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Radar hydrology: rainfall estimation

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Abstract

Radar observations of rainfall and their use in hydrologic research provide the focus for the paper. Radar-rainfall products are crucial for input to runoff and flood prediction models, validation of satellite remote sensing algorithms, and for statistical characterization of extreme rainfall frequency. In this context we discuss the issues of radar-rainfall product development, and the theoretical and practical requirements of validating radar-rainfall maps and new radar technologies. We discuss a framework for reflectivity based rainfall estimation, including estimation of uncertainty of radar-rainfall estimates. Validation of radar-rainfall products is a major challenge for broad utilization of these products in hydrologic applications. In the discussion of radar-rainfall prediction we focus on orographically induced extreme rainfall and flooding, discuss the issues of detection, statistical sample size, and scale effects. We conclude the paper with a set of recommendations for research priorities and experimental requirements to address them.

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1. Introduction

Radar has assisted weather predictions for over forty years but its operational use in hydrologic applications spans only a decade or so. We approached writing this paper on radar hydrology for the 25th Anniversary Special Issue of *Advances in Water Resources* as an opportunity to discuss the research needs in the field. Our approach is not a comprehensive one, we focus on selected issues of radar data use in hydrology drawing on examples mainly from the NEXRAD system in the United States [23,27,29]. We limit our considerations to the use of weather radar for quantitative estimation of rainfall. We do not consider the quantitative precipitation forecasting problem as a recent issue of *Journal of Hydrology* [69] was devoted to it. Our objectives are to discuss those aspects of radar-rainfall estimation for use in hydrology that we consider general yet critically important for the future. The paper contributes to the discussion solicited by [21] on emerging issues in hydrologic research.

Quantitative estimation of rainfall from radar observations is a complex process. It involves issues of engineering design of a complicated and sophisticated hardware with both electronic and mechanical subsystems, signal processing, propagation and interaction of electromagnetic waves through the atmosphere and with the ground, image analysis and quality control, physics of precipitation processes, optimal estimation and uncertainty analysis, database organization and data visualization, and hydrologic applications. The scope of our paper is limited to the estimation and uncertainty quantification issues. Rather than focusing on a particular algorithm or method, we discuss the generic issue of developing radar-rainfall products and their validation. We discuss the questions of estimating the bias and evaluating the random errors of the rainfall products. We also discuss observations of extreme rainfall. Weather radar offers an unprecedented opportunity to improve our ability of observing extreme storms and quantifying their associated precipitation. These events trigger floods and flash-floods, debris flow, and landslides. As they often occur in complex terrain their detection is associated with additional difficulties and their treatment warrants a separate section in our paper.

We close the paper with a set of recommendations for future research. These involve not only theoretical and modeling studies but also the observational and experimental infrastructure necessary to answer many questions we pose herein.

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2. Radar-rainfall estimation

The basics of radar-based observations of rainfall are discussed by many authors including popular textbooks by Battan [8], Doviak and Zrinc [20], Sauvaugot [47], and Reinhart [45] (see also [5,31]). Here we only briefly repeat selected definitions for the sake of consistence of our use of these terms in the subsequent discussion. Radar measurements of power of electromagnetic waves backscattered by raindrops are directly related to a physical quantity called *reflectivity*, Z, with units of $\mathrm{mm}^6/\mathrm{m}^3$. Estimation of rainfall amounts (rain intensity, R in mm/h, or rainfall accumulation, R_A in mm) involves using reflectivity via a Z–R relationship. This relationship could be given in terms of a power law of the type $Z = aR^b$ as discussed in [8], a look-up table [46], or, perhaps, a neural network. We will come back to this issue shortly.

Radar reflectivity data are typically obtained in the form of a volume scan, i.e. a sequence of sweeps for increasing antenna elevation angles. A volume scan is available every 5–15 min and consists of data given in polar coordinates. The volume scan reflectivity data, collected on a polar grid with a resolution of about 1° by 1 km, are converted to radar-rainfall maps (here we call them *products*), i.e. regular grids with a typical resolution of 2 km by 2 km, or 4 km by 4 km. The conversion includes applying a Z–R relationship, usually in polar coordinates, averaging the polar grid to a rectangular grid, and selecting or averaging the information on the vertical extent of the storm.

