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CLIMATE AND METEOROLOGICAL INFORMATION REQUIREMENTS FOR WATER MANAGEMENT

A REVIEW OF ISSUES

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CLIMATE AND METEOROLOGICAL INFORMATION REQUIREMENTS FOR WATER MANAGEMENT

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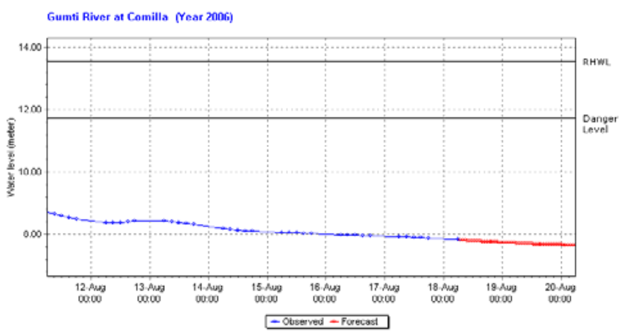



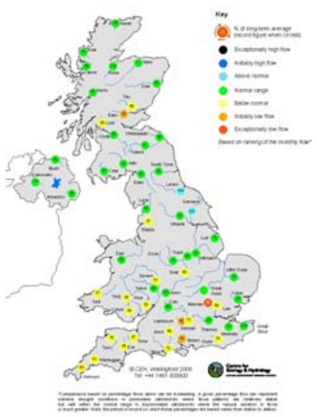

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1. Introduction

At first sight, the connection between the weather and climate and the terrestrial water cycle appears fundamental, and it is thus obvious that a high level of synergy should exist between the disciplines involved. However, perhaps surprisingly, the opening statement of the report on the Expert Meeting on Water Management Need for Climate Information in Water Resources Planning (Ref. 1) states: "climate information is presently not widely used by water managers". This meeting went on to explore in some depth a range of issues in both the present situation and looking to the future. Attention towards the future focussed on the increased need for information and understanding, given concerns about the potential impacts on the water cycle through climate change, for whatever reason, and increasing uncertainty and vulnerability.

The outcome of that meeting has influenced the Commission for Hydrology (CHy) work programme, and the focus of the World Climate Conference – 3, held in Geneva from 31 August to 4 September 2009, was on the proposals to create a Global Framework for Climate Services (Ref. 2). This conference looked at a wide range of climate sensitive sectors, and this review will concentrate on a specific activity in the CHy progamme, namely to "Prepare guidance material on the climate information requirements of water resources managers for operations, long-term planning and design".

There are numerous initiatives, plans and strategies in place, largely driven by the recognition of the need for high quality data and information. Some of these are broad based, dealing with global initiatives such as the Global Observation System (Ref. 3) and others are highly focussed (Ref. 4). The Group on Earth Observations (GEO) has specifically examined the role of monitoring for benefit to society in the water sector (Ref. 5). Their task considers all types of earth observations, including ground, in situ, airborne, and space-based observations. The investigation includes both direct measurements and derived parameters, as well as model products. The objective of the GEO programme seeks to identify earth observation needs from all geographic regions with significant representation from developing countries and participating organizations can use the results in determining priority investment opportunities for earth observations.

Most recently an update (Ref. 6) has been made of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (United Nations Framework Convention on Climate Change). This comprehensively reviews needs for monitoring and data management from a stable reference network of stations. Its aims will rely heavily on national co-operation and agreements on data exchange and supply, and is therefore a highly ambitious exercise. At this scale it can only represent the broadest aspects of the meteorological and climate interface, which while doubtless suited to the needs of global and regional climate models, will have limited application on local and sub-national scales where data requirements are most significant.

With this considerable body of reference material available, this review does not aim to provide a comprehensive digest of these initiatives or an exhaustive examination of topics or methods, but rather seeks to highlight areas where interaction between the meteorologist, climatologist and the water manager can be demonstrated for the mutual information and understanding of all parties. Throughout the report, the term "climate" will refer to both meteorology and climatology, on the understanding that these two foci have a common atmospheric science basis, but are usually differentiated by matters of temporal and spatial scale. Similarly, "water management" will apply to the general features of the water cycle and management of water resources, rather than specifics of distribution, treatment and drainage design.

2 Scope of Report

In providing better understanding between climate and water management, this review will, where relevant, adopt the approach of a SWOT analysis (strengths, weaknesses, opportunities and threats). As well as some recent initiatives noted in the preceding section, the basic data requirements and methods for water management are covered in the WMO Guide to Hydrological Practices (Ref. 7). In Volume I, Chapters 2, 3 and 4 deal with the climate observations required for water management, whilst Volume II deals with applications and management activities. Table II.4.1 from that publication is a particularly useful reference point. This table itemises the various data requirements from the hydrological cycle, which apply to different water sector applications. Not all are meteorological or climatological in nature, so the aim of this review is to concentrate on those that are. This review aims to identify the fundamental gaps and weaknesses that fail to produce the desired synergies between climate, meteorology and water management. It is evident that there is much debate and effort being expended with the intention of matching practical capacities with the theoretical requirements, but consideration of the broad range of applications for which meteorological can apply to water management can help to justify the effort.

There is a variety of reasons for the mismatches between practice and theory, which are the basis of the lack of synergy and even understanding between suppliers of climate data and water management activities. Quite often these are functions of the scale of operations, e.g. water management operates on a catchment scale, whereas meteorological information is generally available on a broader basis. Similarly water management design depends heavily on historical data, whereas use of operational data may depend on data delivery and assimilation into models. An assessment of gaps and needs has been identified by the UN Intergovernmental Panel on Climate Change (IPCC) (Ref. 8): some are technical and some organisational, and examples are given below.

- Difficulties in the measurement of precipitation remain an area of concern in quantifying global and regional trends. Precipitation measurements over oceans (from satellites) are still in the development phase.
- Many hydrometeorological variables e.g., streamflow, soil moisture and actual evapotranspiration, are inadequately measured. Potential evapotranspiration is generally calculated from parameters such as solar radiation, relative humidity and wind speed. Records are often very short, and available for only a few regions, which impede complete analysis.
- Snow, ice and frozen ground inventories are incomplete. Monitoring of changes is unevenly distributed in both space and time. There is a general lack of data from the southern hemisphere.
- More information is needed on plant evapotranspiration responses to the combined effects of rising atmospheric CO_2, rising temperatures and rising atmospheric water vapour concentration.
- Quality assurance, homogenisation of data sets, and inter-calibration of methods and procedures could be important whenever different agencies, countries etc. maintain monitoring within one region or catchment.

More specifically the IPCC identifies major uncertainties in understanding and modelling changes in climate relating to the hydrological cycle as including the following:

- Confidence in attributing some observed climate change phenomena to anthropogenic or natural processes are limited by uncertainties in radiative forcing, as well as by uncertainty in processes and observations. Attribution becomes more difficult at smaller spatial and temporal scales, and there is less confidence in understanding precipitation changes than there is for temperature. There are very few attribution studies for changes in extreme events.

- Uncertainty in modelling some modes of climate variability, and of the distribution of precipitation between heavy and light events, remains large. It is necessary to improve understanding of the sources of uncertainty.
- In many regions where marked spatial variations in climate are generated by topography, there is insufficient information on how climate change will be expressed at these geographic scales.
- Climate models remain limited by the spatial resolution and ensemble size that can be achieved with present computer resources.

With respect to the climate/water interface, the IPCC report identified the following gaps and research needs:

- Further work on detection and attribution of present-day hydrological changes is required; in particular, changes in water resources and in the occurrence of extreme events. As part of this effort, the development of indicators of climate change impacts on freshwater, and operational systems to monitor them, are required.
- There remains a scale mismatch between the large-scale climatic models and the catchment scale – the most important scale for water management. Higher-resolution climate models, with better land-surface properties and interactions, are therefore required to obtain information of more relevance to water management. Statistical and physical downscaling are currently the only methods available.
- Most of the impact studies of climate change on water stress in countries assess demand and supply on an annual basis. Analysis at the monthly or higher temporal resolution scale is desirable, since changes in seasonal patterns and the probability of extreme events may offset the positive effect of increased availability of water resources.
- The impact of climate change on snow, ice and frozen ground as sensitive storage variables in the water cycle is highly non-linear and more physical and process-oriented modelling, as well as specific atmospheric downscaling, is required.
- Methods need to be improved that allow the assessment of the impacts of changing climate variability on freshwater resources. In particular, there is a need to develop local scale data sets and simple climate-linked computerized watershed models that would allow water managers to assess impacts.
- Feedbacks between land use and climate change (including vegetation change and anthropogenic activity such as irrigation and reservoir construction) should be analysed more extensively; e.g. by coupled climate and land-use modelling.

The above points need to be considered in the context of each aspect of the use of climate data for water management in practical terms. This review therefore deals with data and activities, rather than re-iterate many of the theoretical and technological approaches which too often represent an ideal not achievable, for a variety of reasons.

This report has drawn on practical experience from hydrometeorological projects in a number of countries and situations, aiming to adopt a pragmatic rather than theoretical consideration of the issues. The ultimate goal for climate and meteorological services should be to replicate the higher quality service interfaces that do exist in some parts of the world, but it is recognised that many technical and bureaucratic obstacles will remain.

3 Structure of Report

The report is based on a framework set out in Tables 3.1 and 3.2. Table 3.1 identifies a variety of *Purposes* in water management. Each of these *Purposes* has one or more *Features* that require their individual sets of climate data. The aim of the report is to define the detail of data to meet the needs of the various *Purposes* and *Features*. Many of the data items listed in Table 3.1 appear as requirements for several different features, but this does not mean the data type, e.g. sampling interval, reporting format, will be the same in each case. Thus some purposes and features may require data components to be processed to give a particular variable, such as potential evapotranspiration, whilst for others an individual data item, e.g. temperature may be needed for a specific purpose. Further definition of data needs will be examined in the context of *Decision Type*, as defined by Table 3.2. The discussion of Topics in Section 4, which comprises the core focus of this review examines the individual components of data requirements, set out for each *Purpose* and *Feature* from Table 3.1. Section 5 examines some of the key practicalities and problematical issues and what needs to be done to improve interaction. The discussion ranges across data sharing and inter-agency co-operation, considers equipment, networks and data collection. It also suggests how institutions could develop their approaches to meet broader demands, along with limitations and major drivers, such as resource pressure and changes in climate variability.

