Lecture 1, August 24, 2010 (Syllabus)

Course Title: MULTISCALE HYDROLOGY

Course No: CVEN 5333 Section: 001 3-credits

Instructor: Vijay K. Gupta, Professor of Civil and Environmental Engineering, Fellow of Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder

Meeting Time and Place: 3:45-5:00, T Th, Ekeley (CIRES) W240

Office: Ekeley S-232

COURSE CONTENTS

Fundamental advances in hydrologic sciences have taken place in the last thirty years that are in large part driven by the availability of high-resolution spatial topographic data (GIS: geographic information system), substantial increase in computational power including availability of high-speed personal computers, and new theoretical developments in nonlinear mathematics, physics and geophysics that includes hydrologic science. Many of these advances address the multi-scale nature of hydrologic processes and offer new insights for solving contemporary hydrological science and engineering problems. By contrast, the subject matter of textbooks generally used in 5333 is based on basic hydrologic concepts and engineering tools that were developed before the 1980s. There is no modern textbook at the level of CVEN 5333, which provides an exposition of contemporary advances in hydrology around the fundamental issue of "multiscale variability and parameterization" and the corresponding tools required for research and applications. A new book, W. Brutsaert, Hydrology: An Introduction, 2005 (key reference for the course) barely scratches the surface of many new concepts from nonlinear science that are required. There is a great need to modernize the graduate "surface-water hydrology" curriculum. I have been developing a two-semester sequence 5333 and 6333 for several years, and the work is still in progress. Two important areas of hydrologic applications are floods and droughts. There is a huge literature on floods, and far less on droughts. The focus of 5333 is floods, and 6333 would deal with droughts and hydro-climate variability.

Key developments during the 1960s, building on research in the previous half century, led to *two disparate approaches to hydrologic analyses, one statistical and the other deterministic*. The statistical approach consisted of the regional (spatial) quantile analysis of annual flood frequencies in 'homogenous regions'. The US Geological Survey (USGS) developed it. The deterministic (spatially distributed) approach consisted of semi-empirical physical equations and was meant to predict flow hydrographs and peak flows on the time scales of individual rainfall-runoff events. The two approaches, one statistical and the other deterministic, were developed to solve practical engineering problems. The regional statistical analysis of annual flood frequencies was designed to predict floods of a given return period for the design of highways, bridges and spillways at ungauged locations. Rainfall-runoff models were developed for planning and project design; the Stanford watershed model is one early example of such a model. The dichotomy of the two approaches to hydrologic analyses has been firmly rooted in current hydrologic research, education and practice.

It was also recognized in the early 1960s that the two approaches must be closely connected because physical rainfall-runoff mechanisms generating floods were the basis for the flood values used in statistical analyses. For example, federal agencies other than the USGS have often used deterministic rainfall-runoff analyses to determine flood frequencies at the outlet of a basin. During 1972-1990, a small body of literature attempted to develop the "dynamics of flood frequency at a basin outlet". A general theoretical framework for connecting the two, i.e. how the physics of the system could be used to determine spatial statistical parameters was not known, and tools had not been developed to address this fundamental hydrologic question.

Beginning in 1990, a small number of papers systematically investigated that regional flood quantiles for different frequencies behave as <u>*power laws*</u> with respect to drainage areas. <u>Power laws arise as a result of *self-similarity, which can be geometrical, statistical or physical.*</u> A small set of follow-up papers demonstrated that spatial statistical variability in peak flows with respect to drainage areas could be predicted as power laws from physical processes. Since 2003, concrete progress has been made to generalize and test these ideas in real networks using real data that are available. We will explain how the *hypothesis of self-similarity* in channel networks is providing a physical foundation to develop a new space-time theory of floods. This theory presents a framework to unify multiscale variability in individual hydrologic processes of rainfall, evapotranspiration, infiltration, runoff generation and routing in channels. It has the fundamental objective to predict statistics of floods in river networks at multiple spatial scales and on multiple time scales ranging from hours and days to seasonal, annual, interannual and longer. It is based on conservation equations and process descriptions.

The material in the two-course sequence can serve as a foundation for developing new approaches to understanding scientific and engineering topics of river basin hydrology (including non-point source pollution) under changing environmental conditions due to climate variability and human activities. It can also help to address other environmental topics belonging to multidisciplinary areas of landscape ecology, stream ecology, and biogeochemistry of river basins. Some of the mathematical concepts covered here have applications to other science and engineering disciplines.

A modern hydrology curriculum needs to address: (i) Students to develop critical thinking for linking multiscale dynamics, geometry and statistics, (ii) analytical ability to understand new concepts from nonlinear science, (iii) introduced to some of the key literature that can help towards their graduate studies. Success of this course depends on how much of these three needs are met.

PREREQUISITES: Students are required to have familiarity with concepts covered in CVEN 5537, Numerical Methods; CVEN 5454, Statistical Methods for Natural and Civil Engineering Systems; and CVEN 4333, Engineering Hydrology.

COURSE TEXT: No suitable textbook is available. W. Brutsaert, Hydrology: An introduction, Cambridge, 2005 is a reference book on reserve in the engineering library. Electronic version of this book can be accessed from any where on the campus, or, using the VPN, anywhere off-campus as well.
http://libraries.colorado.edu/search/r?SEARCH=cven+5333&ReserveType=http%3A%2F%2Flibraries.colorado.edu%2Fsearch%2Fr
Key points outline will be given for each lecture. PDF files of key published papers used in the lectures will be furnished.

COURSE REQUIREMENTS: I will assign HW problems once every two weeks, and they will be due two weeks later. I will introduce a unique, state-of-the-art river network analysis and visualization research GIS tool CUENCAS that my research group has developed over the last decade. I will assign HW problems on the application of CUENCAS as part of developing a numerical laboratory for this course. The final exam will consist of a concise term paper of no more than 10 pages of double-spaced text (including title page, abstract, figures, tables, and references) based on a project of the student's choice. Students will discuss with me and pick a topic by March 1. Students will present key findings from their term papers in ten-minute talks as the final exam. Grade will be based on:

- Homework (50%)
- Homework on numerical laboratory (15%)
- Final term paper written report and oral presentation (35%)

COURSE OUTLINE (Subject to modifications) (30 Lectures T Th. schedule)

1. EXPLANATION OF COURSE OBJECTIVES AND CONTENTS (1)
2. THE GRAND CHALLENGE OF UNIFICATION ACROSS MULTIPLE SCALES (1)
3. STATISTICAL POWER LAWS (SCALING) IN REGIONAL ANNUAL FLOOD FREQUENCIES, AND PHYSICAL UNDERPINNINGS (4)
   - 3.1 USGS regional flood quantile analysis
   - 3.2 Impact of USGS Regional approach in engineering practice
   - 3.3 Power laws in annual flood quantiles in homogeneous regions
   - 3.4 Power laws in annual flood quantiles in river basins
   - 3.5 Water balance and power laws in annual flood quantiles
   - 3.6 Estimation of mean annual runoff via water balance: A Case study
   - 3.7 Physical understanding of scaling in annual flood quantiles via rainfall-runoff events

4 POWER LAWS AND SELF-SIMILARITY UNDER A CHANGE OF SCALE (4)
   - 4.1 Power Law and Self-Similarity: Dynamic, Geometric and Statistical
   - 4.2 Power Law As a Solution of a Functional Equation
   - 4.3 Geometric Self-Similarity and Fractals
   - 4.4 Examples of Fractal Geometry
   - 4.5 Functional equation, Self-Similarity and Fractals

5. SELF-SIMILARITY IN DRAINAGE NETWORK TOPLOGY AND GEOMETRY (4)
   5.1 Multiple Spatial Scales of a Branched Network via Strahler Ordering
   5.2 “Horton Laws” of Drainage Composition
   5.3 Mean Self-Similar Tokunaga River Networks and Horton Laws
   5.4 Topologic Fractal Dimension of Tokunaga networks
   5.5 Hack’s law and Tail Probability Exponent of Basin Areas for Tokunaga Networks

6. TRANSFORMING RAINFALL TO RIVER FLOWS (2)
   6.1 Review of Clark’s unit hydrograph and convolution
   6.2 Network width function and Geomorphologic Instantaneous Unit Hydrograph (GIUH)
   6.3 Physical interpretation of Clark’s unit hydrograph from GIUH

7. FORMULATION OF MULTI-SCALE RAINFALL-RUNOFF DYNAMICS (6)
   7.1 Power laws in floods for rainfall-runoff events
   7.3 Multi-scale formulation of rainfall-runoff dynamics in river basins
   7.4 Mass-balance equation for the hillslope-link system partitioning a river basin
   7.5 Momentum balance equation in a channel link
   7.6 Derivation of GIUH from rainfall-runoff dynamics: Idealized example
   7.7 Prediction of scaling in peak flows from GIUH and tests against observed scaling: Two examples using data
   7.8 Stochastic generalization of GIUH and prediction of scaling parameters in peak flows from physical processes: Goodwin Creek basin, MS case study

8. THE SCIENTIFIC CHALLENGE OF SOLVING THE CONSERVATION EQUATIONS IN A NETWORK (4)
   8.1 The challenge of space-time rainfall variability
   8.2 The challenge of incorporating self-similarity and randomness in networks
   8.3 The challenge of dynamic parametric complexity
      8.3.1 multi-scale parameterization of Infiltration and runoff generation
      8.3.2 hydraulic-geometry and multi-scale parameterization of flow dynamics

9. TOWARDS A UNIFIED UNDERSTANDING OF MULTISCALE VARIABILITY OF PEAK FLOWS (4)
   9.1 Linking event scaling with annual scaling in peak flows
   9.2 The role of climate variability in space and time
   9.3 Predictions in a changing climate and in ungauged basins