A PROPOSED COMPUTER-ASSISTED GRAPHICS-BASED INSTRUCTION SCHEME FOR STOCHASTIC THEORY IN HYDROLOGICAL SCIENCES

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Abstract

We describe the initial concept for a computer-assisted instruction strategy that can be developed to improve the current state of learning in the classroom of the following two topics in geoscience education: (1) stochastic theory in hydrologic sciences; and (2) the role of hydrologic process controls in satellite-based monitoring of flooding. Our scheme is founded on a spacetime stochastic model to generate precipitation distributions from satellite data and a user-friendly Graphical User Interface (GUI) that connects the stochastic model to hydrologic modeling tools. The stochastic model, being rich in application of wide ranging concepts of stochastic theory, is considered an ideal medium to translate stochastic theory to problems on modeling variability of systems that may arise in a student's future professional work. The GUI will provide full interactive control to students to couple the stochastic model with hydrological models of varying levels of complexity and observe independently the corresponding streamflow simulation graphically. An existing Modular Modeling System (*MMS*) developed by the United States Geological Survey (USGS) is selected as the main educational software architecture for this purpose. Through our proposed end-to-end graphics-based instruction system, students are expected to learn more effectively the following: (1) the implications of applying alternative stochastic theories on the simulation end-product (i.e., stream-flow from hydrologic models driven by satellite rainfall data); (2) the importance of various hydrologic process controls on flood phenomena; and finally (3) relevance of the various assumptions embedded in application of stochastic theory to real-world problems and the corresponding influence on modeling variability that students may encounter in their future professional work.

Key word: Geoscience education, stochastic theory, hydrologic sciences, computer-assisted instruction, graphical user interface.

Introduction

Stochastic theory is a very important subject matter in any engineering discipline. It describes the omni-present uncertainty in man-made or natural systems and further helps us to mathematically model it. Thus, most engineering curricula at the undergraduate/graduate level have some element of stochastic theory delivered as learning objectives. However, research accumulated over the last two decades indicates that the existing teaching paradigm of stochastic theory that is conventionally adopted in classrooms may be inadequate and in need of modernization. For example, the noted statistician G.E.P. Box once commented *"Although statistics departments in universities are now commonplace, there continues to be a severe shortage of statisticians competent to deal with real problems"*.[6] This sentiment has also been echoed by Godfrey[16] as follows: *"For too long we in the statistics profession have tolerated poor statistics teaching, which produces courses that are often rated as the worst course or the most useless course that graduates in other fields claim they have ever taken. We too often teach what appears to the students a collection of unrelated methods illustrated by examples taken from coin-tossing, card-playing and dice-rolling. And then we expect the students to be able to translate this wide variety of methods with simple gambling* *examples to complex industrial problems involving the application of a large number of methods"*. Romero et al.[25] provide an excellent summary on the current limitations of teaching stochastic theory to engineers and make a compelling case for the need for innovative pedagogical experience that extends beyond text-based instruction and explores new paradigms.

In the modeling of natural phenomena of hydrologic origin (such as floods) for geoscience education, stochastic theory receives enhanced emphasis due to current awareness of the limitations of deterministic approaches[4], scale incongruity[12], and the wide-spread heterogeneity in naturally occurring variables of the land form (e.g. vegetation, topography, soils, geology, etc.). The stochastic theory, however, comprising the concepts such as random process, density function, moment generating functions, geostatistics and spatial correlation, random field generation, time-series analysis etc., can appear very challenging to students unless particular care is taken to demonstrate these concepts via real-world examples that students can actually 'take back home'. Yet, the conventional teaching paradigm for stochastic theory to model the variability of such natural systems continues to rest mostly on pure text-based pedagogy involving rigorous stochastic theory books [7],[24]. It is often difficult for students to make the correlation between the academic study of stochastic theory and the application of that theory to hydrologic phenomena. It is our general opinion that, these complex mathematical concepts on stochastic theory, while no doubt rigorously presented in books, can actually appear intellectually intimidating to students if proper care is not taken on mode of instruction of the concepts.

