technology and by guiding developing countries towards the level of the technology-developing countries;
(c) A standardization and an improvement of the transmission code, e.g. by increasing the transition to CREX, BUFR and GRIB codes instead of the traditional FM formats.

Apart from technical and organizational adjustments, the WWW will in this decade probably be influenced by changing requirements and priorities. In this context, the following should be

Figure 6.4 — Circuits connecting the world and regional centres (RTH).
mentioned:
(a) Safety of life and mitigation of natural disasters;
(b) Agriculture and food production for an increasing population under variable and, in many cases, unfavourable climatic conditions;
(c) Conservation of resources, particularly of water and energy, and the management of natural resources;
(d) Study and exploitation of marine resources (oil, gas, minerals, fisheries);
(e) Protection of the environment (atmosphere, inland waters, oceans, soil and biota);
(f) Transportation (land, sea and air);
(g) Building and industry;
(h) Health, recreation and tourism.

6.2 DEMANDS OF HYDROLOGY AND WATER RESOURCES MANAGEMENT ON THE WWW

As Chapter 1 shows, for most hydrological and water resources applications, non-real-time data are required. Such data can in general be made available without difficulty to the hydrological services by the Meteorological Services. The situation is different in the case of real-time forecasts. Here, the data are needed immediately after measurement.

WWW can be used by hydrology and water resources management in two ways:
(a) Use of the meteorological data exchange via the WWW;
(b) Use of the WWW for the current transmission of hydrological data.

Some Hydrological Services use meteorological data exchanged via the WWW for their forecasts. Generally, the network of the meteorological (synoptical) stations, whose data are exchanged via the WWW, is not very dense, so there is considerable inaccuracy in the areal values determined from the climatic data transmitted. For this reason, many Hydrological Services have established additional automatic stations from which data can be recalled.

In many countries, the WWW is used for the current transmission of hydrological data. For this purpose, measured data are fed into the WWW network and transmitted to the data centre continuously but also in real time for forecasts. In such countries, the Hydrological Services do not need to set up their own transmission networks and can thus save costs. In some regions (e.g., central Europe) where this was not possible up until now because the WWW network was used at maximum capacity for the transmission of meteorological data, the use of the network is now possible as a result of the introduction of new transmission techniques with high transmission speeds.

Where free capacities in the WWW network still exist, greater use of the WWW should be made by the Hydrological Services for the transmission of their data. In regions which do not yet have an extensive network for the transmission of hydrological data at their disposal and where WWW capacities are not available, an extension of WWW would be reasonable.

For the exchange of hydrological data, WMO has developed a special code, HYDRA (WMO, 1995) which is adapted to the WMO code for the exchange of hydrological data. Application of this code facilitates the exchange of hydrological data and the taking over of meteorological data. In addition, there is a code for hydrological forecasts (HYFOR) (WMO, 1995). This code is designed to facilitate the exchange of hydrological forecasts, e.g., flood forecasts.

6.3 PILOT PROJECTS

In the mid-1970s a study was carried out to investigate to what extent WWW could be used for hydrological purposes. The Rhine basin in Europe and the John River basin in North America were selected for the purposes of this study.

For the Rhine basin, the result was that meteorological data were already being intensively used by the Hydrological Services, however, in a conventional way, e.g., on data carriers (magnetic tapes) or by telex. An exchange of data via WWW was not possible because the WWW system was already overloaded. By increasing the transmission speed and by setting priorities and non-real-time data determination, the use of the WWW system would today be possible.

The situation in the John River basin is different. Unlike in the Rhine basin, the public telephone system is wide-meshed so for this basin it appears quite reasonable to use WWW’s telecommunication system.
CHAPTER 7

HYDROLOGY AND WATER RESOURCES PROGRAMME

7.1 HYDROLOGY AND WATER RESOURCES PROGRAMME

Within the framework of the United Nations, a number of international organizations deal with water, inter alia, WMO, the Regional Commissions, the United Nations Educational, Scientific and Cultural Organization (UNESCO), the United Nations Environmental Programme (UNEP), the World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP) and the World Bank. The WMO Hydrology and Water Resources Programme (HWRP) covers the operational aspects of hydrological services.

