Preface

Weather radar and hydrology

1. Introduction

The growing concerns about environmental and climate change issues, as well as the emergence of the concept of sustainable development enshrined in the European Water Framework Directive (WFD) legislation, has modified the requirements for future hydrological observation and modelling initiatives and techniques. Originally, the focus at larger catchment scales was on the water flow at a limited number of locations, essentially for operational purposes such as flood prediction, dam regulation and hydropower production as well as hydrological process understanding. Water is now considered under its multiple functions such as water supply, hydrological risk, hydropower, irrigation, tourism, ecological value, to name a few. The demand for better hydrological understanding and techniques has thus moved to a more integrated prediction of the water balance components (rainfall, runoff, water storage, transpiration, evaporation, groundwater levels, etc.) at every point within a region [21]. In addition, consideration of land-use and human-induced landscape modifications is now a major concern for water management problems (i.e. for flood forecasting) and impact studies of land use change on stream flow, pollutants and/or sediments transport. For most of these questions, knowledge of the general characteristics of water balance components is not sufficient, more detailed process understanding (i.e. storm responses) throughout the landscape are required. The development of distributed and/or semi-distributed hydrological models, where there is a greater representation of the land-surface heterogeneities and the characterization of distributed inputs, are thus increasingly necessary. The usefulness of distributed hydrological models has been questioned, mainly due to overparameterization problems, parameter estimation and validation limitations [9,43,8]. Such difficulties cannot be ignored but the continuous development of hydrological observation and landscape characterization techniques are likely to offer renewed possibilities in this field. We must recognise there is an inevitable compromise between the complexity of the model proposed, and the spatial data that is available to drive the model (inputs) and robustly evaluate its predictions.

We suggest weather radar technology offers a unique means for characterizing the rainfall variability over the range of scales and with the space-time resolutions required for a large variety of hydrological problems. This is especially true for risk management in urban and mountain watersheds characterized by fast dynamics and for which rainfall monitoring and nowcasting are critical [21,37]. For the largest scales, continental rainfields derived from radar networks may also provide valuable information in terms of water budget in complement with climatologic networks and satellite imagery.

This article is a preface to a special issue journal that has been initiated in parallel to the International Symposium Weather Radar and Hydrology, held in Grenoble and Autrans, France, in March 2008. This event continues a series of symposia originally called Hydrological Applications of Weather Radar that started in 1989 at the University of Salford, UK. This first symposium was followed by the Hannover (1992), Sao Paulo (1995), San Diego (1998), Kyoto (2001) and Melbourne (2004) meetings. The main objective of the 2008 symposium was to promote the use of quantitative precipitation estimates (QPE) derived from weather radar technology in hydrological sciences and their applications. The symposium was composed of two events:

(i) A 3-day conference held on 10–12 March 2008 in Grenoble. The programme was composed of 5 keynote speeches, 52 oral and 80 poster presentations covering the multiple aspects of radar physics, radar QPE and distributed hydrological modelling. This scientific material (abstracts, extended abstracts, oral presentations) can still be accessed on the symposium web site at the following address: http://www.wrah-2008.com.

(ii) A 2-day workshop held on 13–14 March 2008 in Autrans (Vercors). The workshop was dedicated to thematic discussions aimed at summarizing the symposium results and investigating future research directions.

In the following, a presentation of the most promising techniques for radar rainfall QPE is proposed in Section 2 prior to a discussion about some of the challenges of distributed hydrological modelling (Section 3). A set of recommendations is made in Section 4 to foster the use of weather radar in hydrologic sciences. Section 5 briefly introduces the articles of the special issue.

