21 Towards Reduction of Uncertainty on MEDCLUB (MEDiterranean CLimate Ungauged Basins)

MAURO FIORENTINO & VITO IACOBELLIS

INTRODUCTION

The IAHS decade on Predictions in Ungauged Basins represents an important chance for the scientific community to support sustainable management policies for water-related issues such as the correct governance of all exploitation conflicts, the protection of natural ecosystems, the prediction and mitigation of natural hazards.

In recent decades we have witnessed an increase of interest towards environmental topics which has stimulated a huge number of scientific and technical papers. Moreover, new and far more powerful instruments, in terms of both computational capacity and data availability, are available for Earth observation. Nevertheless, sometimes it seems that the progress of knowledge is not as fast as one could expect as a direct consequence. The main reasons for this situation are probably found in the complexity and heterogeneity of hydrology and the related processes that still dominate the struggle between models and scientists. Moreover, the use of new kinds of data is not always straightfoward but requires much effort for successful assimilation into prediction models, while the availability of powerful computational instruments may lead to the temptation of working on blind trial-and-error procedures, thus requiring faster and faster computers.

On the other hand, this rising tide of data and instruments can be viewed as an abundant, vital and necessary resource. With enough preparation, we should be able to tap into that reservoir—and ride the wave—by utilizing new ways to channel raw data into meaningful information. That information, in turn, can then become the knowledge that leads to theory.

GENERAL PERSPECTIVES

Before attempting to address the matter of prediction, and before focusing on Mediterranean areas, it is probably appropriate to share some perspectives regarding what is called knowledge, in the framework of knowledge management (Bellinger, 2004), and trying to translate those principles in the field of the scientific research. Following Fleming (1996), consider the following observation as a basis for thought relating to the diagram in Fig. 21.1: *A collection of data is not information. A collection of information is not knowledge. A collection of knowledge is not theory*.

The idea we would like to stress is that information, knowledge, and theory are more than simply collections. Rather, the whole represents more than the sum of its

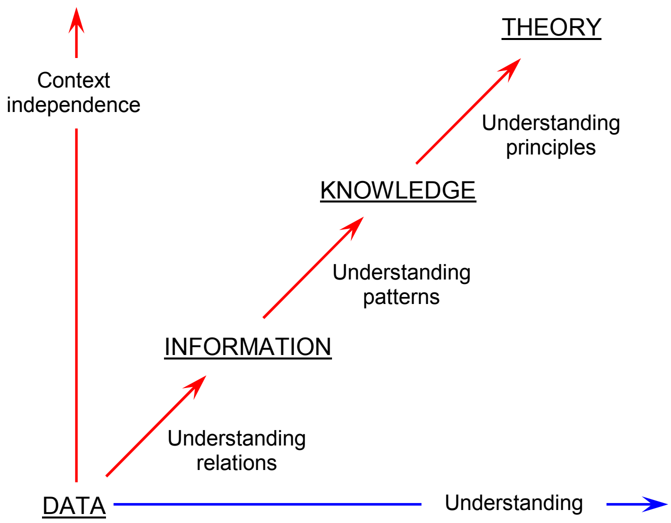

Fig. 21.1 *Continuum process of learning.*

parts and has a synergy of its own. The advances in understanding from “raw data” to “theory” implicitly leads towards context independence which means generality. On the other hand, stepping further along the understanding process we may achieve useful insights through the analysis of context dependence which serves as a basis for transferability into ungauged basins.

Learning from data is one of the first inspiring principles of PUB. The large amounts of data, of different kinds, that are available today, and even more that will be available in future years, is considered to be the powerful fuel of the engine of research. Nevertheless, sometimes data are to be considered as “oil” and we need to carefully refine them, before use.

When we assimilate a piece of data, our first action is usually to attempt to find a way to attribute meaning to it. We do this by associating it with other data and within a certain context. But a collection of data is not information, which implies that a collection of data for which there is no relation between the pieces is not information. The pieces of data may represent information, yet whether or not they are information depends on the understanding of the person perceiving them. Information is quite simply an understanding of the associations or the relationships between pieces of data, or between pieces of data and other information.

While information entails an understanding of the relations between data, it generally does not provide a foundation for why the data is what it is, nor an indication as to how the data is likely to change over time and space. Information has a tendency to be relatively stationary in time and context dependent. Information is a relation between data and, quite simply, is what it is, with great dependence on context for its meaning and with little implication for the future nor for transferability in space.

Beyond relations there is pattern, where pattern is more than simply a relation of relations. Pattern embodies both a consistency and completeness of relations which, to an extent, creates its own context. Pattern also implies transferability and predictability across space and time scales.