How is the Z–R relationship selected in the above procedure? We distinguish two general approaches. In the first approach, which we will term the drop size distribution (DSD) approach, Z–R relations are derived from raindrop size distribution observations, typically made at the surface and representing a sample volume of the order 1 m^3. Because rainfall rate and radar reflectivity factor can both be derived from observed raindrop size distributions, Z–R relations can be computed directed by statistical methods (for example, regression of natural logarithms of reflectivity versus natural logarithms of rainfall rate in the case of power law Z–R relationships). In this approach, a Z–R relationship is selected based on analysis of raindrop size distribution data for a given dominant rainfall regime.

The second approach is similar in relying on statistical estimation procedures to relate measured values of radar reflectivity to rainfall rate. The fundamental difference is that in the second approach, which we will term the optimization approach, radar reflectivity measured in the atmosphere by a radar is related to surface observations of rainfall rate (typically from rain gauge networks). In this case, radar reflectivity observations with a characteristic scale of approximately 1 km^3 are related to surface rainfall rate observations. This approach is motivated by the observation [5] that the largest sources of error in radar-rainfall estimates are not driven by DSD control of Z–R relations, but by sampling properties that relate radar reflectivity factor at the surface to radar reflectivity aloft (incomplete beam filling, bright band, evaporation below cloud base, updraft/downdrafts, hail contamination aloft, etc.). In the optimization-based approach, some measure of "closeness" of the radar-rainfall products and the surface rainfall reference data obtained by rain gauges is minimized.

The DSD approach avoids the scale compatibility problem of comparing radar measured reflectivity at 1 km^3 scale to rainfall rate at 1 m^3 scale, but introduces other problems. There is little evidence that point approximation of Z–R relationship is adequate in view of the existing evidence of spatial and temporal variability of rainfall rate. Another problem with the DSD approach, as demonstrated by numerous authors [15,49, 55], the parameters of these point relationships are highly sensitive to (1) statistical approach used in their estimation; (2) sample size of the data used; and (3) instrument type used to collect the data [12]. It should also be noted that instrumental errors both in the disdrometer used to collect the DSD data and the radar used to perform rainfall estimation are ignored in this approach. This potentially leads to difficulty identifying effects such bias [59] and non-linear transformation of radar-reflectivity measurements [15].

The optimization approach (e.g. [1,17]) treats the Z–R relationship as an empirical formula, in which the key step in algorithm implementation is estimation of the unknown Z–R parameters. The radar-rainfall products are optimized in a well-defined sense, according to a criterion deemed appropriate by the user for a particular application. The approach acknowledges explicitly that products optimal according to one criterion are not necessarily optimal according to another. For example, Ciach et al. [16] show, that root mean square criterion is in conflict with, what they term, "total conditional bias criterion".

The main reason for this is the non-linear character of Z–R combined with the existence of random errors for both the radar-reflectivity measurements as well as the rain gauge data that suffer from significant uncertainty in representing the scale of the rainfall product [25,33, 66]. Another manifestation of the optimization-based approach is scale dependency. As specific radar-rainfall products correspond to well-defined space and time scales, different solutions are obtained at different scales. In other words, optimizing products at a certain scale results in better estimates than simply averaging them from a lower scale [41].

2.1. Bias

Identifying and quantifying bias is perhaps the most important step in characterizing the error structure of radar-rainfall estimates. By "bias" we mean the systematic departure from the true, and unknown, rainfall. There are numerous causes of radar-rainfall bias, including miscalibrated radar, overshooting the cloud systems, improper *Z–R* relationship, and subcloud evaporation of raindrops. All will cause systematic departure of estimated rainfall from the true rainfall. In the following discussion we approach the problem of bias identification from the real-time estimation point of view. This is because in the off-line mode, with the availability of sufficiently large sample the problem of bias adjustment is much simpler.

We also recognize that identification of the bias due to any or all of the above causes is difficult due to the existence of significant spatial and temporal variability of rainfall and the sampling area mismatch of radar and rain gauge sensors. To eliminate the effects of random factors—which include in addition to the rainfall variability, the reflectivity and rain gauge measurement errors—on bias identification, radar-rainfall and rain gauge rainfall accumulation should be integrated over a certain time scale prior to a meaningful comparison. What is that scale? There is no simple answer to this question. If the scale is too short, for example 15 min, clearly significant spatial variability of rainfall will mask the effect of the bias. From one period to the next, from one gauge to the next, we could have large positive and negative differences between the radar and rain gauge estimates of rainfall. As we allow time integration of the data, the random effects average out, and the bias, if present, becomes more obvious. On the other hand, if we wait too long, we may be mixing seasonal effects. The bias in the cold season is likely to be different from that of the warm season as the typical vertical extent of the cloud system and the DSDs are quite different [2,50].

