AIRCURRENTS

INNOVATION IN FLOOD MODELING: PRECIPITATING A SOLUTION TO REALISTIC RAINFALL SIMULATION

11.2011

Editor's Note: Historically, the stochastic approaches used to generate synthetic rainfall patterns have only been suitable over small areas in which the precipitation field is generally uniform. Developing methods for simulating precipitation over a larger range of scales has been challenging. Here, Dr. Boyko Dodov discusses the novel approach AIR developed to meet the challenge of capturing both large- and small-scale precipitation patterns; it couples a Global Circulation Model (GCM) and Numerical Weather Prediction (NWP). The result—now available in AIR's Inland Flood Model for Germany—simulates realistic, robust storm patterns over space and time.

By Dr. Boyko Dodov
Edited by Meagan Phelan

INTRODUCTION

The traditional approach to modeling flood risk has been to define it as the probability that normally dry land—usually at a specific location of interest—will be inundated by water. Within this context, considerable attention has been paid to improving the accuracy of estimating the occurrence of local flood extremes. However, as this article will explain, the total outcome from a flood event occurring simultaneously at multiple locations along a river basin is far more complex and is dominated by the spatial clustering (or dispersion) of separate local precipitation extremes, as well as the evolution and dependence of these extremes over time.

RESOLVING PRECIPITATION PATTERNS AT ALL SCALES FOR AN ACCURATE VIEW OF FLOOD RISK

To illustrate the importance of this larger view, consider the European river networks in Figure 1. These two river basins—the Vltava River Basin and the Odra River Basin—are similar in size, climate, elevation and geology, but differ in network topology upstream from the basin outlet (Prague, in the Vltava River Basin, and Głogów, in the Odra River Basin). Just upstream from Prague, two major tributaries join the Vltava River. By contrast, the network topology upstream from Głogów (in Poland) is dominated not by major tributaries, but by the Odra River, with smaller tributaries joining uniformly along the main river course.

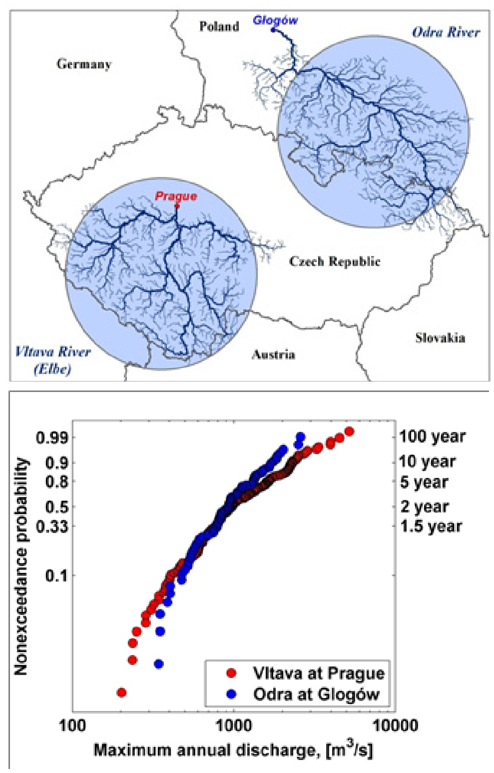

Figure 1 (Top): The Vltava River basin upstream from Prague and the Odra River basin upstream from Głogów. (Bottom): Probability plots for the maximum annual discharges from the gauging stations in Prague and Głogów, respectively: the distribution of peak flows at Prague is much more skewed—reflecting the effect of the confluence of large tributaries just upstream.

This difference becomes important when a major rainfall event—for example, one about 200 kilometers in diameter[1] (represented by the blue circles in Figure 1)—occurs over each of the basins. During such an event in the Vltava basin, it is likely that three flood waves (one from the Vltava River and two from the major tributaries on either side) will join almost simultaneously upstream from Prague, producing a high peak flow[2] and possible flooding. By contrast, the flood waters in the Odra basin will be successively delivered from the small tributaries through the Odra River and downstream, giving rise to a much smoother hydrograph and a lower flood peak.