Table 3.1. Climatological and Meteorological Data Required for Water Resources Management

Purpose	Features	Required Data
Hydrological characterisation	Catchment/Watershed planning General water balance	Precipitation Temperature Humidity Wind speed
Flood management and control	Structures (dams, river training)	Precipitation Temperature Humidity Wind speed and direction
	Flood forecasting and warning	Precipitation Temperature Evapotranspirtation Synoptic information Forecasts and alerts Medium- and long-term forecasts
	Flood plain zoning/Flood frequency estimation	Precipitation Evapotranspiration Temperature Synoptic information
	Coastal inundation	Wind speed Wind direction Synoptic information Forecasts and alerts
Irrigation and drainage	Supply Demand scheduling	Precipitation Temperature Humidity Wind speed Medium/long-range forecasts
Groundwater	Recharge Groundwater flooding	Precipitation Temperature Humidity Wind speed Medium/long-range forecasts
Navigation	Canal systems Dredging	Precipitation Temperature Medium/long-range forecasts
Power generation	Hydropower Cooling water	Precipitation Temperature Humidity Wind speed Medium/long-range forecasts
Water supply	Potable water Industrial processing	Precipitation Temperature Humidity Wind speed Medium/long-range forecasts
Water quality	Pollution control Dilution Salinity and sedimentation	Precipitation Temperature Humidity Wind speed Forecasts and alerts
Fisheries and conservation	Hydro-ecology Hydromorphology	Precipitation Temperature Humidity Wind speed Medium/long-range forecasts
Amenity	Public access Recreation	Precipitation Temperature Wind speed Synoptic information Forecasts and alerts

Table 3.2. Water Management Decisions defined by time scale of application

Decision Type	Climate (10-50 years) Long-term change	Climate (6-12 months)	Weather (1-10 days)
Strategic	Revisit design criteria & standards based on historic information, design flow estimation under non-stationary conditions; development of adaptation strategies, Changes of the hydrological response in basins oriented towards decision support, regulation of water withdrawals and abstractions, water quality issues, transboundary water sharing agreements, Spatial planning, groundwater recharge scenarios,	Drought contingency planning Flood contingency planning (triggers, tactical and operational activities, as below)	Flood warning & evacuation. Demand scheduling and control setting (water supply and irrigation)
Tactical	Review of operating rules towards more robust systems, water allocation schemes (including basin and reservoir storage, defence structures, utilities et al.). Risk mapping (floods, droughts) updates in 5-10 year timeframe.	Seasonal climate forecasts (precipitation, temperature) Risk mapping, e.g. droughts, disease vectors where high seasonal dependence exists Water quality Conservation Transboundary water sharing agreements, Irrigated crop planning	
Operational	Supply demand Reservoir safety Reservoir sizing Land management	Use of output variables derived from oscillations in seasons & regions where there is high predictive skill Operating rules Water and drought orders Water allocations Demand management	Storage management (irrigation, hydropower, peak municipal water demands.) Irrigation scheduling Flood warning Demand management

Explanation Note to Table 3.2

The time frame between the climate (6 months) and weather (10 days) scales of application presents some particular problems. Some applications, such as a crop growing season, or the time lag needed to implement control legislation, focus on a 2-3 month time frame. This level of climate forecasting, although practised, is very generalised, and at best may be able to provide broad category type forecasts, e.g. a 5-tier range from very dry to very wet. Beyond a lead-time of 10-days, what are sometimes termed long-range weather forecasts also lack sufficient detail to assist practical decision-making.

Although a number operational decisions have to be made within the 15 day to 3 month timeframe, e.g. for water supply, long-range forecast detail is often little better than using information on conditions from climatology. These longer range forecasts are in some ways dependent on basin size and climatology. Thus for major reservoirs or river management in Sahelian areas, such as for the Volta Lake or where snow-melt is important, such as for the Indus barrages or northern European lakes, can extend te period of predictability. These operational forecasts can be given in a probabilistic way from an ensemble of model runs, as in Table 3.3. Both examples may be interpreted as suggesting that conditions are most likely to be normal or wetter than average, rather than dry, but a user would have to decide if the chance of dry conditions would be a risk to their operations. In 2010, the UK Met Office ceased to provide these types of forecast on a regular basis because of criticism of lack of precision from users.

Table 3.3. Example of seasonal probability forecast

a) 3-category

Seasonal Rainfall Forecast, March-May	
Conditions	**Probability**
Wetter than average	45%
Average	30%
Drier than average	25%

b) 5-category

Seasonal Rainfall Forecast, March-May	
Conditions	**Probability**
Very wet	10%
Wetter than average	30%
Average	25%
Drier than average	25%
Very dry	10%

Note that the probability spread from climatology (using for example a standard 30-year period) is 33% for the 3-category case and 20% for the 5-category case.

4 Topic Details

Introductory Note

Table 4.1 is given at the beginning of this section as a guide to its contents. For each of the purposes, a cross indicates where a particular type of data, e.g. precipitation, humidity, is required. A short comment is given for each purpose, regarding spatial density of observations and temporal definition of measurements. At the end of each sub-section on a feature, a “Summary of Key Issues” is presented as a text box.

Table 4.1. Summary of Climate Data Requirements

Purpose	Precipitation	Temperature	Humidity	Wind speed	Wind direction	Synoptic Information	Forecasts & Alerts	Med & Long-range Fcsts
Hydrological characterisation	x	x	x	x				
Comment	Spatial density adequate to define variations within and between catchment units. Measurement detail sufficient to estimate current situation, averages and variations over required time units, normally monthly.							
Flood managment and control	x	x	x	x	x	x	x	
Comment	Spatial density must identify local variations. Measurement interval daily for design, sub-daily for specialist design, management and operation on small catchments. Real-time monitoring needed for critical conditions.							
Irrigation and drainage	x	x	x	x				x
Comment	Spatial density must represent demand and supply area variations. Measurement interval daily for design, management and operation. Real-time monitoring needed in multi-purpose systems.							
Groundwater	x	x	x	x				x
Comment	Spatial density adequate to define variations within and between catchment/aquifer units. Measurement detail sufficient to estimate current situation, averages and variations over required time units, normally monthly.							
Navigation	x							x
Comment	Precipitation monthly for planning; daily weekly for operation. Forecasts for operation scheduling							
Power generation	x	x	x	x				x
Comment	As for irrigation & drainage, but additionally needs special arrangements for emergency.							
Water supply	x	x	x	x				x
Comment	As for irrigation & drainage, and power generation, but additionally needs special arrangements for emergency.							
Water quality	x	x	x	x			x	
Comment	Spatial density targeted on specific catchments and river reaches. Measurement interval daily for design, management and operation. Real-time monitoring needed in critical locations and emergency.							
Fisheries and conservation	x	x	x	x				x
Comment	Spatial density targeted on specific catchments and river reaches. Measurement interval daily for design, management and operation. Real-time monitoring needed in critical locations and emergency.							
Amenity	x	x		x	x	x	x	
Comment	Spatial density targeted on specific catchments and river reaches. General conditions monitored for situation updates: real-time information needed in critical conditions.							

Note. Temperature, humidity and wind speed are collectively required for evapotranspiration as model variables.

4.1. Hydrological characterisation

This may be considered as the underpinning feature of water management, in which the primary focus is the river basin (also referred to as *catchment* or *watershed*). It is the field of operation of a management agency, either for a single river basin, e.g. the Tennessee Valley Authority (TVA) or for a collection of river basins over a wider area, such as national agencies like the Environment Agency (England and Wales) or the Bangladesh Water Development Board. The primary concern of a water management agency is with rainfall, river flow and groundwater, and the focus of their activity will be the measurement and analysis of these variables. Historically the main climate variable collected by a water management agency is rainfall, as this, even in the absence of water management or catchment models, will provide an intuitive, subjective or qualitative assessment of the interaction between rainfall, river and groundwater. For the most part, rainfall data are widely available on a daily basis, and can be agglomerated into 10-day, monthly, seasonal values, etc. For specific uses, such as reservoir management or measurement at remote sites, recording raingauges are used. Climate measurements may be collected for specific or general purposes by a water management agency, but they are primarily required for estimation of water losses through evaporation or evapotranspiration.

4.1.1. Catchment/Watershed Planning

This is primarily a *Strategic* function. It relies upon comprehensive historic data from which means, variations and extremes can be estimated. It is usual that the data used have been processed to be in monthly and seasonal form. The climate data items used are: precipitation, temperature and evaporation, either in conjunction with, or drivers for, hydrological and hydrogeological variables. Evaporation data are produced by measurement using evaporation pans or evaporimeters, or estimated as evapotranspiration. The most widely used method for the latter is by the Penman-Monteith (Refs. 9 and 10) equation, which requires measurement of air temperature, humidity (as vapour pressure), solar radiation or duration of sunshine, wind speed and length of day. Issues surrounding consistent measurement of evapotranspiration are mentioned in Chapter 5.

The most basic level of providing data for catchment planning is through a “catalogue” approach, where statistics related to locations and areas are presented. Originally in many countries, this presentation took the form of a year-book. These publications, which were essentially produced manually, were labour intensive, but because of relatively low labour costs in the past were remarkably successful in appearing just a few months after the reporting period. These publications provided good standard of information for exchange of reference material between climate and water management agencies, and in a few cases the information was combined to present both climate and water statistics. Examples of such were the Hydrometric Year Book (UK) and the FAO Agro-Hydro-Climatic Zone maps, the latter being produced in many countries in the 1980s. These maps were excellent examples of cartography, with different variables indicated by iso-lines or graphical diagrams. Geographical Information System (GIS) software now provides a powerful tool to evolve this approach, involving the use of relational databases and user selection of overlays and data processing functions.

However, there are few instances outside of the more developed countries, e.g. USA, Australia, New Zealand, of comprehensive visualisation of data-sets. Their establishment requires a lead agency to host the site and have the responsibility for a range of decisions on what the system will provide, including:

- Maintenance of the website
- Regularity of updating

- Content and format of presentation
- Control of access, e.g. user controlled, open public access
- Management of queries

4.1.2. General Water Balance

This may be estimated in a similar way to that used for planning functions, using data types described in 4.1.1. However, it can be utilised in both *Tactical* and *Operational* spheres, and is thus well suited to being used in catchment or watershed models, where the time-step can be adjusted to suit the application. In the tactical role, a water balance or catchment model needs to be periodically updated on a scale of weeks to consider such requirements as releases for irrigation and power scheduling, and thus the component data has to be regularly updated. Updated data in these applications are often part of a more complex decision support framework, which may involve critical actions outside the immediate brief of the collection agency. The time frame for accessing data may well be at different time intervals than regular processing and publication procedures employed by data collection agencies, which are mostly monthly. The present widespread use of data-logging instruments allows data access and processing to be flexible. The management of data access to third parties has to be controlled, either by fixed agreements or financial contracts, or through well-managed public access websites. This is a complex issue, and is discussed further in Chapter 5.

In the operational role data feeds for similar applications as those of a tactical nature may be necessary at short intervals, of a few days or daily. In these cases the data delivery has to be in real or near real time, and be outside the normal processes of data checking and validation. Because of data exchange difficulties between agencies, any water planning model in likely to be developed and calibrated on data solely available from its own agency. This minimises external dependence, and also removes problems of compatibility when models, observation or operational management changes take place. Thus although it may appear logical and economically sound for data to be provided from one specialist agency to another, the practicalities do sometimes make degree of duplication necessary. It is more common for water management agencies to collect climate data for their own requirements, than for climate agencies to collect their own hydrological data.