A computer-assisted graphics-based instruction system can potentially remedy the intellectual hurdle of learning stochastic theory for geoscience education in the class room. We believe that such a system should have the following features: (1) real-world application of a wide range of concepts of stochastic theory via a practical tool that allows modeling of the variability of a natural phenomena; (2) full interactive user control over the tool to allow students to modify, add/remove concepts, and thereby foster excitement and active learning; and (3) multi-media and a computer assisted technology, such as a Graphical User Interface (GUI), that combines (1) and (2) and further enhances the user-friendliness and attractiveness of the modular modeling system. Such a system that allows students to interpret fundamental concepts using an additional medium of an interactive graphical tool, has the potential to stimulate interest in students and possibly even excite them to other innovative applications such as satellite-based hydrologic modeling for flood monitoring. Recent research indicates that multimedia can be effective in enhancing learning when the "learning," "subject" and the "student" are clearly defined.[8]

In this paper, we propose a framework for one possible graphics-based instruction scheme for stochastic theory in hydrologic sciences. Our motivation for such a scheme is driven by the need to improve the current state of learning of stochastic theory to enable inclusion of upcoming space-borne concepts for hydrologic measurements and hydrologic sciences in Water Resources courses. We propose to achieve this on the basis of a user-friendly Graphical User Interface (GUI) that would provide full interactive control to students to couple a stochastictheory rich model with hydrological models of varying levels of complexity. An existing Modular Modeling System (*MMS*) developed by the United States Geological Survey (USGS) is proposed as the main educational software architecture for this purpose. In the following discussion we justify the need for such a graphics-based instruction scheme to augment any education plan on modernizing geoscience education at the undergraduate/graduate level. The paper is organized as follows. We first provide an account on the importance of hydrologic sciences and stochastic theory in geoscience education. The discussion is cast in the context of relevance of curriculum modernization in hydrologic sciences using computers. We then present an account on the motivation for our proposed educational tool. Next we present our technical approach. Finally we conclude our paper summarizing the major features of our proposed instruction scheme.

The Importance of the Hydrologic Sciences and Stochastic Theory in Geoscience Education

According to UNESCO, floods account for about 15 % of the total death toll related to natural disasters.[11] The law of conservation of mass at the land-atmosphere interface requires us to consider rainfall as the primary determinant of floods. Rainfall's intimate interaction with the landform (i.e., topography, vegetation and channel network) magnified by highly wet antecedent conditions leads to catastrophic and large-scale flooding in river basins. Thus, the understanding of the flooding mechanism in the Civil Engineering curricula for a typical water resources course such as 'Hydrology' requires a thorough understanding of the hydrologic sciences and the associated rainfall process that serves as a primary input for its modeling.

However, research indicates that the global availability of rainfall measurements from traditional sources (such as gages) is on the decline. This systematic decline of in-situ networks for rainfall measurement has long been recognized as a crucial limitation to advancing hydrologic research in medium to large basins.[27];[26] As a collective response, sections of the hydrologic community have recentlyforged partnerships for the development of space-borne missions for cost-effective, yet global, hydrologic measurements. Examples are the Hydrospheric State (HYDROS) mission for global mapping of soil moisture conditions[9], the Water Elevation Recovery (WatER) mission for surface flow measurement[2];[1] and the Global Precipitation Measurement (GPM) mission for global monitoring of rainfall[29]. GPM is expected to be in effect during the 2010-2012 timeframe and will utilize a large constellation of Passive Microwave (PMW) sensors in space to provide high resolution global rainfall products at 6 temporal scales ranging from 3 to 6 hours, and spatial resolution of 25-100 km_2[29]; see also: http://gpm.gsfc.nasa.gov). Thus, there is no doubt that the students of Water Resources courses today should gradually become cognizant of these space-borne missions for their data needs for hydrologic research and application in the future, especially if they choose an overseas career on water resources management.

Although there are several sources of uncertainty that complicate our understanding of flood monitoring, the principal source of uncertainty is undoubtedly rainfall.[19] Syed et al.[32] demonstrated that 70%-80% of the variability observed in the terrestrial hydrological cycle is in fact attributable to rainfall. When satellite rainfall estimates are applied, this uncertainty can lead to high uncertainties in runoff simulation.[23] Furthermore, the uncertainty structure of satellite rainfall estimates is more complex than associated with more conventional sources of rainfall measurement.[13] This emphasizes the importance of understanding stochastic theory to understand and subsequently model the complex variability of rainfall and the error associated with its estimation by satellites. Overall, in anticipation of the changing make-up of knowledge and hydrologic data needs for Civil Engineering majors specializing in Water Resources engineering, there is a greater need to shift focus more effectively on the concepts of hydrologic sciences in parallel with stochastic theory.