In the past, the problem of bias estimation and correction in real-time has been approached in the mean-field sense, i.e. trying to ensure that the entire rainfall field in view of a radar does not deviate from that represented by rain gauges. Several authors conducted studies of statistical techniques for this approach, including [2,48,53]. Recently, we note a tendency documented in the literature towards eliminating some of the range dependent biases based on their physical causes [53]. In particular, Vignal et al. [60–62] demonstrated good performance of a vertical profile of reflectivity correction that mitigates the effect of bright band, among other effects. As these effects operate on a short time scale, their effects should be corrected also on such a scale. Vignal and Krajewski [62] also report decrease of random effects in the VPR-corrected radar-rainfall estimates. This is understandable since some of the effects work in the opposite directions, as we discussed above, and thus, when taken together, they "look" random.

Anagnostou et al. [2], McCollum et al. [37] and Seo and Breidenbach [54], attempted to investigate the effect of different time scales on the effectiveness of the bias removal. Still, due to the lack of long-term high-quality radar and rain gauge data sets the question remains largely unanswered. A Monte Carlo simulation study would be an alternative to provide some guidance but its realism is likely to be compromised by the fact that we know little about the statistical characterization of the errors of radar-rainfall.

Our discussion above has implications for the design of operational rain gauge networks. Qualitatively, the rain gauges should be placed in such a way to capture the range effects in all the directions that characterize the rainfall regimes present under a given radar umbrella. It is preferred to place them along the same radar ray as this would eliminate the potential for the near-radar effects due to ground clutter that may affect different azimuths in a different way. Directions where additional effects are expected, such as orographic or synoptic, should be covered by separate gauge sets. The number of gauges per direction does not need to be high as the systematic effects change gradually (but not necessarily monotonically, see [50,62]) with range. We estimate that 4–6 gauges would do the job.

2.2. Polarimetric methods

Research conducted over the past 20 years indicates that radar-rainfall estimation may be improved with additional radar measurements. Research radar systems simultaneously measure reflectivity and phase at horizontal (H) and vertical (V) polarization [11,32,68]. The physical concept behind polarization diversity measurements exploits the fact, that under aerodynamical stress, falling raindrops take oblate shapes, and as a result impact differently the propagation and backscattering of an incoming H and V electromagnetic radar wave. The most common polarimetric radar measurements are (1) the reflectivity factors at H and V polarization (Z_{H}, Z_{V}); (2) the differential reflectivity factor (Z_{DR}); and (3) the propagation differential phase (Φ_{DP}). These measurements provide information that can be related to DSD characteristics, and in turn provide improved rainfall estimate.

Additionally, the polarimetric measurements provide new means for classifying precipitating particles (rain, hail, graupel and snow) and for distinguishing the ground echo due to local clutter and anomalous propagation conditions from precipitation. The two most beneficial aspects of polarimetric measurements may be the elimination of hail contamination effects in heavy rainfall and improved detection of ground returns.

Use of polarimetric measurements in an operational setting presents a host of new challenges. It is not our goal to discuss them herein as others have already done this effectively (e.g. [26,32,68]). Some of the challenges deal primarily with radar system design. Other issues concern the fundamental physics of propagation and interaction of radar waves with precipitating medium.

Our goal is to bring attention to the issue of estimation. The polarimetric measurements are not a panacea to many of radar-rainfall uncertainty sources (with the possible exception of hail contamination). Within-beam variability, subcloud evaporation, cloud overshooting, etc., cannot be solved with the polarimetric measurements. Also, the measurements of some of the polarimetric variables are associated with significant uncertainties. For example, estimation of specific differential phase shift (K_{DP}) is subject to random phase errors of the Φ_{DP} measurements and the backscattering phase shift (δ), which cannot be readily separated from Φ_{DP}. The δ value, which increases with an increase in raindrop size, can be significant at high rainfall intensities and high radar frequencies. This non-Rayleigh effect can introduce serious complications in the evaluation of K_{DP} at the X-band and moderate to high rainfall intensities, and requires careful investigation [36].