When a pattern relation exists amidst the data and information, the pattern has the potential to represent knowledge. It only becomes knowledge, however, when one is able to realize and understand the patterns and their implications. A pattern which represents knowledge also provides, when the pattern is understood, a high level of reliability or predictability as to how the pattern will evolve over time. Patterns which represent knowledge have a completeness to them that information simply does not contain. In our activities, knowledge is traduced in models including methods and techniques for both the description of natural processes and estimation of parameters. Models still may show strong context-dependence but this weakens the more the models arise from physically-based theories.

Theory arises when one understands the basic principles responsible for the patterns representing knowledge. These foundational principles should be universal and context-independent, and we do not know how far we will be able to go in the field of hydrology where difficulties are strictly related to the context-dependence of processes in terms of space and time scales, and also in plurality and heterogeneity of the hydroclimatic zones around the world.

Nevertheless, only if we try to go beyond the linear cause and effect paradigm to study patterns of behaviour and then to study the systemic interrelationships among the parts of systems will we develop a much deeper understanding of the way nature operates: an operational understanding which can allow scientists to work within the system rather than against it.

PECULIARITY OF THE MEDITERRANEAN WORKING GROUP WITHIN PUB

Within the PUB Science and Implementation Plan, under the general aim of reducing the uncertainty of prediction in ungauged basins, PUB acknowledges the need for investigating the plurality of hydroclimatic zones existing around the world. Major differences in hydrological behaviour are observed and a number of different zones are already recognized within the Mediterranean areas. Similarly, a plurality of approaches (from empirical to SVAT models) and a plurality of enabling research programmes (investigating issues related to uncertainty, heterogeneity, field experiments, data assimilation, etc.) are pointed out. The role of the “geographical” working groups is to accomplish the PUB core research targets cutting across all the enabling research programmes with the general intent of constraining the predictive uncertainties, making the best use of the available information, and learning from a comparative evaluation of a variety of models applied to selected basins.

We also note that as “Mediterranean” we can identify large hydroclimatic areas rather than only a geographical zone, having in mind the third of the initial targets of PUB: *understand which processes are dominant or controlling at different scales in the different hydroclimatic regions of the world*.

We will start from the definitions more commonly adopted in literature. The Mediterranean climate is associated with summers generally hot and dry, winters mild to cool and rainy, and warm-temperate coasts. The climate is strongly influenced by westerly air-streams in winter, and sub-tropical high pressure in summer.

So the regions with so-called Mediterranean climates receive relatively low rainfall, with most falling in winter. They also have low summer humidity, which creates high solar radiation intensity and high rates of evapotranspiration in plants. They have moderate temperatures year-round and enjoy the marine influences of their coastal locations. They also often have rugged coastal mountain ranges parallel to the coastline, which influence and modify climatic patterns, forming rain shadows and microclimates.

Nevertheless, within the Mediterranean zones there are a variety of climatic regions owing to the complex configuration of seas and mountainous peninsulas.

Looking at those signatures we can count up to five areas worldwide, which all share a latitude of around 35–40°N or 35–40°S. Besides the Mediterranean Sea basins, the others are California, western South Africa, central Chile, and southwestern Australia.

STATUS, OBJECTIVE AND ACTIVITY OF MEDCLUB

The main objective of the proposed group is the improvement of the techniques for flood and drought prediction and forecasting, with particular reference to the evaluation and reduction of uncertainty for medium-high return period events, in Mediterranean ungauged basins.

The European scientific community has been actively engaged for decades in this field, developing new approaches and methodologies, and supporting the activity of the technical community and the civil protection agencies, and a lot of progress has already been accomplished. National and European funds were, and will be focused on monitoring the meteorological and terrestrial surface factors, by means of remote sensing. Such observations provide databases, more and more extensive, that often are made of measurements of quantities not directly exploitable. They need to be correctly implemented inside hydrological models and also exploited for understanding the physical processes that develop inside watersheds.

We believe that the development of new methods (or perfecting the existing ones) for reducing prediction uncertainty, will necessarily pass through the individualization of the fundamental physical processes and of the relevant sub-models, underlying the complete hydrological process. Floods and droughts are extremes of the same complex and continuous process of "transformation" known as the water cycle, so the role of the climate–soil–vegetation interactions, as well as the impact of human activities, need to be investigated in depth, in order to take into account the nonlinear and non-stationary events that can influence prediction.

In many regions of the Mediterranean areas the hydrological regimes have been deeply altered by the construction of dams with a diffusely claimed feedback on local and regional climate. Moreover, the ever-increasing demand for freshwater has led to a general overexploitation of groundwater resources far beyond the natural recharge rates, causing salt water intrusion in coastal areas and water table depletion in continental territories.