A significant data item in water balance activities is the estimation of evapotranspiration (ET) as a major component of losses on a range of spatial and temporal scales. In the context of water balance terminology, evapotranspiration is generally taken to mean the combination of open-water evaporation and the more precise definition, which relates to water losses by vegetation. Estimation of ET in practical terms has always been a problematic topic. ET requires the measurement of:

- air temperature,
- atmospheric humidity,
- radiation balance,
- wind speed;

all of which require integration over a daily period. Considerable problems exist in relating what are highly site-specific data to the ranges of vegetation and soil type encountered over a catchment. In the past the effort involved in station maintenance and data processing sometimes led to the abandonment of networks, as many coarsely- scaled catchment models proved insensitive to small fluctuation in ET, and monthly regional averages were deemed sufficiently representative. Given the above, the provision of adequate data and statistics for ET estimation should be a fundamental point of agreement between the climate data providers and the water managers.

SUMMARY OF KEY ISSUES – HYDROLOGICAL CHARACTERISATION
Shortfall of climate information within water management
Lack of suitable observation stations
Lack of comprehensive long term records – published and archive
Problems in justifying upgrading of networks for measurement and transmission
Opportunities for collaboration with climate service
Collaboration on network development – also avoids duplication
Agreements on data sharing
Collaborative project management and implementation
Links between websites

4.2 Flood management and control

This aspect has both tactical (planning) and operational aspects, and in some cases different aspects fall under the control of different organisations. For example the responsibilities for planning and design of flood management can fall within the brief of planning and infrastructure agencies, whereas operations for major flood defence, which includes such measures as flood forecasting and warning may be the responsibility of water management or meteorological agencies. Interaction between agencies and via them to the public can make this aspect somewhat complex.

4.2.1 Structures for protection and retention

This aspect is a particular sub-set of catchment management, and covers such aspects as dams, diversion structures, river bank and infrastructure protection. It requires very thorough knowledge of hydrological and meteorological information, and because of the critical nature of design requirements, relies on accurate, comprehensive and reliable statistics. Aside from hydrological data, these will include the following meteorological and climatological variables:

- Daily rainfall
- Sub-daily rainfall, at least hourly
- Wind velocity and direction

Daily and sometimes sub-daily rainfall are variables collected by both climate and water management agencies, and the greater density of raingauges in networks used by water management agencies_may reduce the need for data from climate agencies. However, in remote areas, or areas where water management agencies may not have had a previous interest, the rainfall data may need to be sourced from the routine observations of the climate agency. Sub-daily data are collected more sparsely than daily data by both water management and climate agencies.

Problems may arise with regard to the way these data are processed and archived. A climate agency will more usually store sub-daily data on a clock-hourly basis as part of the general requirements for station returns of the national network. Water management agencies may not have a similar statutory requirement to make sub-daily data routinely available, and data can be stored in a part-processed or raw form. Problems arising from this will be discussed in more detail in Section 5.

Both types of agency will record these data for general purposes, and may not necessarily have data for the relevant time-frame, location or in the format best suited to a design application. This may require the planning or designing organisation having to augment data by installing their own observation sites. It is always advisable that the climate and/or the water management agency ensure that the instrumentation and their siting comply as closely as possible with national and international standards.

Wind velocity and direction are most important for dam design, where wind set-up for wave protection is required, but may apply to exposed sections of river embankments. Wind set-up requires information on mean windspeed, duration of winds above certain thresholds, persistent direction and maximum gust velocity. This level of data is usually on available from synoptic stations in the national climate network, as it requires continuous monitoring. This results in such data being sparsely measured in relation to site-specific requirements, and also necessitates detailed processing.

4.2.2 Flood forecasting and warning

This is a highly specialised activity and the World Meteorological Organization has published a manual on this topic (WMO N° 1072) (Ref. 21). This topic is therefore not discussed at length here. Because of the need to deliver critical information in near real time, flood forecasting and warning depends on high levels of technology in data measurement, transmission, assimilation and processing. The operating systems must also have a high level of reliability: as an example, the radar rainfall feed from the UK Met Office to the national Flood Warning Centre is required to meet a specification of 99% delivery over a period of time, e.g. a month. Similar strict specifications apply to the delivery of other items and also stipulate the maximum duration of outage of observation equipment or delivery systems, e.g. 12 hours.

The main data items involved are: precipitation; temperature; synoptic information; forecasts and alerts. Although the primary objective is to forecast river flood conditions, the process requires some highly specialised meteorological information, which can realistically only be supplied by a national meteorological agency. The climate (meteorological) components for flood forecasting and warning are principally radar measurement of rainfall, weather satellite information, numerical weather prediction and quantitative precipitation forecasting. These all have very particular requirements for the application to a flood forecasting and warning system, and provide a highly significant area of existing and potential co-operation between climate and water management agencies.

At the national level, flood forecasting and warning function may be hosted by a water management agency or a meteorological agency. In either case responsibility for data collection lies with separate operational units, so even internally there may be issues over providing suitable meteorological information to flood forecasters. At the higher technical levels in both meteorological fields the educational and work experience background of specialists can be very different, so developing the mutual appreciation of needs can require careful planning. The WMO Manual on Flood Forecasting and Warning recommends that the supplier of meteorological services to the flood forecasting unit provides training at suitable levels to assist the understanding of weather forecasts, radar rainfall measurement and warning statements.

4.2.3 Flood Frequency Estimation

This is a strategic issue, necessary for design safety of major infrastructure, such as dams, nuclear installation, or for policy to account for future climate variability or change. Although usually an exercise in the statistical analysis of maximum river levels and discharges, climate and meteorological data are required as part of the extrapolation of the more extreme events, where the combination of variables has to be made with the proper judgement. Climate and rainfall records are also very useful for the extension of time series and flood estimation by hydrological models. For example, there is not necessarily a direct equality between rainfall probability and flood probability (i.e. that the 100-year flood event is produced by the 100-year rainfall). Some estimation methods take this feature into account (e.g. the ReFH method, UK, Ref.11), but other models may reflect the effects of catchment structure, antecedent conditions and statistical methods may assume that a flood of a given probability is produce by a rainfall of lesser probability. In these and other estimation methods relying of extreme value analysis, use of archive record sources outside those managed by the water management body may be required. Meteorological services in many countries have access to longer rainfall and climate records than say the irrigation or hydro-electric service. As an example, the Kenyan Meteorological Service is the repository of rainfall and climate data collected by many different agencies, such as health, agriculture, forestry an education going back to the times of the colonial administration.

The calculation of probable maximum precipitation (PMP) is a special aspect of flood frequency estimation. In order to follow the methods laid down by WMO in the latest, 2009 edition of the Manual on Estimation of Probable Maximum Precipitation (Ref. 12), a considerable amount of detailed data is required from a meteorological service. These data include humidity (dew-point and wet-bulb temperature), wind speed and direction, both as observations and time series for the analysis of maxima. Even within a meteorological service, these data may be hard to access, or be in a part-processed form.

4.2.4 Flood plain zoning and flood risk mapping

This is primarily a strategic matter, being a specific part of characterisation and planning. The aim is to identify parts of the flood plain, with different categories of risk for planning and development purposes, broadly to define which parts are subject to more frequent flooding, and therefore to be avoided for domestic habitation and critical infrastructure. The relative risk and potential impact on areas are frequently defined by use of historic records and where these may not be adequate, though hydrodynamic model studies. The key to both are thus to have adequate historic precipitation data to estimate flood probability and causative patterns of key flooding events. Long-term daily records are required, and these should be sufficient to provide a reasonable estimate of spatial distribution of rainfall. Timing may be an issue to plan more tactical aspects of flood plain zoning, so sub-daily data from recording raingauges are often required. The networks maintained for water resources purposes and flood monitoring are generally adequate for this, but the key requirement is maintenance of long-term and consistent records, as knowledge of rainfall extremes are important because of association with flood peak flows and therefore maximum inundation.

4.2.5 Coastal inundation

Coastal flooding, which may also include flooding in estuary areas, can be caused by range of conditions relating to tide, wind speed and direction and atmospheric pressure. Areas showing particular physical structures, including narrowing coastal bays and shelving sea-bed, can be particularly susceptible to a combination of meteorological conditions, defined as a storm surge. The North Sea between England and the Netherlands, and the head of the Bay of Bengal are well known examples, where tracks of intense depressions (cyclones) set up specific atmospheric pressure and wind conditions, which cause dangerous surges on top of high tides.

The principal observations involved, wind speed and direction, atmospheric pressure and tides, are generally the responsibility of meteorological services, but coastal flood warning operations are often shared between the meteorological and water management agencies. This arrangement is important in populous areas, where rivers reach the coasts, or in large estuaries, where the combination of tidal levels and river flow become critical for flooding of low-lying coastal land. It is often the case that the meteorological causes of tidal flooding are also those that will cause river flooding, which calls for the need for a high level of co-operation between organisations responsible for the two types of flood forecasting and warning.

The main application for the service is in an operational context, but strategic and tactical elements are important in the formulation of national flood emergency planning, and regional flood forecasting and warning services. Meteorological forecasts play a significant role for this feature, but are only part of an effective system. The level of sophistication and capacity in the forecasts are important, the most advanced services having numerical weather prediction (NWP) facilities linked with tidal surge models at their disposal. Taken in conjunction with satellite observations and radar monitoring, detailed weather forecasts can provide a long lead time to allow for preparedness.

Coastal forecasts are mostly the role of weather service providers, and may be directly linked with data feeds to complex surge and tidal forecast models. The forecasts have to be accessible to the land-focussed flood warning services, and this entails a high level of data sharing if land-based flood warning is the responsibility of the water management agency. Even where linked models are not available, the format and language of the forecasts require careful consideration. As an example, the coastal forecasts in India and Bangladesh originated as a service to inshore mariners, and although both countries now have well developed satellite and cyclone tracking facilities, there has been little or no change in the structure and wording of coastal forecast products, leading to confusion amongst users.

SUMMARY OF KEY ISSUES – FLOOD MANAGEMENT AND CONTROL

Shortfall of climate information within flood management and control

- Climatological data with which to calibrate flood estimation models
- Extended rainfall data sets for extreme probability analysis
- Observation data for forecast and warning models, fluvial and coastal

Opportunities for collaboration with climate service

- Collaboration over use of historic data sets
- Delivery of near real-time observations for operational support, e.g. weather radar, wind observations
- Detailed forecast information, especially rainfall occurrence and thresholds
- Training to understand weather forecast information and products

4.3 Irrigation and drainage

This is a very broad-ranging topic relevant to many parts of the world, and can be considered to have relevance to all levels of decision types. At the highest, strategic, level irrigation and drainage require consideration in terms of long-term national planning, and involve many more bureaucratic operators than just the meteorological and water management agencies. However, as data providers, these two rank in importance alongside the agricultural agency.

The water management agency will have a leading responsibility for supplying hydrological data for planning and management, of both the overall water resource and control of operations. However more broad scale operations may fall within the responsibility of the meteorological agency, in providing seasonal and other long-range forecasts. In many countries, e.g. Sri Lanka data collection and management are divided between two agencies: the Irrigation Department collects hydrological and rainfall data and the Meteorological Department has a specialised Agro-climatological Department to collect and maintain climate and evaporation data.