The Relevance of a Computer-Assisted Education Component

For the study of water resources in general, there exists a wide body of literature describing various teaching methods based on the use of computer technology. For example, the 2001 December issue of *Journal of Hydraulic Engineering (American Society of Civil*

Engineers - ASCE) devoted an entire issue to the subject of teaching hydraulic design. Jewell[15] illustrated the utilization of equation solvers to facilitate instruction in various areas of hydraulic engineering. Other studies include Huddleston[14] on the use of spreadsheet applications, Baker et al. (2002) on the use Finite Element software and Whiteman and Nygren[34] on the perspective of maintaining a balance between theory and computer software application. However, little literature seems to exist on potentially effective ways to impart computer-assisted instruction on concepts of stochastic theory for hydrologic sciences. To the best of the authors' knowledge, the closest analogue to a computer-based scheme for instruction of concepts on stochastic hydrology is the **G**eneralized **L**ikelihood **U**ncertainty **E**stimation- GLUE-Software[4]p 239) currently available as a WindowsTM program. The GLUE software however offers little flexibility to students for the interactive build-up of hydrological models.

Our Proposed Computer-Assisted Instruction Scheme

The General Framework

The proposed instructional software will be based upon a user-friendly Graphical User Interface (GUI) that connects a stochastic model to hydrologic modeling tools. The simulation software will be used by students to supplement their active learning process by allowing them to interactively build hydrological models of varying levels of complexity and couple them with a stochastic model developed by the authors. This stochastic model, rich in application of stochastic theory is named 'Two-Dimensional Satellite Rainfall Error Model (*SREM2D*)[13] It can be used to create satellite-rainfall fields from accurate and high resolution reference rainfall data. These satellite rainfall fields can then be propagated directly to hydrologic models of various levels of physical complexity to observe independently the corresponding uncertainty in stream-flow simulation *graphically* (*Figure* 1). The students can thus compare their own observations to appreciate the direct link of theory to what they observe in practice. Constructivist theory postulates that such highly interactive learning environments in which the student has an enhanced degree of control should result in greater and deeper learning.[18];[28];[36] Furthermore, educational media that utilizes multiple methods of engaging the student in learning activity has a greater potential for meeting the individual learning needs of the student.[22] An existing GUI[21] that allows the interactive building of hydrological models from a suite of hydrologic modules will be modified for addressing the student's learning needs. To avoid cognitive overload and poor performance for students with weaker computer backgrounds[35], it is also important that the proposed GUI be very user-friendly. Since designing a course solely for the purpose of introducing the students to the proposed software is beyond the scope of any curriculum modernization effort, a core manual based on Keedy's[17] "20-80" rule will be developed. This rule will essentially identify the 20 keystrokes associated with 80 percent of the power of the software. When students first learn the package, they do not need to know the most efficient way to do something, but instead they need to know the easiest way to learn and remember.[33]

The Stochastic Model: Two Dimensional Satellite Rainfall Error Model (SREM2D)

Current satellite error models focus primarily on the sampling uncertainty due to the low frequency of satellite overpasses.[10];[31];[3] The assumptions common in all these frameworks are: (1) perfect algorithm and noisefree instrument; (2) 100% coverage of the area during satellite overpasses; and (3) fixed sampling intervals. These assumptions – while in some cases providing a basis for assessing a lower limit in runoff errors - in general provide a framework that may not be adequate for assessment of flood monitoring potential of satellite rainfall data (e.g. GPM) in medium to large basins.[12]

In view of the above limitations, the first author has developed and verified a two-dimensional satellite rainfall error model (*SREM2D*) that will be used for the proposed instruction scheme. *SREM2D* uses as input “reference” rain fields of higher accuracy and resolution representing the “true” surface rainfall process, and stochastic space-time formulations to characterize the multi-dimensional error structure of satellite retrievals. The major dimensions of error structure in satellite estimation modeled by *SREM2D* are: (1) the joint probability of successful delineation of rainy and non-rainy areas accounting for a spatial structure; (2) the temporal dynamics of the conditional (rain > 0 unit) rainfall estimation bias; and (3) the spatial structure of the conditional random deviation. The spatial structure in *SREM2D* is modeled as spatially correlated Gaussian random fields while the temporal pattern of the systematic deviation is modeled using a lag-one autoregressive process. The spatial structures for rain and no-rain joint detection probabilities are modeled using Bernoulli trials of the uniform distribution with a correlated structure. This correlation structure is generated from Gaussian random fields transformed to the uniform distribution random variables via an error function transformation. It has 9 parameters in total. Complete details on *SREM2D* are described.[13]

Anticipated Educational Value of SREM2D

As observed from the preceding section and in *Figure* 2, the satellite rainfall error model –*SREM2D*- applies a wide range of stochastic concepts and interacts at the interface between surface hydrology and meteorology. Using *SREM2D* as the teaching tool, the following concepts of stochastic theory and their real-world application can be easily demonstrated: (1) Probability theory; (2) Discrete and continuous probability density functions; (3) The concept of a random process; (4) Bernoulli and Binomial trials; (5) Time series analysis based on auto-regressive process; (6) Geostatistical theory – the concept of spatial autocorrelation, correlation length, variograms and kriging; and (7) Random field generation using the turning bands algorithm. *Figure* 2 provides a schematic summary of the major stochastic concepts manifested in *SREM2D*. To the best of the authors’ knowledge, there currently is no other stochastic error model in the pertinent hydrologic science literature that applies a wider array of stochastic concepts.

Specific Design Lay-out: The Graphical User Interface (GUI)

We propose our GUI to be built upon the existing architecture of the Modular Modeling System (*MMS*;[21],[21] (see *Figure 3*). To address the problems of model selection, application and analysis, a set of modular modeling tools, termed the *MMS*, was developed by Leavesley et al..[20],[21] The approach being applied in developing *MMS* was to enable a user to selectively couple the most appropriate hydrologic process algorithms from applicable models to create an "optimal" model for the desired application. Where existing algorithms are not appropriate, new algorithms can be developed and easily added to the system. This modular approach to model development and application provides a flexible method for identifying the most appropriate modeling approaches given a specific set of user needs and constraints. Our proposed scheme specifically targets the Precipitation-Runoff Modeling System (*PRMS*) component of the *MMS*[21] for the coupling with *SREM2D*. Very recently, a climate generator was coupled with *MMS* to evaluate the statistical properties of the 11 climate time series as well as the resulting stream-flow hydrographs from *PRMS* on the basis of 100 ensembles (personal communication with Dr. Leavesley). This clearly indicates our proposed design is technically feasible.

The proposed GUI system will also allow/challenge students in the class room to pose science questions of their own and consequently attempt to seek answers independently in an active learning format. In addition, the GUI will solidify learning of concepts on: (1) role of hydrologic process controls in flooding; (2) probability distributions of discrete/continuous variables associated with MC error propagation; (3) spatio-temporal dependency; (4) random field generation; (5) scaling issues; and (6) the connection to theoretical derived distribution theory based on analytical approaches.

Conclusion

We have proposed a computer-assisted instruction scheme to improve the current state of learning in the classroom of the following two topics in geoscience education: (1) stochastic theory in hydrologic sciences; and (2) the role of hydrologic process controls in satellite-based monitoring of flooding. Instruction of stochastic theory will be imparted through a stochastic model to generate satellite rainfall. A user-friendly Graphical User Interface (GUI) that connects the stochastic model to USGS hydrologic modeling tools will facilitate the learning of hydrologic process controls in satellite-based monitoring of flooding. The stochastic model, being rich in application of wide ranging concepts of stochastic theory, is considered an ideal medium to translate stochastic theory to problems on modeling variability of systems that may arise in a student's future professional work. The GUI would provide full interactive control to students to couple the stochastic model with hydrological models of varying levels of complexity and observe independently the corresponding stream-flow simulation graphically. Through our 12 proposed end-to-end graphics-based instruction system, students are expected to learn more effectively the following: (1) the implications of modifying/ replacing competing concepts in stochastic theory on the simulation end-product (i.e., stream-flow from hydrologic models driven by satellite rainfall data); (2) the importance of various hydrologic process controls on the land surface that constitute the flood phenomena; and finally (3) relevance of the various concepts on stochastic theory to real-world problems on modeling variability that students may encounter in their future professional work.

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David Huddleston received his PhD from The University of Tennessee (1989) in Engineering Science and M.S in Engineering Mechanics from Virginia Polytechnic Institute and State University (1978). His research interests are on computational fluid dynamics (CDF), computational design coupling CFD with nonlinear optimization, water resources engineering, open-channel flows, fluid mechanics, applied aerodynamics. His educational interest is on the use of computer technology for the instruction of hydraulic engineering.

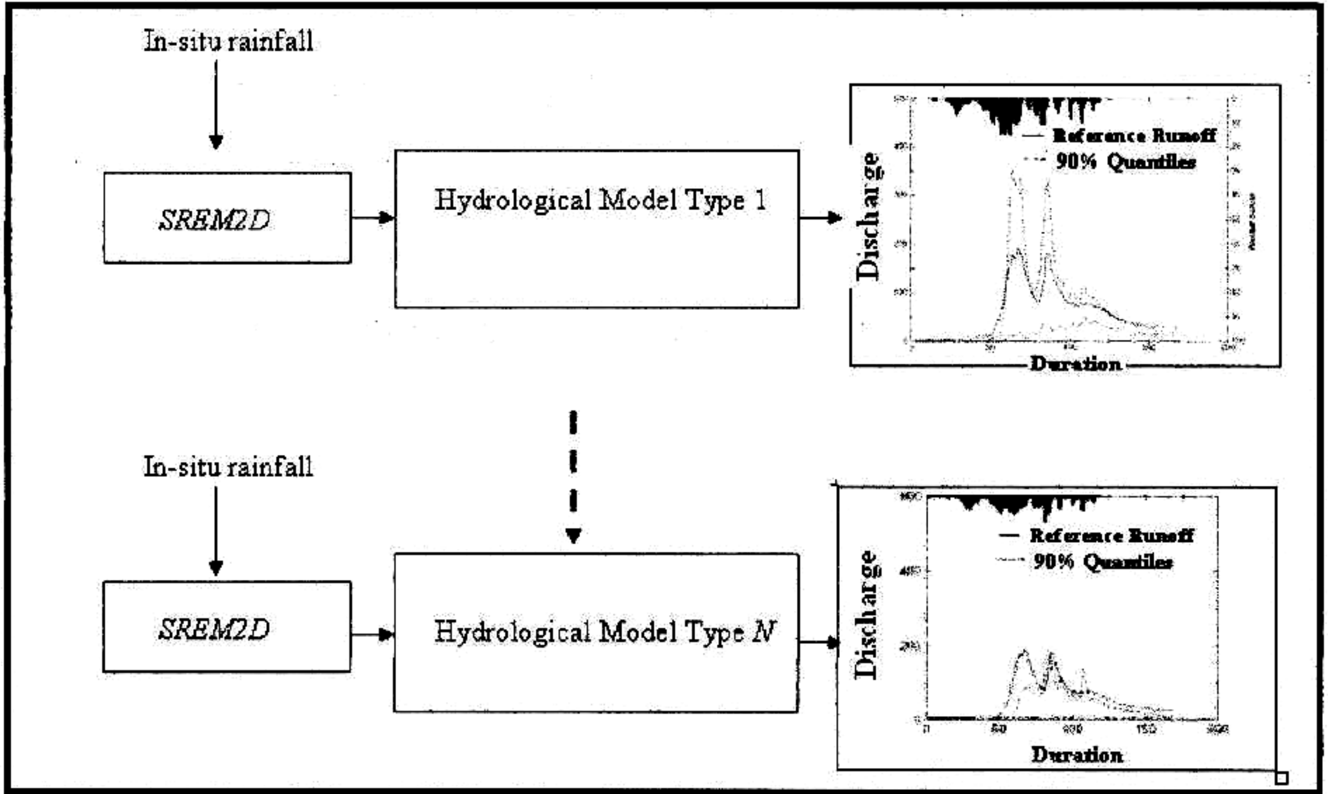

Figure 1. Schematic showing the coupling of *SREM2D* with hydrological models and the resulting simulation uncertainty in streamflow. The dotted lines in streamflow simulation are the 5% and 95% percentiles representing the range of uncertainty. Each hydrological model from *Type 1* to *Type N* represents a combination of process controls and hence different levels of complexity.

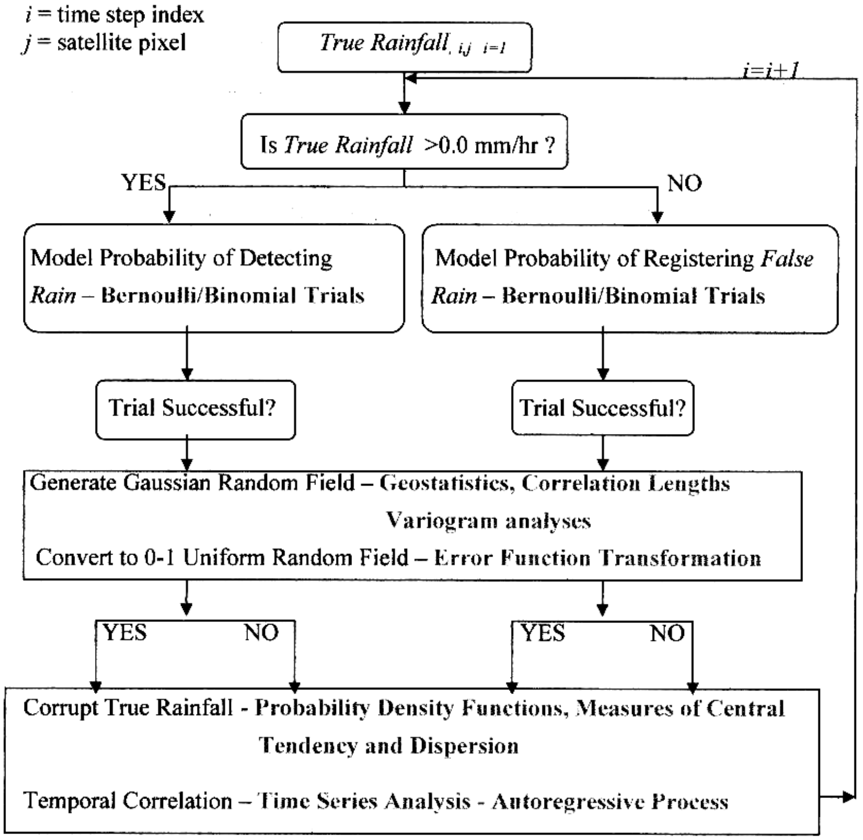

***Figure* 2.** Schematic of *SREM2D* showing application of a wide range of stochastic concepts highlighted in red for the space-time stochastic corruption of rainfall (*after Hossain and Anagnostou, 2006*).

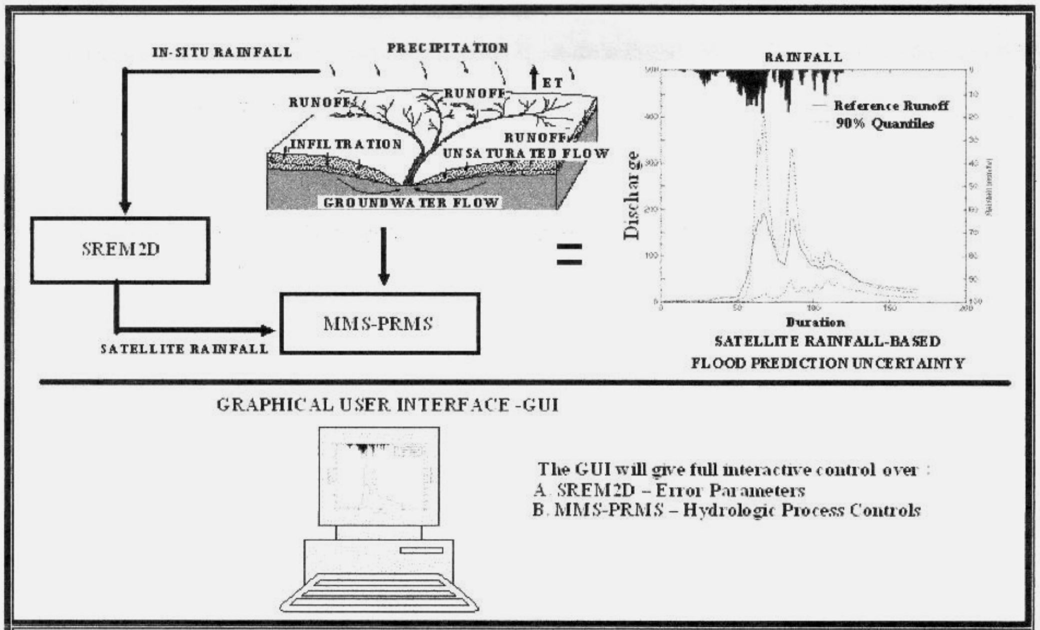

Figure 3. Schematic for the proposed GUI for computer assisted instruction scheme on stochastic hydrology and the role of process controls in flooding. The GUI integrates *SREM2D* and *PRMS* modules on a user-friendly computer system.