The tendency for increased flood risk immediately downstream from major confluences has attracted considerable interest in the scientific community. It is illustrated in the bottom of Figure 1, a probability plot for the annual maximum peak flows from the gauging stations in Prague and Głogów, respectively. The 1½ to 2 year discharges are about the same, which means that the conveyance capacity of the two rivers is equivalent. Not surprising, since river channels tend to adjust their shape to the height reached at the maximum discharge they can carry without overflowing, which is generally assumed to be equivalent to the 1½ to 2 year annual peak flow.

The 100-year flows, however, are twice as large (note the log scale of the horizontal axis) for the Vltava River, meaning the same channel has to convey twice the amount of water during a 100-year flood event, thus making the hazard level at Prague much higher compared to the one at Głogów, despite the similarities the two river basins share.

As river networks vary in their configuration at multiple resolutions—ranging from a few kilometers up to large basins such as those of the Elbe and Rhine—it is critical to represent precipitation patterns in a statistically robust way at each scale. From the example above, it is clear that to simulate flood risk in Prague, precipitation patterns must be considered across the entire river network—the configuration of which changes as the scale does. However, although simulating realistic precipitation patterns at either a small scale (a few kilometers) or a large scale (continental) is manageable, simulating realistic precipitation patterns at all scales simultaneously is no trivial task, and requires a blend of both stochastic and numerical modeling.

LIMITATIONS OF THE EXISTING (PURELY) STOCHASTIC APPROACHES TO PRECIPITATION MODELING

In general, there have been two approaches to stochastic precipitation simulation. The first is based on the Poisson point process, which describes single events—in this application, precipitation cells—occurring continuously and independently.

However, precipitation cells are not typically independent; they cohere, or cluster, in space and time over large areas. Thus, to represent this coherence, a modified version of the Poisson point process was introduced; namely, the Neyman-Scott pulses model, which allows for the simulation of clustered precipitation cells in space and time[3]. It simulates rainfall pulses that occur with pre-specified characteristics (i.e., shape, size, frequency) calibrated with observed precipitation data. Over time, numerous modifications to this process have been introduced in the hydrologic literature.

A more sophisticated approach to simulating precipitation fields, providing more realistic looking precipitation fields, is based on geostatistics, used to represent spatial distributions of spatial data, and random field theory, which—in loose terms—is the implementation of probability theory in space and time[4].

Under this approach, the dependency between rainfall intensities at different locations is measured as a function of the distance between these locations. The greater the distance, the less likely those rainfall intensities are to be part of the same storm cells. An example derived from daily precipitation data is illustrated in Figure 2. Here, the correlation coefficient between stations is highest within the first 200 kilometers (again, the size of a typical storm). After that, the correlation coefficient dips below 0.4, reflecting a lack of relatedness between the precipitation intensities at these locations.