A number of meteorological services provide forecasts and advisories to farmers and growers to help their water management. The Australian Bureau of Meteorology is highly advanced in its services to agriculture, under its wider remit on its Water and the Land web site. The site integrates information from diverse bureau services and presents links in groups organised by weather elements, including rainfall, cloud, temperature, wind, pressure, El Niño and La Niña conditions, humidity, evaporation and sunshine. Tables of daily data are published that include the full range of variables for the calculation of potential evapotranspiration and a 24-hour measurement of evaporation is included for most stations.

A growing alternative to obtaining information from a meteorological service is for major irrigation users to have their own observation networks of automatic weather stations (AWS). By using a number of AWSs with the appropriate software, detailed irrigation scheduling can be managed down to local levels for different soil types and crops. The market for providing specific advice to irrigators is also one where independent (commercial) meteorological services can successfully meet a demand.

There are many examples of national and international agencies which provide early warning of critical drought conditions. One such is the AGRHYMET Regional Centre in Niger, which is a specialized institute of the Permanent Interstate Committee for Drought Control in the Sahel (CILSS). Its aim is to contribute to achieving food security and increased agricultural production in the CILSS member states and to improve the natural resource management in the Sahelian region, by providing information on climate, meteorology, and hydrology for contributing to food security and the protection of natural resources. The cooperation between EUMETSAT and AGRHYMET was established in 1996 and fosters the use of METEOSAT data for operational and development activities, including rainfall estimates, training, and agro-meteorological and hydrological applications. This service potentially has great benefits, particularly as it serves a number of countries where the national meteorological services have only limited capacity. However limitations arise if there are no clear pathways for the information to be disseminated within a given country between the usual recipient, the meteorological service and water management organisations. Web links and web sites, and their operating platforms need to be properly maintained and accessible.

4.3.1 Supply

This may be considered as a specific sub-set of hydrological characterisation, as the process whereby the requirements for water resources are assessed. The supply sources for irrigation and drainage can come from surface water and groundwater, and the overall management of these are the responsibility of a water management agency. However, the day-to-day operations will be done by the irrigation managers, based on resource availability, demand and constraints put in place by general water and environmental management, e.g. abstraction licences or permits.

Managing the supply on a small, individual abstraction, or for a major system, requires some information on meteorological forecasts, mostly in the medium term (days and months) and in the longer term, (years or longer) where planning and strategy have to be considered. Both operations and longer term planning are based on a set of control conditions, and knowledge of when these may be approached is important. Thus the meteorological service could usefully provide forecasts, information on variability patterns, such as the rainfall associated with *El Nino* and *La Nina* cycles. In countries where these phenomena have significant influence, such as South Africa and Australia, the meteorological service is geared up to provide the necessary seasonal projection, and more importantly, the water management agency has a contingency planning structure ready to be implemented.

The spatial and temporal scale of climate change modelling lends itself to the more strategic aspects of supply planning. Projections may be useful in deciding long-term plans for the development of infrastructure, but it must be borne in mind that climate change will not proceed at a regular, fixed rate, but will be related to the nature and variability of extremes over time. It is important that both the meteorological and water management agencies realise this when transposing the information from projections over an intermediate period, i.e. the projected situation for 2050 cannot be used to define a proportion of change for 2030.

4.3.2 Demand scheduling

This activity is focussed on the management of irrigation in the timing and quantitative distribution of water. The mechanical operation of irrigation systems vary: major irrigation systems in tropical and semi arid areas tend to work on a fixed schedule of releases and delivery for a number of days, e.g. 1 week or 10 days. Schedules may be fixed according to a pre-determined schedule on “average” conditions determined by crop type and its growing cycle. This could clearly be inefficient, but consistent monitoring of precipitation and the meteorological variables needed to estimate evapotranspiration is required if more informed and controlled scheduling can be implemented.

Irrigation agencies often operate their own monitoring of rainfall and evaporation, and the balance of the two over a 10-day period, combined with a knowledge of the crop status, is used to decide the level of water delivery over the next period. Many of the basic observation systems in these systems, comprising daily raingauges and evaporation pans were set up decades ago, e.g. in India, Indonesia, China and central Asia, and the quality of instrumentation and record keeping in some cases may have declined over time. The accuracy and representativeness of pan evaporation data is questionable, and there is some doubt as to how far their data is in fact used operationally, as opposed to use in compiling statistics. Lysimeters are a much more accurate means of measuring point evapotranspiration, but difficulties in their calibration and maintenance has prevented their widespread use. The use of climate stations to provide observations for the estimation of evapotranspiration is not always a well developed facility with irrigation agencies, who may derive these data from a general network of agro-climate stations, operated by the agricultural service or the agro-meteorological branch of the meteorological service. This limits the availability of suitable data for near real-time operations.

Meteorological services could perhaps provide enhanced information for demand scheduling by making available observations from a national or regional network of automatic weather stations (AWS). The latest versions of AWS have sophisticated software for the estimation of evapotranspiration. One ambitious plan proposed in Bangladesh was to replace the ageing network of manually instrumented agro-climate stations by installing a network of 40+ AWS in locations representative of the main soil/crop types in the country. Linked by satellite telemetry to the agricultural extension department, this network could provide a daily update of water balance to improve the response of water scheduling.

SUMMARY OF KEY ISSUES – IRRIGATION AND DRAINAGE

Shortfall of climate information within irrigation and drainage

- Good quality of historic climatological data for accurate estimation of evapotranspiration
- Regular and prompt updating of climatological data
- Seasonal and long term weather forecasts targeted for agricultural management

Opportunities for collaboration with climate service

- Shared development and management of agro-climate observation stations
- Agree demand drivers for supply of data and forecast products

4.4 Groundwater

Groundwater, either within defined aquifers or as a support to river base-flow, is a highly important resource for the supply of water to the full range of uses. In arid and semi-arid climates, given suitable geological conditions, it can provide the only reliable, large volume source. Its management is a sub-division of the overall brief for water management, and in many countries is done on a departmental basis within the water management agency. In other situations its monitoring and management as a resource is the responsibility of a geological agency or a water supply company. The principal requirement for meteorological data is generally as part of the data set for water balance and, by the nature of groundwater processes, these data are required in longer time steps (weeks to months) for operational and planning purposes. Forecasting of groundwater conditions is becoming increasingly important as the resilience of many aquifer supplies is coming under pressure from increased demands, and reduced capacity due to previous over-exploitation.

4.4.1 Recharge

Groundwater is usually characterised by an annual cycle of drawdown and recharge, and its use as a water supply depends on its management within this cycle. There are also cases, due either to the configuration or type of aquifer, or major cyclical climate patterns, e.g. El Nino-La Nina, that cycles over more than one year can occur. Confined aquifers, where recharge is delayed, can show response to rainfall conditions weeks or even months later. Large artesian basins, such as those in the interior eastern areas of Australia and the eastern Sahara, can have responses to seasonal rainfall patterns in peripheral mountains, lagged by several years. It is therefore important to monitor data from a wide area and extended periods to identify trends, especially where critical decision have to be taken regarding water supply. Remote sensing with satellites, using vegetation response as surrogates for rainfall activity, is an option that is increasingly available nationally and internationally, through major meteorological service websites.

Aquifer recharge and/or runoff take place when there is a continued excess of rainfall over evaporation, sufficient to exceed initial losses, and produce runoff and allow downward percolation through superficial deposits into the aquifer. Recharge therefore takes place during rainy seasons, e.g. monsoon seasons in the tropics, winter in temperate latitudes. When rainy conditions begin to predominate, it is first necessary for the soil moisture deficit (SMD) to be replenished. The magnitude of SMD prior to recharge is a function of evapotranspiration, vegetation and soil type. The UK Met Office MORECS system (Ref 13) has for many years provided a weekly reference evapotranspiration (ET) and SMD data set covering the whole country on a 40km grid, from which can assist water managers to estimate the aquifer status in respect of continued draw-down and recharge potential.

Groundwater management is done by reference to known trigger levels, which may be particular aquifer water or storage level, or demand criteria. When trigger points are reached, pre-defined changes in abstraction pattern, sometimes defined as “Rules” are required. The aim is that optimum abstraction should continue until the commencement of recharge, all the time avoiding the complete loss of the source. Implementation of rules is frequently governed by a bureaucratic process, such as the issuing of drought orders, which have statutory times to be put in place. There is clearly potential in this situation for forecasts to be useful to operators, to help identify the continued duration of dry conditions, or drought, and the magnitude of rainfall in the forthcoming wet season. These forecasts are typically required for periods of 3 to 6 months, possibly a year, and as yet there are significant limitations to the quantitative accuracy of such forecasts. At least, these forecasts may provide an indication of whether the next months/season will be drier or wetter than average, and some may present a 5-category forecast from very wet to very dry.

4.4.2 Groundwater flooding

Groundwater flooding chiefly occurs when aquifer water levels (water table) rise to above ground level, a situation brought about by high rainfall quantities over extended periods. Because of the delayed response in vertical and horizontal flow in aquifers, flooding often takes place some time after the causative rainfall events, and may persist for some time (days, weeks), as outflow is also controlled by the aquifer characteristics. The specific conditions leading to groundwater flooding need to be identified from analysis of rainfall linked to past events and correlation with reference groundwater levels. Local rainfall data are normally collected by the groundwater management agency or accessed from the parent water management undertaking, but additional help could be provided from the national meteorological service (NMS) giving information on the wider meteorological conditions obtaining during such critical events. Knowledge of these specific conditions and their likelihood of occurrence over an extended period could assist in preparedness.

Prolonged heavy rainfall in 2000 and 2001 led to concurrent major river flooding in areas of southern England and northern France. As many of these catchments are associated with major aquifers, particularly chalk, the flood conditions were extended for some weeks after the rainfall events, due to high groundwater conditions. In major wetland areas, such as the Okavango swamp in Botswana and the Sud marshes in southern Sudan, the conditions of the preceding wet season strongly influence groundwater controlled flooding.

SUMMARY OF KEY ISSUES – GROUNDWATER

Shortfall of climate information within groundwater

- Good quality of historic climatological data for improving calibration and accuracy of models
- Regular and prompt updating of climatological data
- Seasonal and long-term weather forecasts targeted for groundwater resources management

Opportunities for collaboration with climate service

- Shared development and management of climate observation stations
- Agree demand drivers for content and provision of data and forecast products

4.5 Navigation

Navigation is a vital means of transportation of heavy goods within major river basins, e.g. the Mississippi, Rhine, Mekong. In many cases these major rivers extend through many countries, which presents the added complication of water management, data sharing agreements and weather-climate services from different NMSs. Climate information is required to assist use of current and forecast information on river conditions in relation to transport needs.

