HWR 528: FUNDAMENTALS
SYSTEMS APPROACH TO HYDROLOGIC MODELING
CORE COURSE¹ (3 Units)
Fall Semester Every Year
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GOALS:
a) Familiarity with the language, methods and tools of systems analysis (SA)
b) Understanding of the usefulness of the SA approach in development and use of computer-based dynamical systems models for solving scientific and engineering problems.
c) Familiarity with Dynamic Systems Modeling using Matlab™

CATALOG DESCRIPTION: Introduction to the language, methods and tools of systems analysis and computer-based modeling, and their application to the science, risk assessment, management, and planning aspects of hydrology & water resources.

GRADING: Regular grades (A B C D E) – 35% Assignments, 35% Term Project, 20% Quizzes, 10% In-class participation.

PREREQUISITES: Math 254 (Intro. to Ordinary Differential Equations) and ECE 175 (Computer Programming for Engineering Applications) or equivalents, or consult with course instructor.

DESIRABLE BACKGROUND: MATH 125 (Calculus I), MATH 129 (Calculus II), SIE 305 (Intro to Engineering Probability & Statistics).

MATERIALS REQUIRED: MATLAB™ Student Edition (available free through UA agreement with Matlab), access to a personal computer.

OFFERED: Fall, Tuesdays and Thursdays 9:30am-10:45am

KEY CONCEPTS: systems approach; linear & non-linear systems; dynamical model; simulation, forecasting, prediction & scenario analysis; analytic & synthetic approaches; deterministic & stochastic approaches; Markov processes; invariants; sensitivity analysis; performance evaluation & measures; identifiability; consistency, accuracy & precision; parameter specification; regression; response surface; calibration; optimization; Taylor series expansion; iterative local & global search; effectiveness & efficiency; evaluation of results; checking assumptions; sources of uncertainty; ensemble approach.

DESIRED OUTCOMES:
a) Understanding key concepts of dynamical modeling incl: model components, invariants of a system, simulation (historical) & forecasting & prediction, sensitivity, optimization, model evaluation and uncertainty analysis etc., as listed under “Key Concepts”.
b) Ability to develop and apply simple models of dyn. systems to problem of interest.
c) Familiarity with the language and methods of systems analysis

CLASS FORMAT: Two 75-minute lecture periods a week (Tues/Thurs).

CONTENT:
• Lectures (22); Quizzes (10); MATLAB™ Assignments (5); Term project (Present. + report)

¹ September 30, 2010
LECTURE TOPICS:
L1: Course Introduction
L2: Modeling & The Systems Approach
L3: Dynamical Systems & State Space Models
L4: Markov Processes & Linearity of Systems
L5: Linear Models in Hydrology
L6: Systems Perspective on Watershed Behavior
L7: Matlab Part I – Basics/Arrays
L8: Matlab Part II – Operations & Scripts
L9: Non-Linear Hydrological Models
L10: Programming Concepts - Building a Dynamical Model in Matlab
L11: Matlab Part III – Modeling Toolbox & HyMod Model
L12: Deterministic & Stochastic Simulation
L13: Sensitivity Analysis
L14: Evaluating Model Performance
L15: Measures of Performance & Regression Theory
L16: Function Response Surfaces
L17: Fundamentals of Non-Linear Optimization
L18: Derivative-Based Non-Linear Optimization
L19: Non-Derivative Non-Linear Optimization Search
L20: Downhill Simplex Method
L21: Evaluation of a Calibrated Model
L22: Review of The Class

QUIZZES
Q1: Models & Systems Approach
Q2: Dynamical Systems
Q3: Markov Processes & Linear Models
Q4: Matlab Arrays & Array Operations
Q5: Systems Perspective & Matlab
Q6: Simulation & Matlab Statistical Operations
Q7: Sensitivity Analysis & Performance Evaluation
Q8: Evaluation of Model Performance & Linear Regression
Q9: Response Surfaces & Non-Linear Opt
Q10: Non-Linear Optimization Methods

MATLAB ASSIGNMENTS
A1: Load & Plot Leaf River Data
A2: Program ILLR & Run Simulation
A3: Program Nash Cascade & Run Simulation
A4: Watershed Simulation, Perturbation Analysis & Manual Calibration using HyMod
A5: Use Automated (DSM) Optimization to Calibrate HyMod

TERM PROJECTS
P1: Student Presentation (Powerpoint 10 mins)
P2: Written Project Report (15 pages)
LECTURE CONTENT:

L1: Course Introduction
   Instructor information; Introductions; Website; Teaching philosophy; Systems courses sequence; Course purpose; Expectations; Absence policy; Grading; Materials required; Class format; Course curriculum; Course schedule; Assignments; Desired Outcomes; Meeting day/time; Valuable guidelines.