In this context, the worldwide accepted definition of desertification has much to do with drought and global change. In fact, the complexity of land (and soil) degradation phenomena is triggered by the interaction chain linking climate forcing and human activities.

The road in this direction can be considered as already taken. In fact, MEDCLUB is born from a group of researchers already involved in a project focused on "Field experiments at basin scale for the analysis of Climate–Soil–Vegetation dynamics and their impact on hydrological processes and extremes", is ongoing, and will hopefully gain more value through the harmonization of other contributions coming from every researcher committed in the spirit of PUB.

Within this framework, MEDCLUB objectives will be pursued in collaboration with the already established PUB core research projects, and will hopefully lead to the identification, within a Mediterranean context, of: (1) processes which are dominant or controlling at different scales; (2) the role of ecological functioning and human impact on hydrological basins and associated ecosystems; and (3) a classification of model performance in terms of time and space scales, local climate, data requirements and type of application.

The same research, developed through comparative evaluation within the network of PUB working groups will also lead to the correct identification of different classes of models in the unifying framework of model harmonization.

In the following, the strategy to be developed by the MEDCLUB working group will be discussed with reference to the six science questions that outline the enabling research topics directly relevant to PUB.

1. *What are the key gaps in our knowledge that limit our capacity to generate reliable predictions in ungauged catchments? Regional analysis as a MEDCLUB starting line.*

MEDCLUB activities arise from the consideration that current best performing methods, in terms of accuracy of prediction of extremes, are still those based on statistical regional analyses (e.g. Rossi & Villani, 1998). These methods are also generally based on the hypotheses of process stationarity and statistical homogeneity of climatic and physiographic variables. Such models are susceptible to improvements and reduction of uncertainty through a deeper analysis of the spatial variability of the hydrological information. These methodologies are limited by the use of extrapolation procedures needed to extend the probability distribution to high return periods. These well known limits deeply affect the prediction uncertainty. This gap is also greater if one tries to remove the hypothesis of stationarity without adding more information.

For example, it should be rather surprising that the most used methodologies are still those based on annual maxima series of rainfall or discharge, while, at least in principle, they could benefit from the huge amounts of Earth observation data which are now commonly available but not directly exploitable in the framework of prediction.

Moreover, the problem of the non-uniqueness of solution in the estimation of parameters and in the identification of models has been pointed out in numerous international studies that agree on the need for methodological alternatives to model calibration, such as objective estimation procedures (Beven & Feyen, 2002).

In other words, the necessity of taking into account the effects of climate, the climatic forcing on the vegetation–soil system and human activities, becomes striking. Neglecting the effects of the spatial–temporal dynamics of the climate–soil–vegetation system in prediction models causes not only a considerable growth in uncertainty but also a strong bias of hard *a priori* evaluation.

In fact, many processes observed in Mediterranean areas are characterized by interannual and multidecadal fluctuations that are not easily detectable and, even without considering the effect of climate change, it is important to understand the basic processes for the extremes evaluation in order to take into account all the dependences and nonlinearities that affect the extremes' behaviour and their frequency.

For example, in the framework of statistical methods for the estimation of return periods and risk of failure of water supplies, due to the major complexity of hydrological phenomena such as those with temporal persistency (river flows, low-flows, aquifer levels and reservoir volumes) a general application method does not exist (Fernandez & Salas, 1999). Moreover, the intrinsic shortage of hydrological samples, particularly for drought analysis, requires the use of stochastic simulations which, in the case of ungauged or ephemeral streams, means the modelling of precipitation (e.g. Veneziano & Iacobellis, 2002) be adopted as input to deterministic rainfall–runoff models.

2. What are the information requirements to reduce predictive uncertainty in the future? The role of climate–soil–vegetation dynamics.

The instruments and objects through which MEDCLUB proposes to overcome such gaps are: (a) field experimentation for the analysis of the base processes supported with the use of new observation technologies; (b) the development of models representing such processes and the analysis of the impact of such dynamics on base processes and the frequency of extreme events.

As Rodriguez-Iturbe (2000) stated: "*the water balance is at the heart of the problem and its corrected modelling, including nonlinearity and complexity of the space–time dynamics and soil, climate, and vegetation characteristics*".

The base processes considered herein essentially refer to three areas:

– soil–atmosphere interaction: energy budget models for soil and low atmosphere interaction, and the interface with the hydrological models;
– analysis of the vegetation dynamics: models for the description of growing state or stress of different species of plants, based on the analysis of the biomass variation and species competitiveness;
– assessment of the hydrological properties of soils and their representation for distributed models applications.