4.5.1 Canal systems

Canals require water to be available in controlled quantities throughout reaches to provide adequate depth for shipping movement at all times. Water is managed by an interconnected system of pumping, gravity feed, storage and overflows. Thus it is a specific aspect of water management, with the canal agency closely collaborating with the water management agency. The information requirement from the NMS would therefore be for rainfall observations and forecasts for water management, and for low temperature observations and forecasts. In climates where severe winters are experienced particular forecasts of severity and persistence of freezing conditions are important for planning and maintaining operations.

4.5.2 Dredging

Dredging to maintain adequate channel size to accommodate vessels is normally the responsibility of a waterways or port management agency. The hydrological involvement in dredging is mostly advisory, in supplying river flow data in major river flow reaches or estuaries. As an example, the Flood Forecasting and Warning Centre of the Bangladesh Water Development Board (BWDB) has a dry season responsibility of providing a weekly situation report on the state of rivers which provide key inland water transport in that country. Other departments of the BWDB have the responsibility of periodic river survey, but dredging is carried out by the Inland Waterways Transport Authority (IWTA). In a strongly seasonal monsoon climate such as Bangladesh, meteorological input is of minor importance, as river flows in the dry season are rarely affected by rainfall events, although forecasts of the extended duration of a dry season could be of benefit.

In major river navigation systems such as in North America and Europe, forecasts of wet periods and cold weather can be important. High flow events can result in extensive sediment movement, which require subsequent maintenance dredging. Forecasts of cold weather are important to prepare for river freezing and ice blockages. Forecasts of thawing conditions are equally important to prepare for ice break-up and dangerous movement of river ice-flows.

SUMMARY OF KEY ISSUES – NAVIGATION
Shortfall of climate information within navigation
Regular and prompt updating of climatological data for operational support
Seasonal and long-term weather forecasts for navigation operation and dredging
Opportunities for collaboration with climate service
Agree demand drivers for supply of data and forecast products

4.6 Power generation

The location of power stations is inextricably linked to rivers and coastal locations for two main reasons. Firstly, the presence of water can be the major power source itself, either through river or estuarine generating plant, and second it provides cooling water for the power generating system (oil, coal or nuclear fuelled). The monitoring and forecasting of hydrological and meteorological conditions, is therefore very important.

4.6.1 Hydropower

Hydropower generation is dependent on reliable availability of water, either as river flow, or via control through a level control barrage, or storage in a reservoir impounded by a dam. Thus river flow forecasts, which in turn need appropriate meteorological forecasts are required, and the type of forecasts and data items will be the same as for water supply. Quite often, hydropower installation is part of a multi-purpose river regulating system, where suitable topographic and geological features allow. A reservoir-based system may combine the functions of water supply and irrigation (see sections 4.3 above and 4.7 below) and come under a specialised catchment agency, e.g. the Mahaweli Authority in Sri Lanka and the long established Tennessee Valley Authority (TVA) in the USA. Such agencies can also have a flood control and river-regulating role. For example, in recent years the Mahaweli Authority of Sri Lanka (MASL) has refocused activities from project implementation to river basin management and supports its own monitoring systems.

Frequently power generating sites may be in remote areas, where access and topography limit the availability and usefulness of monitoring sites. Although the managing agency or water authority may have their own monitoring networks, there is a considerable role to be played by remote sensing, for which the meteorological agency may be better placed. There is a practical operational aspect to this, as demonstrated by the experience of hydrometeorological monitoring in Papua New Guinea. During the 1970s and 80s an extensive network of automatic weather stations (AWS) was installed and operated by the Bureau of Water Resources, as there were considered to be considerable prospect for the development of hydropower on both local, regional and national scales. The initiative thus attracted considerable government and international funding, in order to create a substantial database for planning. When it became apparent that the prospects for development were not so great, the recurrent funding support became problematical, as access to many of the AWSs was only by helicopter. Attempts were therefore made, with WMO support, to explore the potential for remote sensing, using the then ARGOS (Advanced Research and Global Observation Satellite) system, which would entail a marked switch in management to the national weather service and international agencies.

The operation of integrated hydrological and meteorological monitoring systems to support the sometimes complex operational water management models is of considerable importance, but is also costly. Optimum management carries significant economic benefit. The advantages of basin-wide rainfall forecasting has been well demonstrated by a long running project for the Volta River Authority in Ghana, initiated by the UK Met Office, and now operated by the Authority with co-operation from the national meteorological service and from NMSs in neighbouring countries.

4.6.2 Cooling water

The location of many power generation sites which use either fossil fuel or nuclear power as the energy source require adequate supplies of cooling water. Flow forecasting, particularly of the severity of a low flow situation is therefore critical. The power generating authority may thus be dependent on both hydrological and meteorological forecasting, or a combination of the two. Prolonged dry seasons can cause problem if rivers fall below critical levels for operation. In the case of markedly seasonal climates, especially where the dry season is also one of high temperatures, the temperature of source and return water may also have a bearing on power processing. High ambient water temperatures may in themselves have critical impacts on fisheries and the general aquatic habitat (see below), so the higher temperature of returning cooling water may further exacerbate these conditions.

4.6.3 Critical safety

The integrity and high level of reliability of power generation is of paramount importance to society, and are part of high level strategic and tactical decisions. In addition to the operational needs described above, sites also have to take into consideration severe or catastrophic events which may cause long-term outages of supply or loss of the structure. Power generation sites have to be designed to a high level of safety, so need to be specifically included in forecasting and warning services. This should cover phenomena such as floods, high winds, tidal conditions and localised intense rainfall. It is therefore necessary that meteorological and climatological information can be sufficiently defined to be of relevance to site management. Equally, the site or infrastructure management needs to understand the nature of critical weather types and how this information can be made available and utilised.

Nuclear power sites require special consideration for safety. The UK government has recently launched a programme to ensure standardisation of design to meet extreme conditions up to the 10,000-year rainfall event. According to site location, this may entail risk from rivers, the sea and storms, or a combination of these sources. Comprehensive meteorological and climatological data, for rainfall, humidity, temperature, wind speed and direction are required to ensure the highest levels of confidence in the results. There are possibly applications here for local-scale climate modelling, e.g. of meso-scale convective systems, once climate model definition in time and space have improved.

SUMMARY OF KEY ISSUES – POWER GENERATION

Shortfall of climate information within power generation

- Good quality of historic climatological data for strategy and planning for development and operation
- Regular and prompt updating of climatological data and medium term forecasts for load management
- Extreme weather forecasts for operational and infrastructure safety

Opportunities for collaboration with climate service

- Agree demand drivers for supply of data and forecast products
- Assistance with design for extreme conditions and climate impacts

4.7 Water supply

The overall requirement for meteorological and hydrological data to support water supply undertakings is the same as that for water resources, and largely concerns tactical and strategic decisions. However, in many cases these decisions have to be more site specific, either to a catchment, localised sources or well-fields, which themselves operate in a broader water resources context. The information requirements may be satisfactorily met by local hydrological and hydrogeological monitoring, but the broader understanding of meteorological and climatological conditions may require particular effort by the meteorological service to focus data and statistics to the user needs.

4.7.1 Potable water

Supply of potable *water* is most likely to be under the management of a utility company or water undertaking, either national or private. They clearly have the requirement to monitor their sources, either surface water – run-of-river or impoundments, or groundwater sources, for both quantity and quality. They may also have their own local monitoring facilities for rainfall and evapotranspiration, but for more general climate and weather data, they will have some reliance on a meteorological organisation for forecasts and overview of current conditions, e.g. drought status.

Worldwide, water undertakings are having to become increasingly cost-conscious, especially as in the private sector they have to meet demands for dividend payments to shareholders. Even where water suppliers are ostensibly nationalised, many have adopted an operating pattern where costs have to be met from revenue. The use of meteorological data and information is becoming more important, both for operations, e.g. demand forecasting, and for longer term management and planning. There are opportunities here for the use of long-range, e.g. monthly or seasonal forecasts to be applied to seasonal models for resource management, and also for future projections on a period of years or decades, where climate change and variability information will play a part in long-term strategic planning.

4.7.2 Industrial processing

Understanding of meteorological and climatological aspects for this feature is similar in many ways to those for cooling water. Process water needs to have a high level of reliability to meet a demand that is more or less constant, unlike the seasonal or shorter period fluctuations that affect water sources. As well as the quantity of water being critical, quality may also be of importance. Low flows may cause unacceptably high levels of unsuitable chemicals to exist in the water, and conversely spate flows may produce high levels of suspended sediment which are unsuitable for a particular process. Returning process water may be contaminated, even if treated, and it is usually a requirement for discharge to be dependent on receiving water volumes to provide adequate dilution to protect the aquatic environment. Thus meteorological and climatological contributions to the forecasting and prediction of periods of spate or low flow can be of considerable benefit to those hydrological forecasts involved.

SUMMARY OF KEY ISSUES – WATER SUPPLY

Shortfall of climate information within water supply

- Good quality of historic climatological data for accurate demand forecasting
- Regular and prompt updating of climatological data and statistics
- Seasonal and long term weather forecasts targeted for supply management

Opportunities for collaboration with climate service

- Shared development and management of climate observation stations
- Agree demand drivers for supply of data and forecast products

4.8 Water quality

The catchment wide management to maintain water quality in rivers, lakes and groundwater is primarily a function of the water management agency. The maintenance of quality is implemented through complex legislation covering chemical, biological and physical characteristics, and a broad range of users, e.g. agriculture, industry, municipalities all have controls under which they must operate. The need for quality maintenance is becoming more stringent, as national and international targets for ecological and conservation measures are put into place. The European Water Framework Directive is typical of such an initiative, where targets to achieve improvement in quality status in water bodies is targeted through biological and ecological indicators, rather than the previous, more simple chemical standards. Most of the requirements and actions with regard to weather information that have been mentioned in the previous sections applies to water quality, which as a function of quantity, will have the same broad needs for meteorological information as water resources.

4.8.1 Pollution Control

Incidents of water pollution arise for several reasons, and response to these incidents can often have a dependence on meteorological conditions for their management and restoration of normalcy. Problems relating to marine incidents are outside the scope of this report, but responses to oil or chemical pollution in rivers, lakes and estuaries may also be influenced by weather conditions, particularly wind speed and direction. It becomes important for clean-up operations to be quickly aware of how weather conditions may changeover the space of a few hours and days.

A particular issue for the short-term management of sewage is the risk of combined sewer overflows (CSOs). Combined sewers, where foul water and surface water are carried in the same system are widespread in many countries, and when heavy rainfall occurs, rapid surcharge of the system will result in spillage of untreated sewage. It is important for sewer management to be able to identify the types of conditions that cause CSOs. Knowledge of conditions leading to past events can assist with design and management, balanced by the financial benefits that could arise from better preparedness. By their nature, sewered catchments are very small (less than 10 km^2) when compared to river catchments, and being predominantly in built-up areas, have a rapid response. It is therefore necessary to monitor rainfall on a localised scale and over very short time intervals. Effective monitoring is beyond the scope of tipping bucket raingauges (TBR), so high-density radar, with a pixel size of 1 km^2 and measurement interval of 5 minutes could provide useful information.

