INVESTIGATING FLOOD PREDICTION UNCERTAINTY OF HYDROLOGIC MODELS DRIVEN BY SATELLITE RAINFALL DATASETS

1. BACKGROUND

There is no doubt that one of the major utilities of a remote sensing rainfall product is in its application to a land surface hydrologic (or Rainfall-Runoff) model to predict flood events. But rainfall-runoff models have uncertainties arising from a number of sources, namely: I) the error due to poorly defined boundary conditions; II) the error due to the modeling structure, as the model itself is only an approximation of the hydrologic reality and, III) the error due to input data. Beven (1989) has pointed to the limitations of the current generation of rainfall-runoff models and argued that the possible way forward must be based on a realistic assessment of predictive uncertainty. Recently, I studied the impact of radar rainfall estimation error on runoff simulation uncertainty through an explicitly formulated parameter uncertainty framework known as GLUE (Binley and Beven, 1991). GLUE – Generalized Likelihood Uncertainty Estimation – is a likelihood-based framework that allows investigation of input error interaction with modeling uncertainty and thereby providing the means for understanding how the input error structure manifests to flood prediction uncertainty. For the complex terrain where the my investigation was carried out, it was observed that radar rainfall adjusted for certain systematic errors using gauge rainfall as ‘ground truth’ would significantly decrease the uncertainty in runoff simulation. In particular, it was observed that radar rainfall adjusted for mean field bias and the vertical profile of reflectivity effect yielded similar runoff uncertainty characteristics as that for a dense gage network. The adjusted algorithm had a higher return in runoff uncertainty reduction for the same rainfall error reduction than the unadjusted counterparts by a range of 10% to 65%. In terms of simulating peak runoff, the reduction in uncertainty with adjustment ranged from 50- 55% while for simulating time to peak it was between 50% and 65% (Hossain et al., 2001; Hossain et al., 2002).

In another investigation studying the suitability of current and future planned passive microwave (PM) satellite observations as direct data source for mitigation of flood related hazards, I had observed that increase in sampling frequency from six to three hours significantly decreased runoff simulation uncertainty (Anagnostou and Hossain, 2001). Most importantly, I found that the time resolution in satellite sampling and rainfall retrieval error have a complex interaction and non-linear uncertainty propagation in rainfall-runoff transformation process. In terms of runoff volume (and peak runoff), the bias reduction from six to three hourly sampling ranged from 22% to 28% (and 25% to 56%) when considering instantaneous PM satellite estimates with no bias and 100% standard error. This runoff volume and peak runoff error reduction owing to sampling increase was observed to magnify when satellite estimates were corrupted with systematic error, which exemplified the significance of temporal resolution in hydrologic applications of noisy satellite estimates.

What has been evident from my previous studies and other concurrently similar investigations is that, in order to identify a given hydrologic model’s reliability in prediction at a given space time scale, one first needs to understand the complex interaction of errors during the rainfall-runoff transformation process (as also stated by Beven, 2001). This interaction of errors is currently not fully understood and has often hampered realistic use of rainfall data products for
flood predictions (Grayson et al., 1992; Beven 1996; Beven 2001). Furthermore, with the advent of satellite precipitation remote sensing technology and techniques, which is leading to great improvements in both accuracy and resolution of global precipitation monitoring, new challenges are arising in the field of hydrology with a most central question being the identification of the best procedures to combine sensor estimates from multiple platforms that are optimal in terms of hydrologic variables (e.g., runoff, soil moisture, evaporation) prediction at different scales and watershed/meteorological characteristics.

2. STATEMENT OF THE PROBLEM

Although it is only natural to expect that the current generation of hydrologic models will be improved as our understanding of the hydrological processes advances, it is often strongly argued if such an expectation is justified for the near future (Beven, 1996). There are many aspects about the hydrological systems that are essentially unknowable, especially the nature of flow processes below the ground in structured soils. One practical alternative strategy to bypass such unknowns in hydrology has been to apply the flow equations at a scale (of space and time) to which they are appropriate (Woods et al., 1995). But problems still exist to such alternative techniques of improving model predictability even if the hydrologic systems are assumed stationary (Weinberg, 1972; Philip, 1978). A decade ago, Beven (1989) and Grayson et al. (1992) initiated a meaningful debate to highlight the current limitations of distributed physically-based models. It was concluded that unless a fundamental change in hydrologic model philosophy arrived along with an improvement in measurement techniques, this current scenario of limitations of hydrologic models is not expected to improve in the near future. It has also been shown that the process descriptions used in the current models may not be appropriate; that the appropriate model parameter values may vary with grid scale; that techniques for parameter estimation are often at inappropriate scales; and that there is sufficient uncertainty in model structure and spatial discretization in practical applications that these hydrologic models are difficult to validate (Beven, 1996).