<u>The land–atmosphere interaction models</u> The kinematic complexity of flow fields in the atmospheric boundary layer and the dynamical richness of the relevant energy and mass exchanges with the soil are of great scientific interest and potential synergic development. Land surface models (LSMs) have been developed to simulate mass and energy transfers, and to update the soil moisture and thermal conditions through time from the solution of surface moisture and energy balance equations (e.g. Noilhan & Planton, 1989).

There is a gap between the scales of hydrological distributed models and that of the limited-area models, such as MM5, WORF, LOKALMODEL and BOLAM. Many attempt to combine the atmospheric processes with a detailed hydrological description, e.g. Entekhabi *et al.* (1992).

In this field, the spatially extended model proposed by Porporato *et al.* (2000) considers, at the synoptic scale, the main phenomena occurring in the lower atmosphere.

The LSM model developed by Albertson & Kiely (2001) is based on the "force-restore method" of Noilhan & Planton (1989) and Deardorff (1978). Montaldo & Albertson (2001) improved the force-restore soil moisture approach for the case of stratified soils. The LSM version has also been improved to enable the assimilation of surface soil moisture observations (e.g. provided by remote sensing measurements) for robust root-zone soil moisture predictions (Montaldo *et al.*, 2001; Montaldo & Albertson, 2003).

Vegetation dynamics Vegetation has a double role in the water balance: an active role in determining the evapotranspiration and infiltration rates, and a passive one in terms of response to dry periods. The vegetal ecosystems are responsible for many feedbacks on the processes controlling the meteorological dynamics and the flood-formation mechanisms. From a global viewpoint, these mechanisms play a fundamental role for the comprehension of the desertification and climate-change-induced phenomena, both because of the complex interactions between the hydrological system and the vegetal ecosystems, and because of the fragile equilibrium conditions of the latter (e.g. Eagleson, 1982).

Vegetation regulates the energy and mass exchange through the biosphere–atmosphere interface. Vegetation density dominates the functioning of hydrological processes by controlling interception, infiltration, evapotranspiration, surface runoff, and consequently groundwater recharge. Changes in the fractions of the landscape covered with deep rooted shrubs, shallow rooted grasses, and bare soil, have first order influences on rates of evapotranspiration and recharge. In particular, numerous experiments have shown variation in catchment response to changes in vegetation cover, such as an increase of basin water yield by decreasing evapotranspiration with a reduction of forest cover (e.g. Allison *et al.*, 1990; Zhang *et al.*, 2001).

The amount of vegetation also influences the partitioning of incoming solar energy into sensible and latent heat fluxes, and consequently changes in vegetation levels will result in long-term changes in both local and global climates (e.g. precipitation and temperature changes) and in turn will affect the vegetation growth as a feedback (Cayrol *et al.*, 2000).

Many considerations emphasize the importance of a quantitative analysis of the water stress condition of vegetation. The expected result is the formulation of a fully analytical model for vegetation water stress, based on the analysis of soil moisture and water stress thresholds.

Soil hydrology Soil hydrology is generally concerned with the description of these basic hydrological processes, as well as the prediction of their evolution under spatial scales comprising plots and hillslopes or an entire catchment, and across temporal scales ranging from hours to some years and more (Kutílek & Nielsen, 1994).

Within this range of space and time scales, soil hydrology shows a definite multidisciplinary character, and in this context the relationship with agricultural ecology is specifically important if one considers that vegetation exerts a key control on the dynamics of the major phenomena occurring in soil. Moreover, distributed models also require information on soil spatial variability. Romano & Santini (1997, 2002) have recently obtained good results for the determination of unsaturated soil hydraulic properties by a simplified approach based on pedotransfer functions (PTFs) enabling the hydraulic parameters to be estimated from more easily measurable, or already available, soil physico-chemical properties .

3. *What experimentation is needed to underpin the new knowledge required? MEDCLUB candidate basins for field experiments.*

MEDCLUB activities include experimental field campaigns on five basins located in different climatic, vegetation, and other conditions. These are: Tovel and Val Rendena Creeks (Italian Alps), Fiumarella di Corleto–Agri Basin (south Appennines), Mulargia Creek in Flumendosa Basin (Sardinia) and Candelaro basin (southeast Puglia).

Databases of three pilot-basins (Agri in Basilicata, and Tovel and Val Rendena in Trentino) are already available. For these basins a high precision DTM has been prepared using laser altimetry. The experimentation will be extended to the two other pilot-basins: the Flumendosa and Candelaro basins, which are of particular interest for the evaluation of semiarid environments and drought analysis.

The main characteristics of these MEDCLUB candidate basins are:

Fiumarella di Corleto basin (32 km^2) Subcatchment of the Sauro River (tributary of the Agri River, Basilicata). In the basin, instrumentation for measures of precipitation and discharge are installed; a high precision DTM is available as well. MEDCLUB is working on measurement campaigns with tensiometers, TDR probes and tension-infiltrometers for soil hydraulic characterization. In the first year of activities a soil–landscape map and a high-resolution vegetation and land-use map will be produced, with a quantitative assessment of the vegetation cover (biomass and leaf area index for individual plants) and a root-system sampling of different vegetation species, in order to quantify its distribution and depth.