2. The most promising techniques for radar rainfall estimation
implemented for conventional radars (i.e. single-polarization non-coherent Doppler radar in the following), residual artefacts may significantly alter rain reflectivity values and the subsequent radar data processing steps. An agreement exists now about the main radar error sources related to both instrumental and sampling properties [75,45,37]: calibration, attenuation due to wet radome, ground clutter and beam blockages, attenuation due to gas and rain, vertical heterogeneity of the hydrometeors (referred to as the vertical profile of reflectivity – VPR- in the following), reflectivity-rain rate conversion (Z–R relationship), rainfall advection. Volume-scanning protocols and physically-based data processing are now generally implemented operationally to cope with such error sources. Although some noticeable progress has thus been obtained [39,68,69,26] some inherent limitations will continue to exist due to the difficulty in performing an absolute calibration, to the sampling problems (radar resolution varies as a function of range, non-uniform beam filling, non-observation of the low-level altitudes above ground level beyond 60–80 km), to entangled errors (e.g., combination of calibration, attenuation and VPR errors at C-band) and to the high intra-field variability of the Z–R relationship [72].

A major advent in the recent years is the implementation of dual polarization and Doppler techniques in a pre-operational mode for several weather radar networks [76,62,42]. In addition to the reflectivity Z, the differential reflectivity Z_{dp}, the cross correlation rho, and the differential phase shift delta between the horizontal and vertical polarizations can be measured for each radar resolution volume. It is worth noting that the potential for dual-polarisation techniques to eliminate non-meteorological echoes [42] has actually been the main reason why several countries have decided to deploy a network of polarimetric radars. Classification algorithms are used to distinguish several classes of liquid and frozen hydrometeors [67] prior to the application of specific rainrate estimators using various combinations of the radar measurables [62]. Polariometry also offers some interesting possibilities such as self-calibration of reflectivity, attenuation correction [70,41] and DSD retrieval [16,57]. Of lesser direct value for radar QPE, the polarization techniques to eliminate non-meteorological echoes [42] have been initiated to further develop this concept which has some noticeable progress has thus been obtained [39,68,69,26].

3. Distributed hydrological modelling

Recent and ongoing research initiatives such as DMIP (Distributed Model Intercomparison Project; [66]) and PUB (Prediction in ungauged basins; [34]) are focused on distributed hydrological modelling. For PUB the concept is to reduce the uncertainties in the modelling process by improving our understanding and representation in models. We briefly review hereafter some of the related challenges.

One of the difficulties in hydrological modelling is that the spatial and temporal scales of hydrological processes span several orders of magnitude: from a few m$^2$ and minutes for soil infiltration to thousands of km$^2$ and several years for groundwater [13]. Furthermore, depending on the climate and the characteristics of the catchment (topography, land use, pedology, etc.), only one or several of these processes may be dominant. For instance, it is usually recognized that runoff (both surface and sub-surface runoff) is dominant in the case of flash-floods, but that evapotranspiration must be accounted for in long-term simulations. According to the scale of interest, the dominant processes might also change. For example while soil hydraulic characteristics are influential for runoff generation through infiltration excess and ponding at the plot scale, the presence of macropores and preferential flow might be the dominant factor when studying the runoff generated at the hillslope scale. Finally, there are several thresholds in hydrology (e.g., appearance of ponding, snow melting, saturated areas, flooding, etc.) which make the modelling more complex due to the associated high level of non-linearities in hydrological responses [65].

A second type of difficulty arises from the combined heterogeneities of the land surface and the sub-soil. The large spatial heterogeneity of the land surface is driven by topography, land use, geology and pedology and increasingly by human actions. To simplify the problem, hydrologists try to define so-called homogeneous zones, i.e. areas where the hydrological behaviour can be considered as homogeneous. This has led to the definition of Hydrological Representative Units (HRU) [33,10], Representative Elementary Areas (REA) [74], Representative Elementary Watersheds [61]. In terms of modelling, this range of concepts has led to various landscape discretizations. Models are mostly based on regular meshes that are usually derived from Digital Terrain Models (e.g. [1,11,60,18]). However, the continental surface heterogeneity is not well described by regular grids and other discretizations have been proposed such as triangular irregular networks [44], hillslopes [71] and hydroscapes [24].