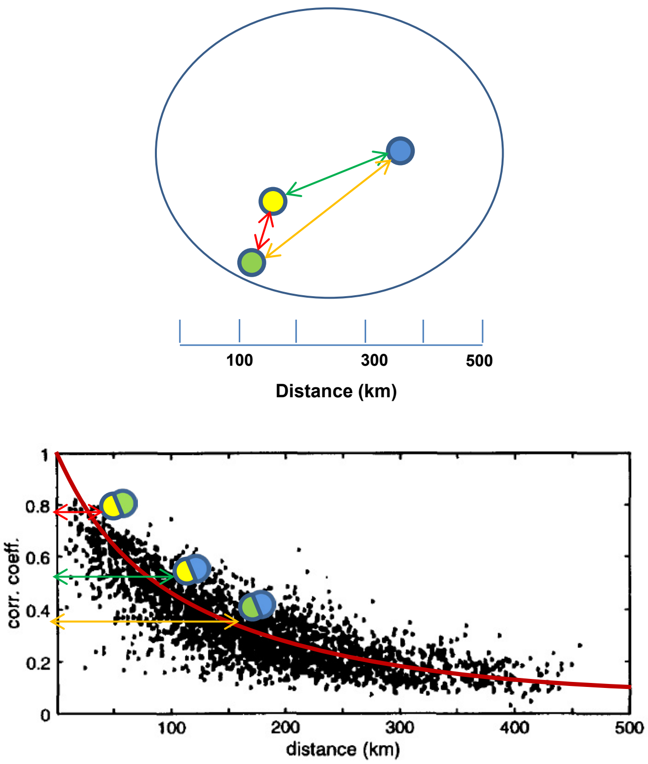

Figure 2: (Top) Three gauging stations, each reporting daily precipitation data. (Bottom) Correlation coefficients as a function of the distribution derived from precipitation data, such as the distribution above. Higher correlation coefficients are associated with the yellow/green gauging stations—closer in space in the top figure. Outside the 200 km region, the correlation coefficients are nearly zero; by contrast, the area inside 200 km conforms to areas of significant precipitation within a single storm system. (Sivapalan & Blöschl, 1998).

Using the geostatistical model, different realizations of random precipitation fields over domains of different sizes can be obtained. Figure 3 shows model output for two possible correlation structures for rainfall. (Note that reds and yellows in Figure 3 indicate high rainfall intensity, while greens and blues indicate lower intensity.) The left-hand panel illustrates a rapid decay of dependence with distance (using a correlation length of 50 km), while the right-hand panel shows slow decay of dependence with distance (a correlation length of 100 km).

The approaches outlined above can mimic and/or reproduce rainfall patterns reasonably well when applied to relatively small areas, or even—by selecting an appropriate correlation length—for a region the size of Great Britain. However, neither approach can be used for realistically simulating floods over large expanses, such as the whole of Europe or the United States, for several reasons.

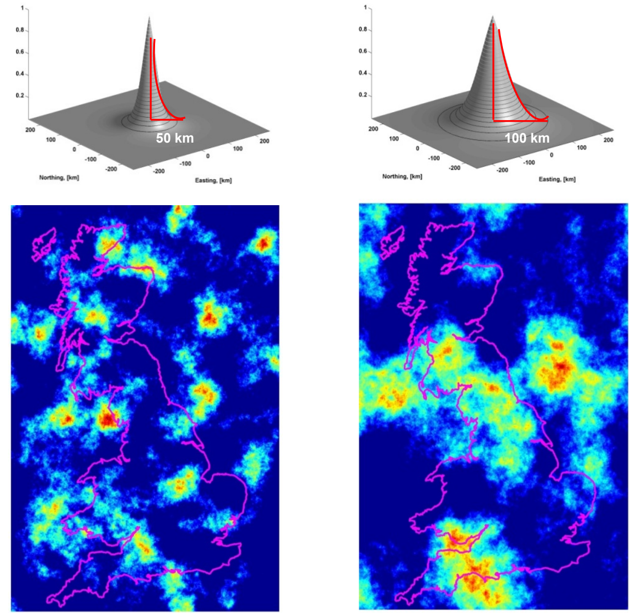

Figure 3. Simulated rainfall patterns based on random field theory. (Top): Two exponential correlation functions with correlation lengths of 50 and 100 km. (Bottom): The maps, based on the simulations from these functions, illustrate precipitation behavior over a domain (Great Britain) many times the size of the correlation length. Both maps show multiple locations of extreme precipitation—an occurrence that would not happen in an actual storm. (Source: AIR).

First, the size of a typical low-pressure system can extend up to several thousand kilometers, while the area typically affected by rainfall within a storm system is usually much smaller—on the order of several hundred kilometers. When a stochastic approach is used to simulate precipitation fields many times the size of the correlation length (that is, when it is used to simulate precipitation fields across Europe) the result will be too many simultaneous occurrences of extreme precipitation, as we saw from Figure 3. A vast record of historical observations reveals that, within a single storm system crossing a continent, this simply does not happen in reality.