For short term response it may also be helpful to have knowledge of impending conditions likely to cause CSOs: these may come from analysis of past events using short lead-time forecasts (Nowcasts) which are becoming possible from high definition numerical forecasts. Considerable potential has been identified in UK in the combination of NWP and radar, which has the capacity to identify characteristics of the development, decay and movement of areas of intense rainfall, and so provide alert triggers useful in preparations to respond to CSO incidents.

4.8.2 Dilution

Dilution is a key method for permitting the discharge of waste which may, even after treatment, still contain some impurities. Depending on the regime of the receiving water, usually a river or a lake, there are obviously advantages to the management and control from a forecast or projection of meteorological conditions, either incidence of rain, or the duration of dry weather. Information on immediate or protracted elevated temperatures is also important, as these can affect the status of the receiving waters. One of the key indicators of water quality and a target for dilution requirements is biological oxygen demand (BOD), which is sensitive to both water and atmospheric temperatures.

International agencies such as the WHO and the European Commission provide extensive information on water quality criteria, and these form the basis of water quality regulation for most national river agencies. The national meteorological service is not commonly directly involved in providing information for dilution monitoring, but clearly temperature data and forecasts will be useful to water managers.

4.8.3 Salinity and Sedimentation

Problems of salinity and sedimentation are most directly the result of droughts, and in markedly seasonal climates are of greater or lesser significance in most dry seasons. Thus meteorological information on the extent of dry conditions is of considerable importance. As salinity and sedimentation are of greatest importance in major river systems, then knowledge of conditions remote from the point of interest is required. Complications also arise when the river system lies within more than one country, and in these cases, agreements on data exchange are necessary. Examples of the lower parts of river systems where sedimentation becomes a problem includes the Indus in Pakistan, the Ganges Delta in India and Bangladesh and the Tigris-Euphrates in Iraq.

The western part of the Ganges Delta which occupies parts of India and Bangladesh affords a good illustration of the problems of salinity and sedimentation. After the high flows of the monsoon season, flows in the Ganges recede for many months. Over the period from December to April flows can reach critically levels. Since 1975, the Farraka Barrage, just upstream of the point where the Ganges enters Bangladesh has diverted water down the Houghly river to maintain acceptable levels of flow through the city of Kolkata (Calcutta). The subsequent reduction of flow passing into Bangladesh most critically affects a major right-bank distributary, the Gorai River, which is vitally important for irrigation and river transport in the south-west (Khulna Division) of Bangladesh. Lack of flow results in extensive deposits of silt forming at the mouth of the Gorai, and the diminished flow allows tidal incursion of saline water to pass far inland, with serious consequences for water quality for irrigation, potable sources and groundwater. Low flows and sedimentation also can have a serious impact on river navigation. There are no arrangements for hydrological, rainfall and other meteorological data from India to be made available to meteorological and river management agencies in Bangladesh, so information on observations and forecast have to be obtained from satellite and other internationally available data.

Salinity build up in the soils of irrigated areas results from excessive evaporation from water in the top surface of the soil, which brings up salts that have been previously leached, often by over-application of water, or maintaining drainage water levels to high. The over-riding requirement for salinity control is through maintaining careful water management and field-scale operation, and this has to be done by the system operator. However, it is an advantage to be informed and aware of wider meteorological conditions. This could be achieved through access to accurate measurements of evapotranspiration and forecasts of temperature and rainfall out to one to two weeks, to improve irrigation scheduling.

SUMMARY OF KEY ISSUES – WATER QUALITY

Shortfall of climate information within water quality

- Good quality of historic climatological data for accurate estimation of evapotranspiration
- Regular and prompt updating of climatological data
- Seasonal and long term weather forecasts targeted for agricultural management

Opportunities for collaboration with climate service

- Shared development and management of agro-climate observation stations
- Agree demand drivers for supply of data and forecast products

4.9 Fisheries and conservation

Fisheries within rivers and lakes are highly dependent on the maintenance of the required water quality to support the whole of the aquatic environment. The maintenance of fish stocks in rivers and lakes is critically important in many countries, as it can provide a significant proportion of the protein intake for large populations. The climate information requirements for temperature monitoring and drought forecasting mentioned in sections on water resources and water quality are equally relevant here. In addition, high temperatures can be critical for some fisheries, as, in combination of water quality with low flow conditions, can produce stress or death of fish stocks.

Conservation is a very complex topic, and in the water sector concerns complex physical and biological relationships in water-bodies and wetlands. Water management may be affected by catchment-wide initiatives, or by site-specific interventions. The latter, when used on preserved area within a wider agricultural or urban setting, may necessitate pumping, maintaining high water levels by restricting drainage, and controls on abstraction and agricultural drainage. Developing management programmes requires thorough understanding of the climatic drivers of the hydrological cycle and the water requirements of the ecosystem that is to be supported. These interventions have to be considered in a long-term context, and once implemented often lead to increased management needs over time.

The overall responsibility for Fisheries and Conservation often lies within the legal and bureaucratic remit of the water management agency, but separate Fisheries Departments may have a more focussed role where fish provide an important industrial or subsistence resource. Conservation agencies can operate on a range of levels, from international bodies such IUCN (the International Union for the Conservation of Nature), WWF (World Wildlife Fund), to national and local conservation bodies. These two organisations have become increasingly involved in decision-making on water resources on several levels. IUCN and WWF have important roles in managing major conservation areas, such as the Okavango swamp in Botswana and Namibia and fragile ecosystems such as coastal mangrove swamps. They do not however generally carry out monitoring, so meteorological and climatological data and advice have to come from international and national meteorological agencies. The wetland areas of concern are often difficult locations in which to operate, so historically have been poorly covered by either hydrological or climate observations. Time and cost constraints on access make operational monitoring difficult, so remote sensing has an important role to play.

In recent years, organisations such as IUCN and WWF have developed their role in policy formulation in respect of climate change. Often their knowledge is dependent on general information and projections, e.g. IPCC, and used by specialists outside the fields of meteorology and climatology. It is therefore becoming increasingly important that meteorological services and international agencies provide more detailed information on a temporal and spatial basis.

SUMMARY OF KEY ISSUES – FISHERIES AND CONSERVATION

Shortfall of climate information within fisheries and conservation

- Good quality of historic climatological data for accurate temperature stress conditions
- Regular and prompt updating of climatological data to monitor fluctuations in catchment conditions
- Seasonal and long-term weather forecasts targeted for fisheries management

Opportunities for collaboration with climate service

- Shared development and management of climate observation stations
- Liaise over development of suitable forecast products relevant to fisheries

4.10 Amenity

This "Purpose" applies to recreational aspects of water, which in many economically developed countries, and in some developing countries, is an important income generating sector. Many water undertakings give significant attention to the amenity value of water management features, e.g. the use of reservoirs for sailing and other water-based sports. The main use of canals in some countries has changed from a commercial to a recreational focus. In its list of basic objectives, the Australian Bureau of Meteorology (BoM) includes promotion of interests in community health, recreation and quality of life.

The Scottish Environment Protection Agency (SEPA) monitors river level and flow throughout Scotland, and a section of their website provides information on river level and conditions for the previous few days at 90 of SEPA's river gauging stations. This information is aimed at fishermen, canoeists and other river users to help with planning their recreational river use. The site is updated every 24 hours, allowing users to monitor conditions in what are often remote areas. Stations have been chosen as being representative of river conditions in the local area. It would thus be a useful adjunct for meteorological information to be similarly available, as water based activities can be subject to risks from high winds, storms, heavy rain and snow.

The United States National Weather Service website has a Weather Activity Planner. This application generates products from a digital forecast data-base. It is intended to allow a user to define and produce a forecast for general planning purposes only, and could be used for an amenity purpose, as individuals can any the particular weather parameter in which they are interested.

The general management of water for amenity does not normally involve critical constraints from a resource point of view. Extremes of low flow may impose limits on recreational use when resources or environmental considerations become more significant. These situations will be part of the general climate and water resource interface, and will not require any different climate information. There are however risks to the users of water amenity from various weather extremes, and the user of water amenity on lakes and reservoirs may need better information on the dangers and incidence of high winds, heavy rain, snow and freezing conditions.

SUMMARY OF KEY ISSUES – AMENITY

Shortfall of climate information within amenity

- Identifying climate features important to water amenity use
- Delivery of relevant climate information to user of water based amenity

Opportunities for collaboration with climate service

- Liaise over development of suitable forecast products relevant to water amenity
- Preparation of relevant background climate and weather information to benefit water amenity

4.11 Concluding remarks

Taken overall, all the above purposes would benefit from climate information, either to augment monitoring coverage, extend and enhance data for design and management purposes, and to provide specialised forecasting and warning information. The range of applications are summarised in Table 4.1. It is difficult to make comments on accuracy, error levels and confidence, as these will vary with component and purpose. There are inherent accuracy issues with monitoring, modelling and estimation that are beyond the scope of this paper. Table 1.2.5 of the Guide to Hydrological Practices gives a convenient summary of recommended accuracy (uncertainty levels) expressed at the 95% confidence level for a range of climate and hydrological data items. The information for key hydro-meteorological variable is given in Table 4.2.

Table 4.2. WMO recommended accuracy (uncertainty levels) for measurement, expressed at the 95% confidence interval

Variable	Accuracy range
Precipitation	3-7%
Rainfall intensity	1 mm/hr
Evaporation (point)	2-5%, 0.5 mm
Wind speed	0.5 m/s
Water level	10-20 cm
Wave height	10%
Discharge	5%

Invariably economic constraints play a significant part in the facilities used, and the balance between costs and benefits will influence what is technically feasible. As it would be unlikely that a water management undertaking could justify the provision of all of the data requirement and services discussed above, there are inherent benefits in coordination between climate services and water management. These are discussed in the next section.

5 Issues and Opportunities for Current and Future Applications

The preceding chapter of this report has examined the ways in which specific types of climate data are used, and in an optimum situation could be used, for the benefit of various foci of water management. There are numerous reasons why the optimum situation of the comprehensive interfacing of climate and meteorological data with water management activities is not more widespread. The New Zealand National Institute of Water & Atmospheric Research (NIWA) presents an interesting template of an organisation which has integrated a comprehensive range of climate and water topics under 13 separate "National Centres". It is unlikely that most countries would be in a position to reorganise their climate and water activities in a similar way. This final chapter examines some of the main problems that have hindered this interaction in the past, and suggestions made as to how the situation might be improved in the future.

5.1 Data sharing and inter-agency co-operation

Even in those cases where meteorological and water management are organised as a single, functional unit (national or regional agencies for weather and water), the day-to-day operations are invariably organised with a degree of independence. This arrangement is inevitable from the separate skill-sets and scientific backgrounds that are associated with relevant technical and professional staff involved. The reasons and purposes for data provision have to be defined and understood, especially when these form part of a service to outside parties. In many countries, there has been a long history of protectiveness toward the responsibilities of individual organisations, e.g., the view that meteorology stops when rain hits the ground, after which the responsibility for monitoring and managing its behaviour becomes the duty of the hydrologist or water engineer.