For process representations, two approaches can be distinguished [64]. The first one is an upward approach where processes are modelled using equations established at very small scales (such as the Richards equation for water transfer within the saturated/unsaturated zone, the St-Venant equation for water flow within a river channel, or the Boussinesq equation for water transfer within an aquifer) and extended to larger scales. Effective parameters, relevant to the scale of discretization must therefore be specified if not calibrated [13]. This approach is difficult to verify due to limitations with current hydrological observation techniques (e.g., for subsurface flow processes). Given the non-linearity in hydrological
processes, it is also difficult to derive theoretical approaches describing how the model parameters might change across scales. The second approach is a downward approach where process conceptualization is derived from the available data, with a minimum of parameters, without representing what happens at smaller scales. The simplest approach to this is data based modelling techniques; other examples of differing complexity of representation can be found in [46,29]. But the establishment of such models requires that data are available at the modelling scale, which is not always the case, and the extrapolation to ungauged catchments and/or potentially more extreme observational events that are not yet characterised within the data is difficult.

In terms of modelling practice, a change in modelling paradigm is certainly required as well as accounting for the uncertainties in model prediction. Modellers were trying to answer the following question: “Which model is suited to my problem?” The question should move to “Which combination of processes is relevant to this problem?” [48]. Adopting this paradigm has two consequences; firstly the spatial and temporal discretization of the model should be adjusted so as to meet the main objectives of the modelling study and the data availability, and secondly the complexity and spatial heterogeneity of model process representation should be adapted to the model spatial and temporal discretization. Addressing these challenges is one way to reconcile the downward and upward approaches of model conceptualisation that provides pragmatic solutions to modelling problems [56]. Some authors have described this process as a learning framework for hydrological modelling [28]. Progress in computer science, such as object-oriented modelling, and the appearance of modular modelling platforms [3], which allow the user to couple various models in an efficient way, makes the exploration of different model representations more possible now and for the future.

This new perspective of pragmatic model development to meet the needs of the application effectively in terms of spatial discretization and process conceptualization will benefit from the availability of new observational techniques that describe landscape heterogeneity and provide hydrological observations at various scales. Weather radar rainfall fields will contribute to progress in this direction. Understanding the variability of storm event rainfalls over catchment areas will improve the quantification of the uncertainties involved in the modelling process by better defining the input uncertainties to models, potentially moving away from the necessarily simplified representation of these estimates in current techniques [36]. Continuous increase in computing power makes uncertainty assessments possible now even for the more complex physically-based models [12]. This should be an important consideration in such studies, especially when using diverse data to assess model structures spatially [35].

4. Recommendations

Besides the necessary development of operational radar networks for rainfall detection and nowcasting purposes, two main recommendations can be formulated to foster the use of weather radar data in hydrological sciences (see also [37]).

4.1. Rainfall re-analyses for hydrological sciences

Huge amounts of radar data have been collected for the last 30 years in almost all types of climate and for many regions all over the world. This wealth of data has not yet been fully exploited. Inspired by what has been done for atmospheric data sets (e.g., NCAR or ECMWF meteorological re-analyses), efforts should be encouraged for using archived radar and rain gauge data to produce long-term rainfall space-time data sets with relevant quantification of the associated errors. However, rainfall re-analysis, mainly consisting in gathering large data sets, performing extensive quality checks and combining them to produce rainfall estimates, is a very demanding task and requires a community wide international effort.

A first issue that needs to be addressed concerns the data that are available to perform re-analyses. Concerning rain gauge data, rain gauge networks date back to the 1950s. However, the diversity in data quality, type, consistency and accessibility is a serious issue. The effort and cost required to develop and maintain rain gauge networks is significant and there seems to be a trend of reducing the density of rain gauge networks as the radar network is improved. Concerning radar data, there has been a strong evolution of the radar networks during the previous two decades both in terms of density and operating protocols. Moreover radar systems collect huge amounts of numerical data, which raises the issue of efficient, safe and fast access archiving solutions. This issue will become even more acute as polarimetry becomes a standard for operational weather radar networks. Although radar networks date back to the 1980s, exploitable radar data will probably cover a much shorter period due to unreliable numerical archiving. In order to produce data sets that are consistent at the continental scale, the question of the homogeneity of different radar networks is important. In Europe, the OPERA project (http://www.knmi.nl/OPera), which aims at harmonizing radar data from 28 countries and at promoting data exchange, is an important initiative in this respect.