Studies on radar polarimetry have concentrated mainly on the S-band frequency and shown that K_{DP} based radar estimators are not affected by radar calibration errors and partial beam occlusion (e.g. [65,67,68]). However, at S-band, these estimators are characterized by relatively low sensitivity to rainfall rate and this, consequently, has negative impact on the product resolution. Since Φ_{DP} sensitivity to the raindrop size is proportional to the radar wavelength, one would expect that at X-band, these limiting values could be lowered by a factor of three. Consequently, the use of X-band wavelength should allow more accurate estimation of light to moderate rainfall rates at higher spatial resolutions. These improvements are primarily important for the accurate prediction of floods in small to medium size watersheds with rapid response to precipitation and for real-time urban water management. Furthermore, partial signal attenuation, which is significant at X-band, is not an important issue for the K_{DP} estimator unless there is complete attenuation. The main complications in K_{DP} rainfall estimation at X-band that need to be investigated are (1) the presence of significant δ in cases of high rainfall intensities, and (2) the effect of DSD variability and oblateness shape model selection on the estimator parameters. To date, research on the use of polarimetric radar measurements at X-band has been limited to a few theoretical [13,30] and experimental studies [36,57] but the proposed estimators lack adequate quantitative validation and error analysis.

Thus, if we realize that rainfall estimates based on polarimetric data are uncertain, the task remains to quantify these uncertainties. From this point of view the requirements for validation of radar-rainfall are the same as for single-parameter radar.

2.3. Validation

The central question for hydrologic application of radar-rainfall products is “How good are these estimates?” In our view this is a question of validation. According to Webster’s Ninth New Collegiate Dictionary, *valid* means “being at once relevant and meaningful,” and *validation* is the “process of determination of the degree of validity of a measuring device”. In this paper, we define validation consistently with the common definition quoted above. Validation is determination of the space-time statistical structure of errors of the radar-rainfall products, i.e. “the degree of validity”.

Clearly, identifying and estimating the full structure of the error distribution is a challenging task. It may be prudent to simplify it to begin with and focus on the first two moments of the error distribution. In the section above we discussed the issue of bias, here we will focus on the error variance. Ciach and Krajewski [14] proposed a general framework for the error variance estimation. They proposed to separate the radar/rain gauge difference variance into two components: one due to the natural variability of rainfall in space over scales smaller than that of the radar-rainfall products, and the second one being the radar-rainfall error variance. The subgrid variability, if substantial, implies lack of good representativeness of the grid scale rainfall by the rain gauges that measure the process at a point [33,66]. The use of this approach, coined error variance separation (EVS) method, requires two important components. First, it requires making an assumption about lack of correlation between the errors of the radar-rainfall and the rain gauge approximation of the grid scale rainfall. Second, it requires knowledge of rainfall variability, at least in terms of its spatial correlation function, at scales below that of the grid dimensions.

The EVS approach was explored by Anagnostou et al. [3] who lacked information on the correlation structure of rainfall, and by Habib and Krajewski [25], who used experimentally derived information on the correlation structure of rainfall fields. Nevertheless, the problem of error covariance remains unresolved. To resolve this problem requires a special experimental setup in which rainfall can be accurately estimated by independent means. With the current technologies this implies a dense rain gauge network, so dense that spatial sampling error could be considered negligible and radar-rainfall products could be directly compared to the cluster-based estimate [39]. High-density cluster data would permit developing and testing framework for estimation of error probability distribution, thus extending the scope of the EVS approach.

In closing of this section, let us also mention another fundamental issue of operational and experimental rainfall measurement and estimation. There is a growing recognition that the historical rain gauge data are of very poor quality. This concerns most of the 15-min, hourly, and daily rainfall data. Following the earlier suggestion by Ciach and Krajewski [14], supported by evidence discussed by Steiner et al. [56], we strongly recommend deployment of dual rain gauge platforms. In view of very high variability of rainfall only gauges sited side by side can provide independent information needed for fault detection and data record collection. Rain gauge data are vital in our quest for improved understanding of radar-based rainfall estimation technologies.

3. Radar estimation of extreme rainfall

Radar estimation of extreme rainfall rates plays an important role in a range of applications dealing with the hydrology and hydraulics of flooding. The extreme rainfall rate setting also raises special challenges for development of radar-rainfall estimation algorithms, validation of rainfall algorithms and design of radar-rainfall estimation experiments. Because of the hydrologic importance of extreme rainfall, we examine these challenges in detail below.