L2: Modeling & The Systems Approach
   Systems (definition, elements & processes, open & closed);
   Models of Systems (definitions);
   Types (maps, conceptual, physical, scale, analog, symbolic, math., numerical);
   Approaches (data-based/analytical/top-down, physics-based/synthetic/bottom-up);
   Uses of Models (understanding, historical simulation, forecasting/prediction, scenario analysis, control);
   Steps in Model Building (perceptual, conceptual, symbolic, computational);
   Cycle of Model Development;
   Modeling Protocol.

L3: Dynamical Systems & State Space Models
   Structure & Components of a Dynamical System (dynamical processes, parts of a model, language/definitions, examples, important questions);
   Continuity Equation as Foundation for Dynamical Models
   Analytic Approaches to Modeling (black-box, input-output, data-based, examples)
   Synthetic Approaches to Modeling (conceptual, physically based, examples)
   Dynamic Modeling (without memory, with memory)
   State-Space Models (state-space representation, simple example)
   Characterization of Dynamical Systems (impulse response, step response, properties of impulse response – gain, dispersion, phase-shift, simple examples)

L4: Markov Processes & Linearity of Systems
   Markov Processes (definition, dimension of state, examples);
   Classification of Dynamical Systems (continuous/discrete, time-invariant/variant, lumped/distributed, SISO/MIMO, Steady-state/transient-state, deterministic/stoch, linear/non-linear);
   Linearity of Systems (input-output linearity, state-output linearity, parameter-output linearity, homogeneity & superposition, examples);

L5: Linear Models in Hydrology
   Conceptual Model of the Watershed System (conceptualization of global hydrologic cycle, land-phase detail, vertical-horizontal simplification, single component simplification);
   Linear Models in Surface Hydrology (Rational method, linear regression, linear reservoir, Nash cascade (impulse response, gamma function), unit hydrograph, time-series models, transfer functions, ABC model)

L6: Systems Perspective on Watershed Behavior
   Conceptual Model of the Watershed System – Hydrologic Perspective (phases of watershed response (after Hoyt));
Conceptual Model of the Watershed System – Systems Perspective (driven & relaxation phases, three-phase concept)
System Properties (stability, observability, identifiability, controllability, sensitivity, uncertainty);
Transfer Function Modeling (Data-based modeling)

L7: Matlab Part I – Basics/Arrays
Getting Started (getting and installing MATLAB, creating your own work directory, workspace management, command history);
Simple Operations;
Documentation, Help and Demos;
Vectors and arrays (array types, data types, data structures, creating and referencing arrays, manipulating arrays, arithmetic operations, concatenation, extracting sub-arrays);
Loading Data and Creating Plots (simple 2-D line plots, other types of plots, example).

L8: Matlab Part II – Operations & Scripts
Creating and Editing script Files (standardization of m-file layout, echo on and echo off, testing scripts regularly, saving and clearing variables);
Utility Arrays and Array Operations;
Statistical Operations;
Relational and Logical Operations;
Special Operations (find, exist, isempty, sort);
Infinity and Missing Values (Inf, NaN, Isnan, Isninf);
Common Mathematical Functions (Trigonometric, Exponential, Numeric).

L9: Non-Linear Hydrological Models
Conceptualization of Non-linear Hydrologic Behavior (Interception, Impervious areas, Infiltration/surface runoff, Interflow, Evapo-transpiration, Percolation, Baseflow, Drainage);
Conceptual Watershed Models (Sacramento Model, Stanford Watershed Model, HBV Model, Xinanjiang Model, Tank Model, HyMod)
Other Approaches of Historical Interest (SCS Curve Number method, API Method, Baseflow separation, Probability Distributed Model, etc.).