Tovel basin (50.51 km^2) This basin of the Trentino region has a complex morphology, mostly of karst origin. Its elevation ranges between 1100 and 2900 m a.s.l. The basin is included in a detailed environmental–biologic–geologic study and is now under a monitoring campaign with the Val Rendena basin. High resolution topographic, hydro-meteorological records, IKONOS and other satellite data and even multitemporal scenes (MODIS, ASTER, LANDSAT, ERS, IKONOS), mostly concerning vegetation cover (NDVI), soil temperature and moisture, albedo, snow cover, precipitation, PTF parameters and soil roughness are available.

Candelaro River basin (>1700 km^2) This has a semiarid Mediterranean regime with a seasonal pattern of drought periods and sudden floods. Located in southern Italy, in the Apulian territory named Tavoliere, below the Subappennino Dauno mountains, Mount Gargano and the Ofanto River, this region, mostly devoted to intensive agricultural activities, is frequently subject to water shortages. Within the Hydroadria project (EU-INTERREG 3-CADSES) and the ArmoniRib project (EU-FP5) an extended data acquisition campaign will be provided for the qualitative and quantitative status of water resources inside the basin, including the setting up of new gauge stations for the remote measurement of piezometric heads, groundwater quality and stream flows, and probes for soil moisture monitoring.

Mulargia River basin (about 65 km^2) is a sub-basin of the Flumendosa River (area ~1800 km^2), located in east-central Sardinia. In the existing funded research projects, an extensive campaign is collecting soil moisture data using TDR techniques at several points to ground-truth soil moisture estimates derived by remote sensing. This data set will be available for testing hydrological models at the basin scale.

4. How can we employ new observational technologies in improved predictive methods? The link with CSV dynamics and field experiments.

The availability of remotely sensed measurements and their use on pilot basins gains more and more importance because it can provide space and time-distributed information. Such systems constitute a mine of raw materials that must be analysed accurately before being usable in hydrological modelling. Satellite observations supply information on many physical variables related to hydrological processes. It is fundamental to define the relationship between remotely sensed products and climate, soil, and vegetation. With this aim, field analysis is particularly useful for the description of relationships and the possible extension of models to ungauged basins.

Recently acquired remotely-sensed data (being extremely accurate and really distributed, and which needs to be assimilated into the simulation models) also include DEMs (digital elevation models) derived from laser-altimeter measurements (performed on the Fiumarella di Corleto and Tovel and Rendena basins) which let us return the basin topography with a horizontal precision of the order of some metres and a vertical precision of a few centimetres. Moreover, thematic maps of soil cover, prepared using passive sensors of various kinds, will be available with a recurrence time in the order of days (instead of weeks) from future remote-sensing campaigns, like ENVISAT and the Italian campaign COSMO-SkyMed.

Other data, which can be assimilated with a reasonable accuracy, are surface temperature, evaporation and some water stress conditions (Castelli *et al*., 1999; Caparrini *et al*., 2003).

This material will be exploited through the field experimental campaigns along with the develoment and employment of innovative eco-hydrological models. The monitoring of water and energy fluxes through field campaigns is important for the understanding, modelling, and prediction of the processes (e.g. Albertson & Kiely, 2001). Evapotranspiration fluxes are measured with the eddy correlation technique (e.g. Brutsaert, 1982) and soil moisture profile using TDR.

The principle state variables of the soil, vegetation and atmosphere system, and in particular soil water content, surface temperature and leaf area index (LAI), from observations by new and old remote sensors such as Landsat and ASAR are also monitored (Montaldo *et al*., 2001).

MEDCLUB is also working on imagery from the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA satellite, that is mostly available to evaluate soil moisture linked with land surface temperature measurement. It will examine the reliability of some soil moisture indexes proposed in the bibliography, in particular the Temperature-Vegetation-Dryness Index (TVDI) proposed by Sandholt *et al*. (2001), based on the “triangle method” of Carlson *et al*., (1995). Such methods, based on land surface temperatures and NDVI (Normalized Difference Vegetation Index) measurements, allow recognition of the behaviour of soils in different conditions of vegetation cover.

Putting together information of different types will effect the model verification. In the experimental alpine basins (Tovel and Rendena), local measures regarding the thickness and the water content of the snow cover, and global measures regarding the flow will make use of satellite images (ASTER, LANDSAT) to determine the spatial distribution of the snow cover and of the albedo.