Hudson [28] presented one of the first experiments designed to measure and parameterize raindrop size distributions in extreme rainfall rate storms (see also [9,63]). Blanchard and Spencer [9] concluded that breakup of raindrops controls the raindrop size distribution for extreme rainfall rates and they observed that for rainfall rates in the range between 100 and 700 mm/h, the median diameter remains relatively constant. These features of dropsize distributions are used to infer that for a given rainfall rate in intense rainfall, a steady-state dropsize distribution develops in which drop growth is balanced by drop breakup. List [35] presents theoretical arguments supporting an "equilibrium" dropsize distribution in heavy rain and shows that in this case Z and R will be linearly related, that is, the exponent b in the Z–R relation for extreme rainfall rates will be 1.

Uijlenhoet et al. [58] show that the linear Z–R relationship holds for extreme rainfall rate drop spectra from Florida (rainfall rates exceeding 100 mm/h). It is also shown in [58] that the prefactor of the Z–R relation varies over a large range. It follows that, even under equilibrium conditions for extreme rainfall rates, bias estimation will play an important role in reflectivity-based estimation of extreme rainfall rates. This point is further illustrated in analyses of radar-rainfall estimates from "warm rain process" storms, which produce extreme rainfall rates [44,50,51]. Development of Z–R estimation procedures, as discussed above, will be sensitive to the weighting of observations from the extreme tail of the rainfall rate distribution. For applications in which extreme rainfall rates are of special interest, validation procedures should explicitly characterize the error of rainfall rate estimates as a function of rainfall rate.

The extreme rainfall estimation problem provides one setting in which ideas from the DSD approach and the optimization approach can be usefully combined to enhance radar-rainfall estimation algorithms. The extreme rainfall setting is one in which previous studies provide a strong basis for presuming that variations in DSDs play a significant role in the accuracy of radar-rainfall estimates. Information on key aspects of the variability in DSD properties can be obtained from polarimetric measurements, like differential reflectivity and differential phase shift. Including these additional radar observations should lead to significant improvements in estimation of extreme rainfall rates. The framework for including polarimetric measurements, however, should be the optimization approach, in which radar observations aloft are compared with surface measurements of rainfall rate.

The climatology of rainfall rates exceeding 100 mm/h is heavily influenced by warm season systems of thunderstorms. The climatology of radar reflectivity observations for these storms, in turn, is strongly influenced by hail contamination [6,7]. The presence of hail in a radar sample volume can severely distort radar-rainfall estimates, due the sixth power dependence of Z on drop diameter. An extreme example of the hail contamination problem is provided by supercell thunderstorms, which are often prolific hail producers and the agents of extreme rainfall rates. The Dallas Hailstorm of 5 May 1995 [52] was a supercell thunderstorm, which produced hailstones (more than 2 cm in diameter) in close proximity to regions experiencing 15-min rainfall rates exceeding 200 mm/h. More than 15 fatalities resulted from flash floods produced the Dallas Hailstorm. Smith et al. [52] argue that supercell thunderstorms play an important role in determining the frequency of extreme rainfall rates in much of the US east of the Rocky Mountains. Hail contamination precludes the development of useful climatologies of extreme rainfall from single parameter radar-rainfall estimates. As discussed in Section 2.2, polarimetric measurements could significantly reduce errors in rainfall rates due to hail contamination.

Warm season thunderstorms in urban environments present an important challenge to radar-rainfall estimation procedures. Flood response of small drainage basins in urban environments is particularly sensitive to "fine-scale" temporal and spatial variability of rainfall. The precise scale boundaries will depend on details of the drainage basin (see [52], for example), but in many settings the relevant scales of variability are comparable or smaller than the minimum observation scales of operational weather radar systems like the WSR-88D (6 min, 1 km). Experimental programs for radar estimation at rainfall at fine space and time scales will play an important role in advances in urban flood hydrology.

The utility of radar-rainfall estimates for extreme flood analysis can be viewed in terms of enhanced capabilities for modeling flood response of a drainage basin. The potential benefits of high-resolution rainfall estimates have motivated advances in hydrologic modeling [10,18,34,38,40,42,43,64]. Advances in operational forecasting and hydrologic design have progressed more slowly although there are exceptions (e.g. see [22]). Radar-rainfall estimates hold particular promise for enhanced flash flood forecasting procedures and for engineering design and management applications in small basins. For these problems, hydrologic processes forced by rainfall rate play a comparable or even more important role than hydraulic processes associated with flood wave propagation. The central difficulty here is often the non-linear response of drainage basins to rainfall rate.