The second issue concerns the choice of methodologies to apply when performing a rainfall re-analyses from radar and other sources of rainfall data.

- Depending on the archived data (raw volume data versus already processed QPE products), the possibility to apply physically-based processing algorithms may vary significantly. Pragmatic and standardised approaches should be implemented to control the stability of the radar signal, to determine the radar detection domain, to identify and remove residual artefacts, to quantify and correct for attenuation effects, and to characterize the vertical profile of reflectivity. Radar–radar merging techniques should receive more attention especially for relatively dense networks operating in rugged topography: an early-merging of volume data may be preferable to merging the QPE products of various radars.

- As already mentioned, conventional radar technology does not guarantee an accurate electronic calibration and the Z–R relationship is highly variable. Therefore recourse to other sources of rainfall data is needed to optimize the radar parameters and/or to control the radar QPE quality. Rather than a simple “radar calibration”, such an operation should be seen as a multi-sensor merging requiring a detailed knowledge of the space-time structure of rainfall and of the instrumental/sampling errors associated with the various sensors used [37,5,73]. The lack of absolute rainfall reference is often invoked; rain gauge networks with adequate densities remain the only practical solution for obtaining such reference values for past data. The issue of representativeness and discrepancies in sampling scales is significant; time integration is a possible way to limit this influence. Other types of rainfall data such as disdrometers, microwave links, and satellite data (in particular TRMM and GPM that offer suitable resolutions) could be progressively incorporated in such merging procedures.

A variety of applications can benefit from the possibility of accessing a standardized long-term rainfall re-analyses (in a similar way to the extensive use of atmospheric re-analyses for many
research or operational applications). For example, rainfall re-analyses will be useful for research and engineering applications like the analysis of extremes, the derivation of space-time “design rainfall”, the detection of climatic trends, the evaluation of meteorological numerical models, the compilation of multiscale water budgets, the forcing of distributed hydrological models. Critical information that has to be provided in conjunction with the re-analyses is the quantification of the uncertainties associated with precipitation estimates to enable ensemble and probabilistic approaches.

4.2. Hydrometeorologic observatories

A synergy between various disciplines including hydrology and meteorology, but also neighbouring disciplines such as geochemistry, ecology, geography, applied mathematics is required to achieve progress in process understanding and modelling in hydrology. Better techniques to regionalise the most appropriate model structures and to define in the landscape what drives the dominant modes of hydrological behaviour are critically needed. Hydrometeorologic observatories (CUASHI initiative in the USA – http://www.cuashi.org; HYDRATE project in Europe – http://www.hydrate.resaf.unipd.it/; [25]) are now proposed worldwide to provide the required datasets. International scientific experiments like AMMA (http://amma-international.org/) and HyMeX (http://www.cnmr.meteo.fr/hymex/) offer additional opportunities for coupled studies on the water cycle including its oceanic, atmospheric and continental components.

Operational and research radars, together with the other instruments evoked in Section 2, have the potential to dramatically improve the description of rainfall patterns. Dense raingauge networks are required to further validate radar QPE and characterize their error structure. In addition, hydrologic experimental design should be based on nested instrumented catchments, to address process understanding and model evaluation at various scales as well as understanding the uncertainties in our observational data:

- Detailed hillslope instrumentation is required to advance the understanding of factors controlling soil moisture redistribution and for upsampling from local to the hillslope scales. Besides conventional instrumentation, hydrogeophysics offers now a variety of new instruments to characterize the soil profiles and the water dynamics.
- Small- and medium-scale catchments (1–100 km²) instrumentation should include the distributed monitoring of soil moisture, evapotranspiration and the other terms of the water and energy budget. Distributed hydrometry could be achieved using new remote sensing techniques such as large-scale particle imagery velocimetry [22]. Very high resolution satellite images and lidar also offer new opportunities for a better description of surface water pathways.
- For regional scale catchments (100–10,000 km²), the collection and organisation of all the existing operational data sets is required. Improving the accuracy of flood discharge measurements using 1D/2D hydraulic modelling and image analysis is necessary. Satellite data providing estimate of soil moisture should also be acquired and processed in order to provide a regional view of soil moisture variability.