Another reason the purely stochastic approaches outlined above cannot realistically simulate precipitation on continental scales is that, at such scales, the patterns in actual precipitation fields follow complex shapes and motions related to the circular advection of various types of storms systems and the corresponding atmospheric fronts. These patterns and motions cannot be reproduced by the purely stochastic approaches discussed above.

Lastly, at large scales, precise snowmelt modeling becomes critical as the runoff from large mountainous and lowland areas must be simulated simultaneously. The snowmelt process is an important hydrologic phenomenon that contributes significantly to flooding, especially in the vicinity of high mountainous areas, such as the Alps. Purely stochastic approaches are not able to capture this process well.

Indeed, no purely stochastic approach exists that can produce realistic and statistically robust space-time precipitation and snowmelt patterns at the continental scale. An alternative approach would be one that is purely physically-based and uses numerical models to simulate the processes in the atmosphere. One such option is the so-called Global Circulation Model (GCM) which describes atmospheric behavior over the entire globe.

USING GLOBAL CIRCULATION MODELS IN CATASTROPHE MODELING: PROS AND CONS

The Global Circulation Model is a mathematical model that simulates atmospheric and/or oceanic circulation over the entire planet for long periods of time. A distinguishing feature of GCMs is that, with all climate components and driving forces included, they can be run self-sufficiently (i.e. without the need for additional information) for hundreds or even thousands of years, simulating different climate scenarios within the 10,000-year event catalog necessary for a typical catastrophe model. In addition, GCM output includes practically all hydrologic components necessary for a robust flood model, including precipitation, snowmelt, soil moisture, temperature, and wind.

Ideally then, GCMs could be used to produce long-term simulations for catastrophe modeling. However, for a realistic simulation of precipitation patterns that represent the vertical structure of the atmosphere as well as the effects of the terrain on atmospheric circulation, a model must have a resolution of at least 100 km, which is impractical with a GCM. The amount of time needed to simulate 10,000 years at different resolutions, assuming the computation is done simultaneously on 100 CPUs, is significant. It would take at least a decade.

Another reason for not relying solely on GCMs for direct precipitation simulation is their reliance on simplified microphysics, which means they may not provide solid representations of precipitation, particularly in mountainous areas. This is why AIR took a different road to solving large-scale precipitation modeling: coupling the GCM and Numerical Weather Prediction.

AIR'S SOLUTION AT A CONTINENTAL SCALE: COUPLING GCM AND NWP

Because the GCM cannot be used alone, AIR coupled the GCM with a Numerical Weather Prediction (NWP) model at a mesoscale (medium-scale) resolution. NWP models are most frequently used for short-term predictions over a region the size of a country or larger (i.e., continent). They are commonly used for local weather forecasting.

In contrast to the GCM, the higher-resolution mesoscale model can provide more detail when necessary; for example, in situations where the environmental conditions change rapidly over time and space, such as with sudden storm conditions. Mesoscale NWP models also use more sophisticated microphysics schemes, which are better for modeling precipitation, particularly for localized extreme cases occurring during summer months. Additionally, they better incorporate the effects of different types of land cover (water surfaces, vegetation, bare soil and bedrock). They also more accurately account for the effects of the terrain on atmospheric conditions, such as the way in which certain low-pressure systems are capable of inundating particular mountain ranges, ultimately producing severe floods. In addition to incorporating the effects of land cover and terrain, NWP models provide a realistic precipitation pattern at the continental scale. However, despite their strengths, NWP models cannot be used for long-term stand-alone runs.

AIR's novel approach to large-scale precipitation simulation benefits from both the GCM and NWP models by drawing on the ability of the former to produce long-term stand-alone runs, while the latter provides a better representation of precipitation physics and a higher degree of detail. AIR's approach is implemented by coupling a GCM running over the entire globe at a coarse resolution, while a mesoscale NWP model nested within the GCM runs over Europe, at a reasonably high resolution.