These observations have important implications for development of radar-rainfall estimation procedures. One of the major obstacles to increased utilization of radar-rainfall estimates for hydrologic modeling has been the absence of quantitative assessments of the accuracy of radar-rainfall estimates. As discussed in previous sections, development of formalized procedures for estimating the error structure of radar-rainfall fields and for validating radar-rainfall estimates is of central importance to radar hydrology. In some settings, the hydrologic application may impose useful constraints on the error assessment problem. In particular, assessment of error structure of radar-rainfall estimates that are used for hydrologic modeling should consider the propagation of errors through hydrologic models. The non-linear response of drainage basins to rainfall forcing implies that errors in extreme rainfall rates will play an important role in hydrologic modeling. Quantification and validation of radar-rainfall estimates for extreme rain conditions are also an important challenge for radar hydrology.

The challenges of extreme rainfall estimation are particularly acute in mountainous terrain. Some of the largest measured rainfall accumulations in the United States and the world [19] have occurred in complex terrain. Landslides and debris flows are added to flooding as major hazards associated with extreme rainfall in mountainous terrain. Radar-rainfall estimation in complex terrain is complicated by ground returns and signal loss associated with beam blockage [31] (see also Andrieu et al. [4] for novel approaches dealing with radar sampling problems in complex terrain). An additional problem is that orographic storms may differ from storms forming away from terrain in terms of microphysical and dynamical properties [44,50]. Despite these difficulties, radar-rainfall estimates hold great promise in improving hazards assessment capabilities in mountainous terrain.

4. Conclusions and recommendations

From the discussion on radar-rainfall estimation we conclude that there is much that we do not understand about the instrument that has been in use for over 40 years. We cannot answer numerous basic questions about radar-rainfall estimation error structure. What is the probability distribution of the errors? Are they dependent in space and time from pixel to pixel and from scan to scan? How do they depend on the rainfall regime? To what extent are they caused by the radar hardware characteristics and to what extent can rainfall estimation algorithms mitigate the error sources? We also know little about the rainfall processes at scales that affect radar-rainfall estimates. What is the spatial correlation structure of rainfall at scales below 2 km? What is the spatial correlation structure of reflectivity and other moments of DSD?

We could ask many similar questions regarding our knowledge of rainfall scaling. Does rainfall rate scale according to a certain way at scales below that of the typical radar-rainfall products? To what extent radar-rainfall error structure affects our understanding of rainfall scaling at higher spatial scales? How does rainfall integration in time affect its scaling properties?

It is clear that the above questions—if we as community consider them important—form a research agenda for the upcoming years. Here we propose several recommendations for the community to consider.

1. Long term monitoring and validation sites, providing detailed information on precipitation, should be developed. The sites should have an areal extent on the order of 100 km^2 and include a mix of radar, surface (rain gauge, disdrometer, and conventional meteorological) and upper air observations. Experimental design should be structured in a way to provide both information of the spatial dependence of rainfall as well as good estimates of areal rainfall for direct comparisons with radar-based estimates.
2. New technologies for in situ measurement of precipitation are needed. If we could build reliable and inexpensive disdrometers to replace rain gauges this would address many needs of remote sensing of precipitation. Instruments with sampling volume just one or two orders of magnitude greater than the current instruments would go a long way towards closing the scale gap in our abilities to observe precipitation. Optical technologies seem to be particularly attractive here.

3. Methodological advances are needed in several areas of radar-rainfall estimation. Of particular importance are advances in rainfall estimation using radar polarimeric observations, estimation of the error structure of rainfall rate estimates, and validation of radar-rainfall algorithms.
4. Most important for radar hydrology is the diffusion of radar-rainfall products into a diverse array of hydrologic applications. The potential of radar-rainfall products for operational flood forecasting is going to be realized in application. There is still tremendous potential for advances in flash flood forecasting. Numerous other applications provide important areas of exploration in radar hydrology. These include engineering design of flood control structures, precipitation frequency analysis, operation and control of urban storm and waste water treatment systems, water supply forecasting, groundwater recharge assessments and non-point source pollution assessments.

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