The purpose of the programme is to promote activities in operational hydrology and to further close cooperation between Meteorological and Hydrological Services (paragraph (e) of Article 2 of the Organization’s Convention). The overall objective of the HWRP is to apply hydrology to meet the needs for sustainable development and use of water and related resources, to mitigate water-related disasters and to encourage effective environmental management at the national and international levels.

The current HWRP consists of five components:
(a) Programme on Basic Systems in Hydrology (the Hydrological Information Referral Service, the Hydrological Operational Multipurpose System (HOMS) and the World Hydrological Cycle Observing System (WHYCOS));
(b) Programme on Forecasting and Applications in Hydrology (climate and water, flood and drought hazards);
(c) Programme on Sustainable Development of Water Resources (participation of Hydrological Services in the national planning);
(d) Programme on Capacity Building in Hydrology and Water Resources (developing and strengthening human resources in hydrology and management of water resources);
(e) Programme on Water-related Issues (cooperation with other organizations).

The activities under the HWRP concentrate on the measurement of basic hydrological elements from networks of hydrological and meteorological stations; the collection, processing, storage, retrieval and publication of hydrological data, including data on the quantity and quality of both surface water and groundwater; the provision of such data and related information for use in planning and managing water resources projects; and the installation and operation of hydrological forecasting systems.

Hydrological problems are also dealt with in other WMO programmes such as the Tropical Cyclone Programme (TCP) and the World Climate Programme (WCP). Support of the WCP is mainly provided by the component programme on climate and water.

Two major sub-programmes of the HWRP are explained below in more detail.

7.2 THE HYDROLOGICAL OPERATIONAL MULTIPURPOSE SYSTEM (HOMS)

HOMS is a sub-programme of the Programme on Basic Systems in Hydrology. The basic document for HOMS is the HOMS Reference Manual (HRM), which is available on the World Wide Web (http://www.wmo.ch/web/homs/homshome.html). Through the Manual, the Hydrological Services of the WMO Members offer and exchange interesting methods and computer programs which can be used for the implementation of daily operational tasks. Each method or computer program, a so-called component, is described on two standard pages following a certain pattern. Technically-related components are combined to form so-called sequences.

The technology is usually in the form of descriptions of hydrological instruments, technical manuals or computer programs, material which has been made available for inclusion in HOMS by the Hydrological Services of WMO Members from the techniques which they themselves use in their normal operations. This is an important aspect of the HOMS philosophy as it ensures that the technology transferred is not only ready for use but also works reliably.

HOMS is organized as a cooperative effort of WMO Members. Participating countries designate a HOMS National Reference Centre (HNRC), usually in the National Hydrological Service. This Centre provides national components for use in HOMS, handles national requests for HOMS components to be supplied by other HNRCs, advises users on HOMS, and generally coordinates and publicizes HOMS activities in the country.

In 1999, a major effort to update the HRM was undertaken. The version now available online is the result of this effort. The number of components has decreased significantly compared with the 1998 version. This decrease in quantity is, however, compensated by a corresponding increase in the usefulness of the individual components, as they have all been updated quite recently. It must be noted that for the HRM to keep this high level of usefulness, it must be updated continually. Therefore, HOMS users are encouraged to visit the HOMS pages frequently to keep abreast of developments.