Recognition of the need for data sharing frequently depends on the understanding that overlapping and duplication of facilities would not be desirable or economic. Data sharing and the development of different services or products have also evolved where a specific focus is required, such as a flood forecasting and warning service. This situation has arisen partly because organisations may not have had the technical facilities or staff skills to provide all aspects of the task, but also because external demands required that more lead-time and more useful outputs were necessary. This situation has occurred in both "developing" and "developed" countries, as illustrated in Box 1.

Under the WMO Integrated Global Observing System (WIGOS), incorporating the unified WMO Information System (WIS), a major international programme is developing (Ref. 14). It is accepted that such international, regional and national co-ordination it is essential to realising the socio-economic benefits to be derived from a wide range of weather, climate, water and related environmental products and services. WIGOS-WIS will enhance the capabilities of Members to access, develop, implement and use integrated and interoperable surface-based and space-based systems for weather, climate and hydrological observations, based on world standards set by WMO and partner organizations. WIGOS is expected to facilitate timely, quality-assured, quality-controlled and well-documented observations. Improved Quality Management procedures will be required to enable enhanced utilization of both existing and emerging observing capabilities. The Guide to WIS (WMO-No. 1061) will be published in an incremental manner over time.

Box 1 – Examples of data sharing for flood forecasting and warning

Bangladesh. Prior to the late 1980s, the National Flood Forecasting and Warning Centre (FFWC) relied on simple hydrological relationships to predict timing and magnitude of flood levels. The Meteorological Department (BMD) provided a simple category-based system for rainfall on a broad regional basis. Two major UN-WMO projects saw the introduction of weather radar to BMD, with a direct line to a live display at FFWC. FFWC also established weather satellite receiving facilities, and a direct fax link was established with the Storm Warning Centre (SWC) at BMD. This greatly facilitated the exchange of near-real-time information, necessary to provide the quality and quantity of inputs for the upgraded hydrodynamic river forecast models. These facilities have been progressively upgraded, to support the required provision of better public services.

England and Wales. Until major, widespread flood events occurred in 1998 and 2000-01, flood warning was a service provided by area and regional units of the river management body, the Environment Agency (EA). The Met Office provided a basic severe weather warning service on an entirely different regional basis, of which forecasts of rainfall quantity and intensity was defined in very general terms. The potential for integrating radar observations with real-time rainfall data recording led to collaboration between the EA and Met Office for joint development of the network, to be followed by improved forecast products. These were more closely related to catchment areas and the rainfall intensity and duration characteristics most likely to produce a flood response. High-level agreements on roles and responsibilities have culminated in the establishment of joint operational Flood Warning Centre with the aim of better co-ordination of flood forecasting at a national level.

SCHAPI the French National Hydrometeorological and Flood Forecasting Centre. Its main missions consist in supporting the 22 FF local services and providing flood watch, focused on FF basins, including assistance, advice on hardware and software, and training. During periods of flood risk, the watch is carried out 24 hours a day, the forecasting services keep the national and local environmental offices informed of any changes in the flood situation, as well as the media though a specialised unit. In liaison with the local FF services, SCHAPI publishes twice daily a vigilance map on internet (http://www.vigicrues.ecologie.gouv.fr). This map indicates the risk levels on rivers monitored for FF, i.e. 20 000 km of the national river network, and uses a colour code to represent the hydrographic network. Furthermore, the map gives access to the real time water levels provided by the gauges located on the hydrographic network. SCHAPI and the local FF local services are on call every day of the year to publish the flood vigilance map. They are activated in response to criteria from the French meteorological vigilance map and the surveillance of the hydrographic network. During crisis periods, the map is updated several times a day.

Many countries have a unified a common hydrometeorological service under one institution (like NWS in the USA) or even in a single department or office (e.g. the Swedish Meteorological and Hydrological Institute – SMHI, or the Czech Hydrometeorological Institute – CHMI). Such arrangement enables the development of common formats and the sharing of products and tools developed to reflect both the viewpoints of meteorologists and hydrologists. Users of the meteorological warnings and flood warnings are overlapping (civil protection, general public) and one set up of warning system (format, links etc.) is of great advantage (i.e. the Meteoalarm system can easily be extended to include flood warnings).

Data sharing and supply between agencies for any focus, requires that formal arrangements are established, covering the types of data required, their frequency of delivery, the reliability of the service and targets for quality. There may be different levels of service, such as general data provision for public information, for specific uses, such as agriculture, or for items which are time-critical, e.g. for public emergency services. Typical aspects any agreement are as follows:

- A high proportion of data or information items should be delivered to meet a specific time frame, e.g. any 6-hour rainfall forecast should be delivered to the receiving agency within a useful time limit, say 30 minutes from issue time.
- For any set of data delivered, the proportion of items should be consistently high, e.g. 90% of all reporting stations.
- Over an extended period of data delivery, such as 1 year, the outages should not exceed more than a small fraction of the period, e.g. 5 days in any one year and no more that 2 consecutive days.
- Response time to restore data delivery from individual sites should be matched to the long-term standard of service.
- Where quantitative forecast (rainfall, temperature) are concerned, these quantities need some form of evaluation and assessment for comparison against subsequently observed values. Performance analysis is not straightforward, and suitable tolerances or limits for indicating success have to be clearly agreed between provider and user.

It must be emphasised that establishing the operational and quality structures listed above are not trivial undertakings.

5.2 Rationalisation of networks

In many of the *purposes* discussed in Section 4, the required data items will be collected by separate agencies. Problems in establishing suitable data exchange arrangements may be a reason for a particular agency not wishing to abandon some instruments, although they may be proving difficult to maintain, or no longer adequate for purpose. The converse case can arise when an organisation decides to close part or all of its network on economic or operational grounds. Examples of this can occur when amalgamation between local government units takes place or a public utility is privatised, leading to local responsibilities for raingauges or climate stations to be abandoned. These changes will usually be outside the control of the water management authority or meteorological service that was the repository of the data. This situation not only leaves gaps in the provision of data without clear alternative sources, but often will affect valuable sources of long-term reference data.

Rationalisation is clearly a desirable goal for many reasons – the over-riding question is what is the optimum network in terms of equipment and coverage that will provide the necessary information for a variety of users without compromising quality? Various attempts have been made to define optimum requirements for climatological and hydrological networks. The guidance on minimum networks in the latest WMO Guide to Hydrological Practices is no longer formulaic as before, but is written to reflect requirements of scale. Recent publications by I. Strangeways, using world-wide experience and examples, are helpful for their careful assessment of the problem (Refs. 15 and 16).

However, with multiple purposes to be met, this is no easy task – a raingauge network for water resources estimation would be inadequate for flood estimation and a climate station network established for synoptic purposes will not be adequate for agro-meteorology. Problems of interpolation will arise as differing levels of spatial detail is required. If multiple use can be demonstrated, then an agency may have justifiable grounds in maintaining and investing in a comprehensive network. Table 4.1 in the previous section includes comment on spatial density requirements.

The expansion in the availability of automatic weather stations can go a considerable way to solving this dilemma. Modern electronic instruments operate by taking very frequent readings, e.g. measurements of temperature and humidity at intervals of a few minutes and rainfall at intervals of 1mm. Their flexibility of sensor timing, data storage, processing and transmission capacity means that once in a suitable database, data items can be applied in many ways. Remote sensing from satellites is an expanding field, with the range of data types and estimation accuracy increasing. It must however be borne in mind that most remote sensing techniques rely on inference or algorithms, rather than direct measurement. Some reliable ground-truth is always required, as is calibration. The great advantage of remote sensing is that it presents the full spatial distribution of a variable. Conversely however, it is problematical to reproduce point data for the types of analysis conventionally used for station data, e.g. temperature, rainfall for statistical analysis.

Despite the opportunities in equipment and data handling described in the preceding paragraphs, the difficulties of measuring the primary variables that are used in water resources management are still significant. The opportunity of improving the coverage of ground based data must not be overlooked. In particular, in mountainous basins and especially so in mountainous basins with significant snowfall, the characterisation of precipitation is extremely difficult, and is a topic that needs attention. Point rainfall measurements may be underestimate precipitation by 30-40% in such regions, and there are very few cases where the density of the network is adequate to capture the degree of spatial variability of precipitation. Accurate observation of flow (and connected to this, the management of rating curves) is another key issue, and equally very often neglected in planning for the future.

Rationalisation of networks coupled with effective data exchange between agencies provides the best solution, and will prevent anomalies such as where separate agencies feel the need to maintain sensors at neighbouring sites. The optimum solution of shared networks and open data exchange will however require consideration as to the means of financial and operational support. The importance of seeking to use open standards for data – as well as for meta-data must be strongly emphasised and encouraged. The use of standards (some currently emerging) will greatly facilitate data and information interchange that has hitherto been difficult. There have been some recent efforts to improve the use of standards in the water resources community – but it would seem that there is much to learn from the meteorological community in this respect. Standards in meta-data are equally important as without this the usefulness of sharing data can often be lessened.

If a particular organisation is charged with the management of a flexible network, it will require either central support (most likely from government) or contracts to supply data and information to users (which might be other government departments, NGOs and private organisations). These arrangements, often categorised by terms like “user-pays” or “income generation”, are not new in the hydrological and meteorological communities, and have not always been achieved with success.

5.3 Standards of equipment and modernisation

WMO provides detailed and comprehensive standards for almost all climatological, meteorological and hydrological instruments. Comprehensive details on instruments and observations are given in the WMO Guide, No. 8 (Ref. 17). Individual countries have adopted these as national standards or have evolved these from international standards (ISO) and national standards in other countries. With many conventional and electronic instruments there has been an unfortunate incidence of cheap copies of accredited instruments on the market, e.g. AWSs, current meters, raingauges. Although it is usual for procurement documentation to be very detailed, some of the measures to ensure transparency may result in the procurement being governed by higher-level rules, which may not relate to the technical appreciation of the specification. Thus experience and knowledge of those drawing up a specification may take into account knowledge and experience of instruments and operating conditions, but be subsumed in requirements to select the lowest bidder.

Specification of instruments needs to cover the detail of components, operating voltages, accuracy ranges and tolerances. As modern recording instruments need to operate unattended and sometimes in harsh conditions, proven high performance of components and weather proofing of housings must be required. A good "rule-of-thumb" is that instruments should replicate or improve upon the manual instruments that they replace. It is good practice for operators and data handlers alike for running new instruments in tandem with conventional instruments at sample sites so that data structures and details can be assessed.

Introduction of new-generation instruments will also entail some changes in operation and maintenance practices, and perhaps some changes in the skill-sets of technical staff. Most remote sensing electronic instruments are now of modular construction, so the repair and maintenance required by mechanical and early-generation electrical instruments is no longer required. It is necessary that those involved with network operational management understand the nature of instruments, can "trouble-shoot" and manage the procurement of spares and replacements. Recommended good practice is that during the procurement exercise, clear specification is made for commissioning, training and familiarisation, warranty and service support. This will obviously increase costs, but ensure that optimum benefits from modernisation are possible. Sustainability is all-important in climate monitoring networks, and this aspect becomes more vital if a number of organisations are reliant on receiving high quality data. Therefore as well as taking pains on ensuring suitable equipment, the costs of future maintenance should be fully taken into account. Future maintenance has to include periodic checks on calibration of instruments, and this may entail the services of a specialist centre, e.g. a national or international independent calibration service for current meters.