Recognizing the above problems in hydrology, we must expect that there will always be multiple acceptable models to represent a basin of interest, all reproducing any observation of the basin runoff to some acceptable level. I therefore believe that we first need to work with existing hydrologic models for flood forecasting within an uncertainty framework, which allows for such inherent *equifinality* in models to match with our current level of observation of flood events (e.g. mainly the stream discharge at the watershed scale). The GLUE is one such elegant and convenient way to implement uncertainty framework to assess a hydrologic model’s predictive uncertainty at a given space-time rainfall resolution of the rainfall input. This method extends the type of Generalized Sensitivity Analysis (GSA) of Spear and Hornberger (1980) by evaluating the simulation results for each model parameter set against some observed data through calculating a likelihood value. Those that are considered non-behavioral are given a likelihood value of zero. The distribution of likelihood values are then used as a weighting function to condition the range of predicted variables (e.g. discharge) from all the behavioral model parameter sets to determine the uncertainty quantiles. With more data becoming available, this distribution allows itself to be updated through the Bayes equation to reflect the state of the art of the model’s predictive uncertainty for a given watershed. The GLUE can be applied to any state-
space variable of interest, like soil moisture, evapo-transpiration etc. and does not necessarily have to be limited to stream discharge.

With the proposed Global Precipitation Mission (GPM), the future (4 years from today) now beckons a new era for earth science community with the promise of data rich remote sensing rainfall products of vital importance to hydrologic forecasting on a global scale. The question to be asked is therefore, “With the spatial and temporal coverage of remote sensing rainfall data increasing in future, how can we achieve their optimal use to achieve less uncertain hydrologic forecasts than what we are capable of today?” It is therefore of urgent need now to perform investigation to understand the aspect of global rainfall input uncertainty and its manifestation on hydrologic simulation uncertainty with its spatial and temporal characterization. One way of answering the above question can be through an investigation of uncertainty of flood prediction for models of varying degree of physical complexity in the GLUE uncertainty framework at the space-time scales relevant to satellite remote sensing. There have been a few applications of GLUE (Beven, 2001), but none involved the study of scales and models of varying complexity (ranging from conceptual to fully distributed and physically-based model). The primary reason for choosing GLUE among the many techniques available (Rosenbleuth, 1975; Kuczera, 1988; Nandkumar, 1997) is that it is an assumption-free technique that can solve the derived-distribution of rainfall-runoff transformation process with the availability of reliable output data (e.g. stream discharge in this case). With such a study I hope to identify the expected degrees of error for a given hydrologic model at specified spatial and temporal resolutions and possibly identify optimal combination from diverse sources of satellite sensor rainfall retrievals that could potentially minimize hydrologic forecasting uncertainty. Another application of my study is in the field of risk assessment for decision-making. The interpretation of flood prediction uncertainty can also be in the evaluation of risk of the model predictions being wrong. Hence any idea behind risk assessment of flood prediction should also include the model’s predictive uncertainty.

3. **Objectives**

The objectives of my scientific investigation are twofold:

1) To understand the implications of satellite rainfall remote sensing uncertainty on flood prediction uncertainty as a function of the temporal and spatial resolution, model’s physical complexity, and watershed characteristics.

2) To formulate useful operational protocols and guidelines for use of hydrologic models for currently available and future planned satellite precipitation measurement missions. The guidelines will also involve risk assessment of flood predictions from remote sensing data associated with a model’s predictive uncertainty.