7.3 WORLD HYDROLOGICAL CYCLE OBSERVING SYSTEM

7.3.1 Introduction

The World Hydrological Cycle Observing System (WHYCOS) is WMO’s response to recommendations of the 1992 United Nations Conference on Environment and Development (UNCED), which called on Governments to establish and maintain effective information and monitoring networks and promote further the exchange of information regarding both surface water and groundwater, with respect to quantity, quality and uses, as well as ecosystems. It was initiated in 1993 by WMO with the goal of improving the knowledge and understanding of the hydrological cycle at the national, regional and global scale, and thus to support rational water resources management.
WHYCOS is modelled on WMO’s WWW, which collects large amounts of data, mostly in real time, available globally, and has long existed in the field of meteorology. It offers a similar structure for hydrological purposes and is being designed and implemented in independent regional components called the Hydrological Cycle Observing System (HYCOS), each of them comprising of National Hydrological Services (NHSs) operating within well defined hydrological regions. WHYCOS does not replace existing hydrological observing programmes, but supplements them. And the National Services maintain their sovereignty over all data and information they share within WHYCOS and participate on a voluntary basis. An important output of WHYCOS is regional data sets that are of consistent quality and can be used in preparing products for water resources assessment and management. With WHYCOS as a vehicle, data from remote sensing measurements in rivers will be transmitted via meteorological satellites to national and regional centres. Here the data will be processed to assist in decision-making for planning development and operation of projects such as retention measures, flood control, a decrease in the effects of drought, the combat of water pollution and regional water resources management. Furthermore, the information obtained could be used on research on the effects of El Niño and impacts of possible changes in climate organization and objectives.

7.3.2 Organization and objectives
To ensure the successful implementation of the programme, its activities are coordinated by a special mechanism as follows (Figure 7.1):

(a) WMO internal coordination mechanism: to link the inputs of the various Departments of the WMO Secretariat. This has been achieved by the establishment of an in-house WHYCOS Coordination Group (WCG) consisting of the Deputy Secretary-General, the Assistant Secretary-General and the Directors of the Departments concerned;

(b) External coordination mechanism: To ensure world-wide operational linkage among the various HYCOS components and to coordinate on all technical aspects of the programme. This has been achieved by the establishment of the WHYCOS International Advisory Group (WIAG) composed of the president of the Commission for Hydrology (CHy) and representatives of the HYCOS regional centres, the CHy Advisory Working Group, the external supporting agencies as well as the WMO Secretariat and the Regional Hydrological Adviser concerned.

The WHYCOS priority lies in the regional needs of the participating countries. The objectives of WHYCOS are:

(a) To establish a global network of national hydrological observatories for the collection of high-quality data concerning the hydrological cycle and to transmit them in real time to national and regional data centres via the GTS;

(b) To strengthen the technical and institutional capacities of the National Hydrological Services by providing the relevant hydrological information on water resources, trends, hazards, etc.; and

(c) To promote the dissemination and use of such information, for example, via the World Wide Web.

7.3.3 WHYCOS stations
The stations are selected by the participating countries. Focus is being placed on existing stations that can be upgraded to satisfy the

![WHYCOS International Advisory Group (WIAG)](image_url)
requirements of both national priority objectives and those of WHYCOS. The criteria for station selection are:
(a) Availability of long time series;
(b) A stable water level-discharge relationship;
(c) Regional significance of the data.

The minimum set of basic data recorded consists of:
(a) Water level/flow;
(b) Precipitation;
(c) Temperature;
(d) Humidity.

Other variables to estimate the potential evapotranspiration as well as selected physical and chemical parameters are required. Provided that countries agree to the exchange of data, the use of satellites under the umbrella of WMO will be free of charge.

7.3.4 Regional components
WHYCOS has been conceived as a vehicle for technology transfer, training and capacity building. Its regional components are being developed and implemented in various parts of the world with financial support provided by the World Bank, the European Commission and the Government of France. At present, three projects are under implementation covering the Mediterranean (MED-HYCOS), Southern Africa (SADC-HYCOS) and west and central Africa (AOC-HYCOS). In addition, there are 12 other projects at different stages of development in such areas as East Africa, Congo, Danube, Amazon and La Plata river basins, the Aras Sea, Baltic Sea, Black Sea and Caribbean Sea basins, the Pacific Islands and the Himalayan and Arctic region (Figure 7.2).
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