5.4 Meeting data requirements and data management

Once a data service has been established, it remains imperative that it is maintained, both for internal use and to meet obligations to third parties (customers). Supply of data and services are normally covered by a contract, usually on an annual, renewable basis. The status of an established contract may sometimes be complicated by technical developments in either the supplier or receiver. For example, the UK Met Office for many years supplied evapotranspiration and soil moisture deficit data to a number of clients, a system known as MORECS (Met Office Rainfall and Evaporation Calculation System). This was on a weekly basis for a 40km x 40 km grid. The Met Office then changed their methods of estimating soil and atmospheric water balance, in order to support the Met Office internal NWP modelling data feeds. The new content and format of data (known as MOSES – (the Met Office Surface Exchange Scheme) was not compatible with MORECS, and was also incompatible with the user systems. It proved necessary to support a "legacy-system" in parallel.

Such services require a considerable effort in data management, not only in maintaining a regular feed of data to users, but to ensure that archive material and relevant statistics are updated. Data management systems have evolved alongside the rapid progress in computer software and hardware, and there are risks, especially with donor provided systems that these can become obsolete and problematical to maintain. Data management systems tend to be the responsibility of a dedicated data management team. It is important for the organisational structures and technical facilities to develop flexibility for data sharing across new internal and external supply requirements, as well as to service web-accessible databases.

Modern climate monitoring and database systems have many in-built functions, in order to handle the large quantities of data quickly. Data management systems also provide inbuilt systems for pre-processing, to convert data into suitable formats for transmission and manipulation. These systems are a highly technical and specialist field, and have been developed by a few NMSs, such as the New Zealand National Institute of Water & Atmospheric Research system TIDEDA (Time Dependent Data) and the CLIDATA package from Czech Republic. These software package provides databases to store and analyse any time series data and evolved from a hydrological database system first developed internally, but now exported to many different countries. These types of comprehensive systems can be purchased or supplied through aid arrangements. Otherwise, general, commercial database packages can be adapted for use, but require specialists to design a system suited to hydro-meteorological applications.

High capacity data *processing and management* packages should not be confused with *data assimilation*. The latter is an important tool in weather forecasting and hydrology, and is a process of automated analysis cycles to assist optimisation. Data assimilation is a concept encompassing any method for combining observations of variables like temperature, and atmospheric pressure into numerical models, such as those used to predict weather.

The availability of data through webservices has become increasingly common in recent years. These are open to interrogation by the user without the need for making agreements each time data items are required, and the effort of the data holder to prepare information. Clearly the data are only available in specific formats, and some data holders may wish to retain some management of which data are freely available, and which require specific arrangement, e.g. supply of unformatted data, as in .csv format, for the user's own analysis requirements. The availability of these services puts an onus on the data holder to maintain an up-to-date, quality controlled database. Costs incurred must be justified, e.g. for national benefit, meeting freedom of data access, etc. Most common items available on web-based services are recent water levels, meteorological observations and weather forecasts.

5.5 Use of information from centralised remote sensing: international co-operation

There is a wealth of information available from major NMS websites, etc, giving observations, forecasts, satellite imagery, rainfall radar imagery and model outputs. These not only cover the NMS country of origin, but other regions of the world. In many cases where a less developed NMS or water management group cannot obtain data of these sort produced nationally, then these international products are a useful alternative. In reality however there are a number of limitations and drawback to using these data.

The scale of information like satellite and radar imagery is often too coarse for practical application to more localised needs. The visual presentations are largely qualitative. For example, although the brightness of radar echoes are indicative of rainfall intensity, and may be assigned a quantitative scale, these are very approximate, and some form of regular calibration is required for reasonably accurate data to be obtained. Similarly infra-red satellite imagery will provide an estimate of cloud-top temperature, which can be related to precipitable moisture, but again need ground-truthing for calibration. Ground-truthing has to be provided by "data collection platforms", which are always automatic weather stations, which need to be part of a highly reliable network. There are and have been a number of collaborative initiatives co-ordinated and developed through WMO and other international agencies, primarily for groups of states or critical climatological and hydrological zones. Some examples are given in Box 2.

Box 2. International Climate Information and Warning Systems
Information Systems

World Hydrological Cycle Observing System (WHYCOS). Collaborative partnerships in groups of countries, e.g. Himalaya-Hindu Kush)
WMO Integrated Global Observing System (WIGOS)
World AgroMeteorological Information Service (WAMIS)

Warning systems
Severe Weather Information System (WMO). Tropical cyclone information, linked to Regional Centres
African Centre of Meteorological Application for Development (ACMAD). Reports on rainfall extremes, seasonal climate variation.
Global Information Early Warning System (FAO). Includes rainfall monitoring via satellite imagery for national and regional areas.
Agrhymet. Climate related agricultural warning for Sahelian countries

Qualitative information will help interpretation of situations, but cannot provide input to models. Use in models ideally requires the information as data feed, which requires a much higher level of technology and integration of data. Use of digital data streams will also require formal supply and delivery agreements. These various opportunities for accessing climate monitoring information and warning material can provide a useful background to water management activities. Informal use of imagery is however difficult to put into an operational routine, as timings of updates may be unsuitable and there is always the possibility of break-down in communication links. In researching the availability of international websites and those from NMS, it has been noted that many are unavailable from time to time, so again cannot be reliably used as part of a regular critical operational use.

5.6 Public awareness and information services

Both weather and water service providers have a role to play in public awareness and to be the definitive source of information for other government departments, the business and industrial community and the community in general. In some cases the provision of information is a statutory obligation, and is the rationale for government funding. In other cases, the provision of information for specific uses or organisations, is covered by some form of service contract. There is therefore a duty to maintain high standards of consistency and veracity. There can at times be conflicts between delivering information promptly, especially in the case of severe weather or flood warnings, and adopting a cautionary approach to avoid publishing information, which may render the provider legally or financially liable, in case of error. The latter issue can be allowed for if information and data are issued with caveats or disclaimers, or information may be given in general or qualitative terms. There is a very wide range of ways in which climate and water information are delivered to the public, from web-based sites which are updated daily or even sub-daily, to annual or one-off reports.

In addition for their being a growing public demand for information on climate, weather and water, the growth of information provision has in part been driven by the need for water and weather agencies to be income-generating. This has come about through requirements of national governments wishing to limit they budgetary support, but also through the organisational models provided as a condition to support by multi-lateral funding agencies, such as the World Bank. Income generation activities are not simple to implement and have not proved to be as successful as anticipated. The greatest problem is how to prepare users for the idea that they now have to pay for services which were previously free, and considered to be a government obligation or service that was centrally funded.

Any information provided to third parties needs to be clear and understandable, and there are always problems of presentation of scientific data and terms in forms that are understandable to the user. The use of ensemble forecasts from numerical weather prediction models has led to the increasing use of probability-based forecasts. This concept is difficult to apply to different users – a technical person may have a different concept of probability (chance) than a public user. WMO has produced guidelines on the communication of uncertainty (Ref. 18): Table 5.1 gives an example of how forecast terminology can be related to probability.

Table 5.1. Likelihood scales, descriptive and percentage equivalents

Terminology	Probability of the outcome
Extremely likely	Greater than 99%
Very likely	90%-99%
Likely	70%-89%
More likely than not	55-69%
Equally likely as not	45%-54%
Less likely than not	30%-44%
Unlikely	10%-29%
Very unlikely	1%-9%
Extremely unlikely	Less than 1%

Where large rural communities with limited literacy are involved, information dissemination may need to be in pictorial form. This wide-ranging focus was the subject of a major UK Department for International Development funded programme in Mozambique (Ref. 19). Whatever services are provided, they need to be sustainable and able to adapt and evolve to meet changing needs.

5.7 Drivers for improvement

The information provided separately and jointly by weather and water services is coming under growing demand because of the greater needs brought about by population and resource pressure in a variety of guises. With the growth of modern technology and the demand for information the need for high-quality climate inputs to improve water management are of very high priority.

Even without the concerns regarding climate change and global warming, there is an urgent need to maintain and develop resilience against meteorological and hydrological extremes. The demand to provide better resilience should be a significant incentive to bring about the improvements in uptake of climate information that are necessary in many countries. Despite the advances of knowledge in climate modelling and updating of projections, these are still primarily on too broad a scale to be adequate for the requirements of water management.

The latest projections for future climate in the UK Climate Projections (UKCP09) (Ref. 19) now provides information on a 25km grid and presents projections, which are developed by an ensemble approach, in a probabilistic manner. This method is more technically sound than the previous presentation of a range of deterministic estimates. This approach does present the user with an appreciation of the uncertainties and error bounds from the different models, but it does not necessarily mean that the veracity or usefulness of model projections can be used with greater confidence than before – see the statement in Box 3.

Box 3. Uncertainty in Climate Projections (from UKCP09)

The effect of modelling uncertainty manifests itself in the different projections from different climate models, both globally and to a greater extent, at local or regional scales where information is critically needed. Local scale differences between projections from different models are no smaller now than those shown 7 years ago, despite improvements to models. For this reason, we cannot assume that continuing model improvement will quickly lead to a reduction of uncertainties in projection,.

Rather than discourage further development and application of climate models, the caveat in the UKCP statement above should encourage the further uptake of climate information for water management. The role of NMHS will be very important in updating and verification of trends and variations, with reference to the general projections on warmer/cooler, wetter/dryer changes (WMO /TD No. 1562, Ref. 20). However, the detailed questionnaire used to provide material for the production of TD 1562 was responded to be a little under half the WMO member states. Many of the number of non-responding states fall into areas of high climate risk, e.g arid lands, low-lying coastal states and sub-Saharan Africa. This suggests that greater effort is needed nationally and internationally to enable NMHSs to offer the level of skill and knowledge needed for effective resilience and adaptation.

Broad, generalised projections on temperature and rainfall trends are inadequate for most strategic uses. For example, a model projection of possible seasonal drought characteristics in 50 years time, cannot provide any useable pointers to what may happen in the next 15-20 years, which is the time horizon over which strategic planning has to operate. On this time scale, and also the shorter time-scales involved either with operational planning and with events or a crop growing season, the model data coverage are mostly inadequate to identify trends which might relate to a significant climate change, as distinct to an apparent extreme which may be within the bounds of historic variability.

The problems involved in maintaining a high quality database and developing better capacity in current observations is unfortunately, due to national-level financial constraints, often beyond the capabilities of many NMSs. Although many agencies press for development and improvements, these contributions are often limited to an advisory nature, and local implementation remains problematical. This situation is something of a conundrum, given that modern technology has advanced knowledge on climate and the ability to measure it, to a very advanced state. This paper has endeavoured to identify the situations where more and better climate data can be used to improve water management and offered pointers as to how better connectivity could be brought about.

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