As a complement to detailed instrumentation, post-flood event field campaigns have to be further developed to gather and analyse the large number of evidence left by extreme flood events even on ungauged catchments. Such surveys appear to be an efficient way of progressing the hydrology of extremes and testing distributed hydrological models beyond their common calibration limits [38, 20, 14]. The availability of accurate radar QPE is again a key element for successful post-flood surveys.

In the next years, one challenge for distributed hydrological models is thus to be able to integrate all these new sources of data together with their error characteristics in a consistent way and to progress in the knowledge of water pathways and fluxes. A second challenge is to tackle the problem of process conceptualisation at various scales (change of scale problem). This must be based on the recognition that when moving to larger scales, the form of the equations should perhaps be modified [47]. McDonnell et al. [54] go one step further in this direction by promoting the adaptation of methodologies borrowed from ecology, focusing on the hydrological functions which can be associated to patterns of heterogeneity.

In situ measurements and models will benefit from a mutual enrichment. One of the promising ways to reach this goal is by extending the technique of sensitivity analysis and data assimilation, used in meteorology and oceanography to hydrology. Recent results [17] are very promising and show that these techniques can be useful in improving measurement networks by identifying the places and time where additional observations can be most informative.

5. Overview of the special issue

This special issue of Advances in Water Resources contains twelve articles, which represent only a partial sample of the scientific material presented during the International Symposium Weather Radar and Hydrology (http://www.wrab-2008.com/).

About radar QPE, Diss et al. [27] offer a convincing assessment of a dual-polarization Doppler X-band radar in mountainous terrain with reference to raingauge measurements and the estimates of an operational S-band radar. With regard to merging techniques, Velasco-Forero et al. [73] propose a non-parametric blending methodology intended to be used in real-time operation for the radar-raingauge estimation while Cummings et al. [23] utilize microwave link measurements for the mean field bias adjustment of an operational radar.

Three papers address more fundamental aspects related to the rainfall spatial variability. With X-band polarimetric Doppler measurements, Moreau et al. [58] analyze the rainfall spatial correlation function in order to assess the representativeness error of rain gauges with respect to areal rainfall and to more precisely characterize the radar instrumental error. In the same line, Mandakapa et al. [52] present a theoretical framework for estimating the spatial correlation of the radar rainfall error. Berne et al. [7] develop a method based on indicator variograms to automatically determine the anisotropic rainfall spatial structure from radar data.

Two articles are about quantitative precipitation forecast (QPF). This important subject is not specifically addressed in the present preface and the interested readers are referred to [55] for a recent review. Herein, Fabry and Seed [32] analyze the accuracy of rainfall nowcasts from the US 3D radar mosaic and consider weather-dependent predictors to try improving the forecast and/or reducing its uncertainty. Barillec and Comford [4] introduce a new variational Bayesian assimilation method for precipitation nowcasting using a spatial rainfall model based on radar data.

Four articles are about hydrologic modelling with radar rainfall input. Focus is given to extremes for which weather radar offers unprecedented observations. Morin et al. [59] present a robust hydrological model utilizing radar data intended to be used for flash-flood warning in a semi-arid region. Bonnifait et al. [14] discuss the hydrologic and hydraulic modelling exercise that was conducted to put in coherence the various sources of data (including
operational data and post-event field estimates) collected for an extreme event. Sangati et al. [63] utilize high resolution rainfall fields and a distributed hydrologic model to test the sensitivity of flash-flood simulations to spatial aggregation of rainfall and soil properties over a range of scales. Finally, Cole and Moore [19] perform an ungauged modelling investigation using a distributed hydrologic model and radar rainfall inputs for instrumented nested catchments.

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