4. **PROPOSED METHODOLOGY**

The proposed study is based on my availability of rainfall remote sensing (radar, satellite) data and coincident in situ hydro-meteorological (rain gage, stream flows, meteorological stations) data from three hydrologically unique regions of the world: A) An alpine region of Northern Italy, B) a southern region of United Kingdom, and C) the Ganga-Meghna-
Brahmaputra (GBM) region comprising the countries of Bangladesh, India, and Nepal. For each of these regions, we have coincident gage, satellite (both passive microwave and infrared), and quality-controlled radar (in C only over Bangladesh) data comprising 2-3 years of multiple flood events. To support the output simulation analyses/validation I have requested streamflow and other meteorological variables for those regions. The river basins in regions (A) (basin area 116 sq. km) and (B) (basin area 135 sq. km) are known for their characteristic surface runoff causing mechanism (Dunnian - saturation excess). The Alpine region (A) is already well known for its major flash floods in recent years. A dense gage network (seven gages) exists within the watershed, which is covered by a C band Doppler radar located 60 km from the basin (Borga et al., 2000). The watershed of region B is also equipped with a very dense network of 49 tipping-bucket recording rain gauges installed as part of the Hydrological Radar Experiment, HYREX (Moore et al., 2000), and a -band non-Doppler weather radar. The Region (C), GBM, is a large watershed (area > 100,000 sq. km) with predominantly Hortonian (infiltration-excess) runoff generating characteristics in the deltaic region. The most catastrophic rainfall events and its corresponding flood events in the world take place in the eastern region of GBM in Bangladesh. Hence my study on GBM is expected to be useful due to the huge economic and human losses caused by floods and the difficulty that the Bangladeshi hydrologic community has faced in flood forecasting through the use of current modeling protocols lacking uncertainty assessment. Another reason for choosing GBM for this study is the availability of coincident data from TRMM and coincident ground radar rainfall data. Currently I am in charge of a data-mining operation with NASA’s Distributed Active Archive Center (DAAC), which involves daily archiving at our local storage disks of TRMM rainfall data products (1B11, 2A23 and 2A25) for large regions (GBM, USA, Africa, Europe and Amazon).

The three distinct hydrologic models I intend to use are TOPMODEL (Beven and Kirkby, 1979), PDM (Probability density model, Moore, 1985) and the fully physically-based and distributed model NTT (Nutrient Transfer Transport) (Hock, 1996). I already have acquired the experience in operating TOPMODEL for scientific studies (Hossain et al., 2001; Hossain et al., 2002; Hossain and Anagnostou, 2002), while I am currently getting acquainted with the PDM. The NTT was developed at our laboratory and there exists adequate user support and literature for its use. Each of the three models is already established and of varying degree of physical complexity. TOPMODEL and PDM are semi-distributed conceptual rainfall-runoff models with wide range of acceptability among the hydrologic community and NTT is a fully distributed and physically-based model with a non-linear kinematic channel routing suitable for flat channel beds of the GBM region (Hock, 1996).

I will develop a stochastic framework to understand the error propagation of different satellite rainfall estimates in runoff prediction for the above three scales and runoff production mechanisms. As a first step I will develop a satellite rainfall error model. I am in fact already in the process of its formulation based upon previously proposed error models for satellite based hydrologic forecasting (Guetter and Georgakakos, 1996). The model will be calibrated using coincident TRMM PR, SSM/I, and Global-IR rainfall datasets. The error model would statistically characterize the sensor’s success in discriminating rain from no-rain, and quantify the spatial structure of the sensor’s rainfall retrieval error at the sensor resolution. As TRMM PR has a more accurate representation of the structure of rainfall than any other existing space-based sensor, it will be used as the ‘truth’ in absence of ground observations. For the GBM region, I
also hope to consider calibrating the error model using the available radar and rain gage rainfall data as “ground truth”. As mentioned above, the calibration parameters of the error model will pertain to the space-time sampling of the different satellite sensors. This error model will then be applied within a Monte Carlo framework on the existing ground radar, or gage, data available at the three regions to simulate satellite-sensor rainfall fields (of both current and future planned sampling frequencies) at different spatial and temporal resolutions. Subsequently, different investigated scenarios of simulated multi-sensor rainfall estimates (pertaining to a given space time resolution) will be used as input to the hydrologic models within the GLUE framework to simulate runoff and other hydrologic variables for the basins. In this data-based simulation research the ground radar/raingage rainfall fields are considered providing the closest to the true rain processes, which are transformed through the model to the most accurate available runoff predictions. Expanding on my experience with GLUE as manifested through my previous work (Hossain et al., 2001; Hossain et al., 2002) I hope to study the space-time implications of satellite rainfall products, combinations of multiple sensors, and other issues that may arise in my research on flood prediction uncertainty relative to what can be achieved with a perfect, i.e. radar, rainfall input. Currently, I manage my own research website at my University’s domain at [http://www.engr.uconn.edu/~faisal/research.html](http://www.engr.uconn.edu/~faisal/research.html) which profiles my research activity and accomplishments spanning the last 6 years on a wide range of environmental management topics. After the start of this project I hope to include regular updates of the study for spurring of debate among the scientific community working on hydrologic applications of satellite data.

REFERENCES:


