A remote sensing-based tool for assessing rainfall-driven hazards

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A B S T R A C T

RainyDay is a Python-based platform that couples rainfall remote sensing data with Stochastic Storm Transposition (SST) for modeling rainfall-driven hazards such as floods and landslides. SST effectively lengthens the extreme rainfall record through temporal resampling and spatial transposition of observed storms from the surrounding region to create many extreme rainfall scenarios. Intensity-Duration-Frequency (IDF) curves are often used for hazard modeling but require long records to describe the distribution of rainfall depth and duration and do not provide information regarding rainfall space-time structure, limiting their usefulness to small scales. In contrast, RainyDay can be used for many hazard applications with 1—2 decades of data, and output rainfall scenarios incorporate detailed space-time structure from remote sensing. Thanks to global satellite coverage, RainyDay can be used in inaccessible areas and developing countries lacking ground measurements, though results are impacted by remote sensing errors. RainyDay can be useful for hazard modeling under nonstationary conditions.

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Software availability

Name of Software: RainyDay Rainfall Hazard Modeling System
Developer: Daniel B. Wright
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Year first available: 2015
Required hardware and software: RainyDay requires Python 2.7 or newer (not tested with Python 3.0 or higher) with Numpy and Scipy. The Netcdf4 and GDAL APIs are also required. RainyDay will run on Macintosh, Linux, and Windows machines
Cost: Free. RainyDay is currently available by request. Open-source release under version 3.0 of the GNU General Public License (http://www.gnu.org/licenses/gpl-3.0.en.html) is planned

1. Introduction

Rainfall-driven hazards such as floods and landslides are the most common natural disasters worldwide, and amongst the most devastating. A growing number of computational hazard models are available to transform extreme rainfall inputs into hazard predictions, including distributed hydrologic models for the movement of water into and through river systems (e.g., Smith et al., 2004); hillslope stability and run-out models for landslide initiation and subsequent motion (e.g. Brenning, 2005; Preisig and Zimmermann, 2010; respectively); and hydraulic models for flood wave propagation in channels and floodplains (e.g., Horritt and Bates, 2002). These models have seen significant advances in recent decades, and have become key components in probabilistic hazard and risk assessment in fields such as natural catastrophe risk insurance, infrastructure design, and land-use planning. The hazard predictions produced by these models tend to be highly sensitive to the amount, timing, and spatial distribution of rainfall inputs. Unfortunately, progress on developing realistic rainfall inputs for probabilistic hazard and risk assessment has been relatively limited. This paper introduces RainyDay, a Python-based platform that addresses this shortcoming by coupling rainfall remote sensing data from satellites or other sources with a technique for temporal resampling and spatial transposition known as Stochastic Storm Transposition (SST) to generate highly realistic probabilistic rainfall scenarios.

Rainfall inputs for long-term hazard and risk assessment require a probabilistic description of three interrelated components:

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duration, intensity, and space-time structure. Efforts to jointly model these components are usually referred to as *rainfall frequency analysis*, a simple term that belies the complexity of the physical phenomena and analytical methods involved. The probability structure of the first two components, rainfall duration and intensity, has been a focus of research and application for decades (see U.S. Weather Bureau, 1958 and Yarnell, 1935 for early examples). These two components are strongly linked and together they determine the probability distribution of rainfall volume (or depth) at a point or over an area. The third component, space-time structure, describes the spatial and temporal variability of rainfall and is determined by storm size, velocity, and temporal evolution of spatial rainfall coverage. Space-time structure can thus be understood as describing the "when" and "where" of extreme rainfall, whereas intensity and duration describe "how much."

Rainfall space-time structure can be an important hazard determinant. For example, a rainstorm that is short-lived and small in spatial extent may pose a significant flash flood threat in a narrow mountain valley or urban area, but may not represent a hazard on a larger river system. Conversely, a month-long rainy period could lead to flooding on a major river due to the gradual accumulation of water in soils, river channels, and reservoirs, but may never feature a short-lived "burst" of rainfall sufficiently intense to cause flash flooding at smaller scales. Similarly, a storm that covers a large area or passes over a series of valleys could lead to more widespread landslide or debris flow occurrences than a smaller or stationary storm. Rainfall space-time structure and its importance as a hazard trigger, therefore, must be understood within the context of the particular geography and scale in question. Due to its complexity, rainfall space-time structure has traditionally been less well understood than intensity and duration, and its representation in hazard modeling has been less sophisticated.

The probability distribution of rainfall depth or intensity for a given duration is usually derived from rain gages and distilled into Intensity-Duration-Frequency (IDF) curves, such as those provided by the National Oceanic and Atmospheric Administration's (NOAA) Atlas 14 (Bonnin et al., 2004). Records spanning many decades are generally needed to define the extreme tail of such distributions. The challenge of measuring extreme rainfall over long time periods and over large areas using rain gages has hindered IDF estimation in many developed countries, while the lack of data in poor countries and in inaccessible terrain means that IDF estimation using such methods is virtually impossible in many locations. Furthermore, measurements of rainfall space-time structure at a high level of detail using dense networks of rain gages are nonexistent outside of a handful of wealthy cities and research-oriented efforts. "Regionalization,"—the pooling of hazard information over a larger area in order to inform analyses at particular locations (see, e.g. Alexander, 1963 for an early discussion of rainfall regionalization and Stedinger et al., 1993 for a review)—has helped with IDF estimation in areas where rain gage densities are moderate or high. These techniques offer little help, however, in parts of the world where rain gages are few or nonexistent, and do not offer a framework for incorporating rainfall space-time properties into hazard estimation. Even where long rainfall records do exist, nonstationarity due to climate change may mean that earlier portions of the record are no longer representative of current or future IDF properties.

Several techniques, which generally fall under the term of *design storm methods*, are used in long-term hazard estimation to link IDF properties to space-time structure for probabilistic flood hazard assessment (commonly referred to as *flood frequency analysis*). Design storm methods include linking rainfall duration to rainfall intensity via a measure of flood response time, such as the time of concentration (e.g. McCuen, 1998), deriving estimates of area-averaged rainfall from point-scale rainfall estimates using area

reduction factors (ARFs; U.S. Weather Bureau, 1958), and using dimensionless temporal disaggregation such as the family of U.S. Soil Conservation Service 24-h rainfall distributions (e.g. McCuen, 1998). Each is highly empirical, laden with assumptions (see Wright et al., 2014a; Wright et al., 2014b; Wright et al., 2013), valid only in certain contexts, and often misunderstood or misused (K. Potter, personal communication, May 6, 2015).

SST explicitly links IDF to rainfall space-time properties, providing certain advantages over design storm methods. Similar to other regionalization techniques, SST aims to effectively "lengthen" the period of record by using nearby observations, albeit using a fundamentally different approach involving temporal resampling and spatial transposition of rainstorms drawn from a catalog of observed rainfall events from the surrounding region. The inclusion of nearby storms at least partially addresses the difficulty of accurately estimating rainfall hazards using short records. SST can be used to estimate rainfall IDF properties and also to facilitate modeling of interactions of rainfall space-time structure with geographic features (such as hillslopes and river networks) at the appropriate spatial and temporal scales. It accomplishes this by generating large numbers of extreme rainfall "scenarios," each of which has realistic rainfall structure based directly on observations. Alexander (1963), Foufoula-Georgiou (1989), and Fontaine and Potter (1989) describe the general SST framework, while Wilson and Foufoula-Georgiou (1990) use the method for rainfall frequency analysis and Gupta (1972) and Franchini et al. (1996) use it for flood frequency analysis. In those days, however, the method was of limited practical use due to the lack of detailed rainfall datasets with large areal coverage. Those studies also did not focus explicitly on the aspects of SST related to rainfall space-time structure nor its implications for hazard modeling.

The recent advent of satellite-based remote sensing provides a relatively low-cost means of measuring extreme rainfall over large parts of the globe at moderately high spatial and temporal resolution (30 min—3 h, 4—25 km), while ground-based weather radar offers higher-resolution estimates (5—60 min, typically 1—4 km) over smaller regions. While the accuracy of rainfall remote sensing can be poor (particularly for satellite-based estimates, e.g. Mehran and AghaKouchak, 2014; and in mountainous regions, e.g. Nikolopoulos et al., 2013; Stampoulis et al., 2013), such data nonetheless offer unprecedented depictions of rainfall over large areas, offering opportunities for hazards research and practice at various scales, ranging from forecasting and post-event analysis to long-term hazard assessment.

In the context of SST, the ongoing accumulation of remote sensing data to lengths of 10—20 years or more "unlocks" many of the as-yet unrealized opportunities offered by SST. Wright et al. (2013) demonstrated the coupling of SST with a 10-year high resolution radar rainfall dataset for IDF estimation, and the method was extended to flood frequency analysis for a small urban watershed using a distributed hydrologic model in Wright et al. (2014b). These two papers, along with Wright et al. (2014a) show that commonly-used design storm practices (ARFs, dimensionless time distributions) have serious shortcomings in representing the multi-scale space-time structure of extreme rainfall and critical interactions with of this structure with watershed and river network features. Wright et al. (2014b) also show that when SST is coupled with rainfall remote sensing data and a distributed hydrologic model, it can reproduce the role that this structure plays in determining multi-scale flood response. The RainyDay software described in this paper was developed to facilitate the use of SST in conjunction with rainfall remote sensing data.

Though SST was developed in the context of flood hazard estimation, it may prove useful for rainfall-triggered landslides and other mass movements, subject to the oftentimes poor accuracy of