5. How can we improve the hydrological process descriptions that address key knowledge elements that can reduce uncertainty? Advancing process description through comparative evaluation of models in the framework of flood and drought prediction.

There are a number of deficiencies which can be identified in the traditional approaches to hydrological extremes estimation. In the case of purely statistic frequency analysis, the approach relies heavily on the assumption of stationarity, which may not be valid for catchments undergoing changes in their regimes associated with land use and/or climate changes. Regional analysis is now a well recognized method of increasing the effective sample size by substituting space for time, but based on the assumption that the basins used to derive the regional frequency distribution (fd) form a homogeneous set. Methods of defining a homogeneous set invariably rely on the analysis of the existing data and there will always be some uncertainty as to whether the regional curve can represent accurately the underlying fd of the basin in question. But the point of greatest concern in dealing with frequency of major hazards is that such methods of estimation are empirical and incapable of representing the controlling physical mechanisms which define the fd of the basin in question.

Apart from interminable debates about which distribution and fitting method to use, the approach lacks a sound physical basis on which to extrapolate a fitted frequency distribution to high return periods, and employs only limited information for estimating the risk. In this respect, only a limited number of studies have been carried out in which space–time rainfall models have been linked with rainfall–runoff models that also involve climate–soil–vegetation characteristics. And even fewer studies have been developed in which climate–soil–vegetation interactions are analysed at different space–time scales.

So far, the controlling physical factors of regional flood fds have not been well investigated. For example, how important is climate (reflected primarily in the rainfall and evapotranspiration regimes which jointly control soil moisture), in comparison to basin factors, and how do these interact to determine the shape of the flood fd? This provides the rationale for the programme of research proposed here which will use analytical and simulation approaches, together with remote sensing and conventional hydrological data, to generate new understanding of the physical factors controlling basin fds, and to develop and demonstrate the use of new methods of risk estimation founded on this understanding.

How much infiltrates, evapotranspires, and leaks depends on the soil moisture present in the soil both when precipitation occurs and between storm periods. Precipitation is the driving factor of the dynamics. The overall theme on the other hand relates to Eagleson's (1978) approach where the dynamic climate–soil–vegetation system is analysed in the light of quantitative relationships characteristic of the whole hydrological balance.

At the quantitative analysis level and in the analytic description of phenomena in progress, many interesting developments have been achieved through application of both hydrological distributed and conceptual models.

The purpose of this project is to further develop and link, different insights that have been reached in the last years of research.

Physically-based distributed models progressed significantly in recent years. The System Hydrologique European (SHE) (Abbott *et al.*, 1986) and its more recent derivatives, MIKE-SHE (Refsgaard & Storm, 1995) and SHETRAN are well known examples, and have the capacity to represent the variability in topography, soils, vegetation and geology within a basin, and the influence of physical factors on flood production mechanisms. However, they are too computationally heavy to allow their use within a derived distribution framework involving extensive Monte Carlo simulation. Simpler models can provide the computational efficiency needed, but interpreting model parameters and results in terms of physical processes in a basin is not straightforward. Franchini *et al.* (1996) have combined a stochastic storm transposition model with the ARNO rainfall–runoff model to obtain a Monte Carlo framework for deriving the fd.

Developing models on the basis that: (i) it is possible to neglect the transients in the water fluxes (in the sense clarified in Iverson, 2000); (ii) topographic gradients dominate the hydrological response; (iii) hydraulic conductivity strongly decreases with depth in the soil and, not independently; and (iv) runoff occurs mostly for saturation excess, was the origin of a series of rainfall–runoff models among which TOPMODEL (Franchini *et al*., 1996) is the most successful product. In particular, TOPMODEL has been demonstrated to be a good tool to model floods in small to medium catchments.

Blazkova & Beven (1997) have linked a stochastic rainfall model with TOPMODEL, and demonstrated the effect of parameter uncertainty on the derived flood fd. Hashemi *et al.* (1998) have linked a generalized point process rainfall model with a simplified version of the ARNO model to carry out a simulation analysis of the factors controlling the flood fd. The results of this work suggested that climate, represented by variations in rainfall, potential/actual evapotranspiration and soil moisture, appears to exercise a strong control on the shape of flood fds.

In parallel with progress on the analytical front, developments in the stochastic space–time modelling of rainfall and in the physically-based modelling of runoff production and channel network routing have opened up a significant window of opportunity for the development of the Monte-Carlo approach to deriving the flood fd.

TOPKAPI (Ciarapica & Todini, 2002), on the one hand preserves the physical meaning of the different processes, and on the other hand it overcomes the lack of physicality of parameterizations in lumped models such as the ARNO and some inconsistencies of TOPMODEL.