INTRODUCING SMALL-SCALE VARIABILITY: A TRIBUTE TO THE FLASH FLOODS

After potentially flood-causing storms are identified from the NWP output, the unique characteristics of each precipitation field—which can determine the likelihood of localized flash floods—are captured in detail. This requires a finer resolution than that used to identify the storm systems.

AIR has developed a sophisticated downscaling technique in which the statistical properties of a rainfall field at a coarser resolution (e.g., NWP output at a resolution of 90 km) are "downscaled," or refined, based on turbulence theory, which dictates how precipitation particles are formed. The result is realistic patterns of precipitation at high resolution (8 km by 8 km).

Thus, the whole range of precipitation scales of interest is resolved: from global precipitation patterns, through precipitation cells generated by individual storms over a continent, down to precipitation fields at an 8 km resolution (Figure 4). Not only are all scales resolved, but this is achieved for all components of the hydrologic cycle that take place in the flood modeling process.

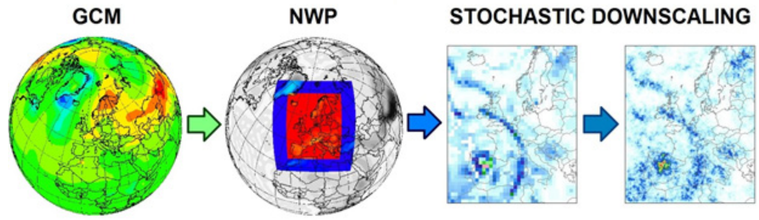

Figure 4. AIR's innovative approach captures all scales of precipitation patterns, from global to local. As the final part of this process, an advanced stochastic downscaling technique introduces statistically robust and visually realistic perturbations at fine scales (Source: AIR).

CONCLUSION

AIR's approach—first implemented in the model for Germany, which has the most highly concentrated flood risk in Europe—overcomes the challenges inherent to a purely stochastic simulation and resolves, both visually and statistically, the entire range of scales from global, to continental Europe, down to eight-kilometer resolution needed for detailed flood modeling.

This is the first time a catastrophe model uses a Global Circulation Model coupled with a regional Numerical Weather Prediction model to provide a representation of precipitation over large areas. It will not, however, be the last. Plans are in place at AIR not only to expand this approach to include other European countries, but to other continents as well. 1 200 kilometers is the size typical of an area of significant precipitation within a larger storm system.

[1] 200 KILOMETERS IS THE SIZE TYPICAL OF AN AREA OF SIGNIFICANT PRECIPITATION WITHIN A LARGER STORM SYSTEM.
[2] PEAK FLOW, MEASURED IN M3/S, IS THE FLOW RATE AT WHICH THE WATER LEVEL IN A RIVER RISES TO ITS MAXIMUM.
[3] ENTEKHABI, D., I. RODRIGUEZ-ITURBE, AND P. S. EAGLESON (1989), PROBABILISTIC REPRESENTATION OF THE TEMPORAL RAINFALL PROCESS BY A MODIFIED NEYMAN-SCOTT RECTANGULAR PULSES MODEL: PARAMETER ESTIMATION AND VALIDATION, WATER RESOUR. RES., 25(2), 295–302.
[4] VANMARCKE, ERIK. RANDOM FIELDS: ANALYSIS AND SYNTHESIS, MIT PRESS (1983).

ABOUT AIR WORLDWIDE

AIR Worldwide (AIR) is the scientific leader and most respected provider of risk modeling software and consulting services. AIR founded the catastrophe modeling industry in 1987 and today models the risk from natural catastrophes and terrorism in more than 90 countries. More than 400 insurance, reinsurance, financial, corporate, and government clients rely on AIR software and services for catastrophe risk management, insurance-linked securities, detailed site-specific wind and seismic engineering analyses, agricultural risk management, and property replacement-cost valuation. AIR is a member of the Verisk Insurance Solutions group at Verisk Analytics and is headquartered in Boston with additional offices in North America, Europe, and Asia. For more information, please visit www. air-worldwide.com.