In this general context, all models use sub-models which account for the complexity of the overall hydrological cycle in which the rainfall–runoff transformation is only a small part. Also, with reference to sub-models, it is possible to recall some crucial advances that research has made in very recent years.

Following on from the early work of Rodriguez-Iturbe *et al.* (1987), stochastic point process models of rainfall have now been developed which can model different cell types within a storm and their evolution in space–time. Numerous applications of point process models have been reported (e.g. Onof & Wheater, 1994; Khaliq & Cunnane, 1996). The ability to incorporate the third moment into the fitting of a point process model (Cowpertwait, 1998) now allows much greater control on the reproduction of extremal properties in generated rainfall time series.

In recent years, a new class of rainfall models has been developed, based on an observed scale invariance property called multifractality. This property is largely inherited from the hierarchical structure of atmospheric turbulence.

The literature on multifractal scaling of rainfall has grown rapidly in the past decade. Veneziano & Iacobellis (2002) developed a model of temporal rainfall that has a pulse structure, multifractal scale-invariance at small scales, and deviations from fractal/multifractal behaviour similar to those of physical rainfall. The iterated random pulse is used for modelling of the storm interiors.

In this context it is worth mentioning the intrinsic relation between the geometric properties of the channel cross-section and the complexity level of the channel network, examining the existence of universal principles, hydrological and energetic, that are able to justify the fluvial evolution at very different spatial scales (Fiorentino & Singh, 1999).

Applying different climatic ambits, varying criteria to find out the critical flows, energetic and self-organization principles will be verified at the channel-scale and basin-scale.

Interesting developments have also been reached by the "derived distribution" approach in which a stochastic model of rainfall is linked to a deterministic model of runoff production and routing to obtain the distribution of a required flood characteristic (e.g. peak discharge, flood volume or hydrograph). Both conceptual and distributed approaches are based on well proven state of the art and provide analytical and numerical tools aimed at the understanding of physical processes.

The derived distribution approach has its origins in the pioneering work of Eagleson who tackled the problem analytically.

Further analytical work has been reported by Diaz-Granados *et al.* (1984), Wood & Hebson (1986), Adom *et al*. (1989), Shen *et al.* (1990) and Cadavid *et al.* (1991). More recently, Iacobellis & Fiorentino (2000) have made a significant advance in developing a more physically-based analytical framework in which interactions between climate, runoff production and the flood frequency distribution are accounted for. Fiorentino & Iacobellis (2001) proposed a theoretical model of distribution of the maximum annual discharge of flood peaks, involving a limited number of physically-based parameters, explicitly considering the mechanisms of generation of the surface runoff, Dunne and Horton types, and related nonlinearities. In subsequent work (Fiorentino & Iacobellis, 2003) the feasibility of parameter estimation for the theoretical probabilistic model through relationships with morphological, pedological and climatic features of basins, and also from remote sensing measurements, was investigated.

The same principles apply to drought frequency analysis; an event originates from a long-lasting period of less-than-normal precipitation which usually covers a season or more. With different delay times according to the water resource involved, the rainfall deficit status results in water shortage even for fundamental human activities and ecological sustainment. Dealing with drought frequency also involves investigation of techniques for the estimation of the return time of runs of deficit. In most cases the propagation of drought from meteorological to its agricultural, hydrological and socio-economic implications implies a complex interactions of processes and process autocorrelation becomes a controlling factor.

Droughts should not be viewed merely as natural meteorological phenomena. Their impacts on human activities and ecosystems derive from the interplay between climate forcing, hydrological cycle and water demands (for civil and agricultural uses) which often worsen the environmental damage (overexploitation of slow recovery resources, drastic reduction of reservoir releases for environmental purposes, etc.). In this way the deep percolation feeding aquifers needs to be evaluated in detail. The continuous simulation of the unsaturated zone and deep flows allow the analysis of the interactions of surface and subsurface water bodies through the year and particularly in the case of seasonal, annual and multi-annual droughts. The modelling of the sub-surface terms in the water balance, validated through historic flow records, is fundamental for the analysis and simulation of meteorological drought impacts on river flow regimes and soil moisture dynamics in riparian zones and river beds.

The major innovative thrust of MEDCLUB will be to use physically-based derived distribution approaches to gain new understanding of how climate and basin factors control the frequency distribution of hydrological extremes. Current practice prescribes how to estimate a frequency distribution, but cannot explain why one basin might have a different frequency distribution to another. Such new understanding would be invaluable in extrapolating frequency distributions, and in identifying homogeneous groups of basins for regional analysis. Moreover, the analytical approach will facilitate the widespread application of the results at regional scales, while the simulation approach will allow more detailed basin-scale studies to be conducted. From an end-user perspective, an ability to understand and explain how climate and basin factors control flood risk would be a valuable advance.

Probabilistic and phenomenological approaches, and combination and cross-validation of the two, are all promising investigation tools for the understanding and modelling of the hydrological processes in semiarid climates.

CONCLUSIONS

In our final remarks we will make reference to the sixth science question of PUB: "*How can we maximize the scientific value of available data in generating improved prediction?*".

As already stated in previous sections, the study of the hydrological processes and the dynamic of the climate–soil–vegetation interactions is of crucial interest for the understanding of extreme events, their frequency and magnitude, the impact of the climate change and finally for the improvement of the prediction and risk-management techniques in ungauged basins. Hence the MEDCLUB activity assumes technical-practical interest associated with the important implications of an economic nature, but also scientific relevance, being linked to the recent development of the new branches of Hydrology and Geophysics called Ecohydrology and Hydrometeorology. These new disciplines combine together different aspects of the Engineering and Environmental sciences, dealing with aspects of Hydraulics, Surface Hydrology, Soil Hydrology, Hydrogeology, Meteorology, Geophysics, and Ecology. As recognized worldwide, the main challenge in the improvement of frequency analysis of extreme events consists in the representation of nonlinearities and the removal of the stationarity hypothesis of processes. This is, also, the only way of understanding the climate change impact.

Moreover, according to the PUB definition of an ungauged basin, we know that, due to the tremendous heterogeneity of natural processes and depending on the spatial and temporal scales of the hydrological observations, every basin may be considered ungauged in some respect. It is clear that the great potential of PUB is directly linked both to the understanding of mechanisms that control the extreme hydrological processes, and to the exploitation of the information potentially available from remote sensing because the last may supply data on wide and heterogeneous portions of territory with great detail in space–time resolution.

Nevertheless, such information is not easily exploitable as a direct input to models and its use places serious problems of elaboration of the observations and of adaptation to the various scales of representation of the hydrological processes (Grayson & Blöchl, 2000; Bashford *et al.*, 2002).

In this general view we conclude that PUB's strongest efforts should be devoted to understanding, and acknowledging that we only learn by connecting new information to patterns that we already understand. In doing so, we extend the patterns. Then, in our effort to make sense of this continuum we relate it to Csikszentmihalyi's interpretation of complexity. Csikszentmihalyi (1993) provided a definition of complexity based on the degree to which something is simultaneously differentiated and integrated. According to this view, complexity evolves along the corridor that leads to knowledge and theory. The diagram in Fig. 21.2, inspired by Bellinger (2004), indicates that what is more highly differentiated and integrated is more complex. While high levels of differentiation without integration promote the complicated status, high integration, without differentiation, produces a coarse condition. And it is obvious that in order to improve modelling and reduce uncertainty we tend to avoid the complicated and are uninterested in the coarse.

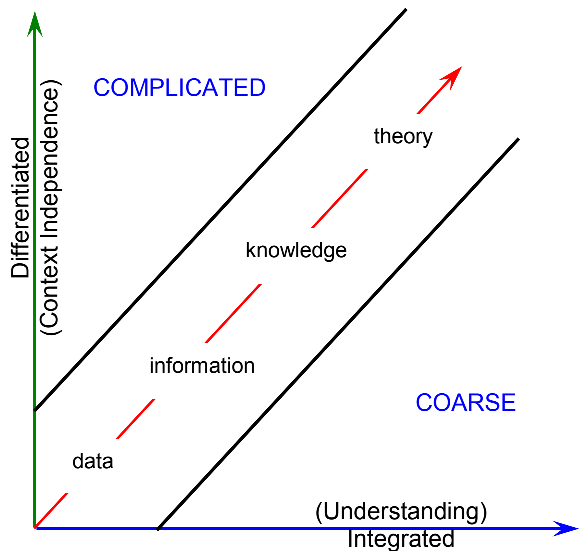

Fig. 21.2 *Differentiated vs Integrated in the process of learning.*

What we find really intriguing is the view that results when we compare this diagram to Fig. 21.1. It seems that "integrated" and "understanding" immediately correlate to each other. But there is also a real awareness that "context independence" relates to "differentiated". Overall, the continuum of data to theory seems to correlate exactly to Csikszentmihalyi's model of evolving complexity.

It could be, from the hydrologist's point of view, appropriate to assimilate "differentiated" with "distributed", and "integrated" with "lumped" and we also could oppose the complexity at the event scale to the relative process homogeneity within a selected window of the frequency domain; these concepts better encompass MEDCLUB strategies.

Finally, we like to conclude simply with the perception that theory like wisdom is a sort of simplified complexity; being aware that, as stated by Jules Henri Poincaré (1854–1912), French mathematician and philosopher of science: *Science is built up with facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house*.

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