L10: Programming Concepts - Building a Dynamical Model in Matlab
Basics of Programming (computer program, operating system, higher level languages, lower level/assembly languages, assemblers, machine code/language, compiled languages, compilers, executables, decompilers, interpreted languages);
Program Structure (Heading, preparation, inputting data and/or run information, Computation, Outputting results, examples to try);
Flow Control (types of flow control, for loops, while loops, if-else-end constructions, switch constructions)
Function M-Files (syntax, examples, properties of function m-file variables, program structures, standardization of programming, advantages of using functions);

L11: Matlab Part III – Modeling Toolbox & HyMod Model
The Simple Conceptual Watershed Model HyMod (Version 1, Version 2);
HyMod Code (Program structure, PDM component, Nash Cascade component for quickflow Routing, Nash Cascade component for slowflow routing, linking the components together – day loop, scripts & functions);
Hoshin’s Matlab Toolbox (Structure, data and run files, outputs, toolbox operations – simulation, simple 1-D sensitivity analysis, 2-D response surface analysis, optimization by downhill simplex method);

**L12: Deterministic & Stochastic Simulation**
Simulation (physical, interactive, engineering, analytical vs. computer based, synthetic environments, specialized meaning in computer science (Turing), purposes, examples);
Emulation (Church-Turing hypothesis, software emulator);
Iso-Morphism (examples);
Deterministic and Stochastic Simulation (definitions, examples, ILLR as deterministic, ILLR as stochastic, ensemble/particle tracking approach, distribution summary approach, types of randomness – homoscedastic & heteroscedastic);
Example using HyMod.

**L13: Sensitivity Analysis**
Sensitivity Analysis (definition, uses – similarity testing, factor importance & function, region of sensitivity, factor independence);
Clarification of Terminology (sensitivity analysis, identifiability analysis);
Perturbation analysis (One-at a time factor analysis, Multi-factor analysis);
Example using HyMod.

**L14: Evaluating Model Performance**
Desirable Characteristics of a Hydrologic Model (Consistency – structural and behavioral, Accuracy, Precision, desirable/undesirable cases of accuracy/precision combinations, why these are important for model identification, which cases contain useful information, which is most/least informative);
Visual Examination of Performance (characteristic features of I-S-O response, viewing under transformation);
Mathematical Evaluation of Performance (closeness of model & world, defining closeness)
Regression approach (scalar measures, examples of possibilities, assumptions) Transformations & Normalizations (Nash-Sutcliffe Efficiency, Normalized Persistence Error);

**L15: Measures of Performance & Regression Theory**
Linear Regression Theory (requirements, solving systems of linear equations, least squares estimation);
Non-Linear Regression Theory (Taylor series expansion, application to dynamical models/chain rule, derivation by least squares estimation);
Model Identification as a Regression/Optimization Problem (single criterion optimization problem)

**L16: Function Response Surfaces**
Response Surface (definition, generating and visualizing 2-D response surfaces);
Characteristics of Response Surfaces ( Regions of attraction, local optima, roughness, flatness, shape, causes);
Examples (MSE response surfaces for ILLR, non-leaky bucket, leaky bucket, tanks in series and parallel, HyMod Model);

**L17: Fundamentals of Non-Linear Optimization**
Fundamentals of Non-Linear Optimization Theory (necessary and sufficient conditions for an optimum, unconstrained and constrained optimization, Lagrangian method, convex and non-convex problems);
Limitations of Non-Linear Optimization Theory;
One-dimensional Optimization ( line & grid search, sectional search, golden section search, Golden ratio, Fibonacci series, quadratic interpolation);

**L18: Derivative-Based Non-Linear Optimization**
One-Dimensional Newton-Raphson search;
Multi-Dimensional Newton-Raphson search;
Marquardt-Levenberg Improvement;
General Form of Quadratic Approximation Search;

**L19: Non-Derivative Non-Linear Optimization Search**
The Model and Iterate Strategy of Non-Linear Optimization;
Strengths and Limitations of Quadratic Approximation Methods;
Deterministic Derivative-Free Strategies ( principles of deterministic local search, grid search, line search, simple and complex pattern search, Rosenbrock’s rotating directions method);
Strategies for Local Search ( Discussion & Class Exercise);

**L20: Downhill Simplex Method**
Downhill Simplex Method ( anatomy of a simplex, types of evolution steps, illustration on a 2-D response surface, logic chart, simplex calculations, setting up the parameter matrix, selection of initial simplex);
Types of Convergence Criteria ( parameter, function, iteration);

**L21: Evaluation of a Calibrated Model**
Modeling Protocol ( model development, data selection, simulation, sensitivity analysis, calibration, uncertainty analysis, performance evaluation, model refinement);
Post Calibration Evaluation ( Check assumptions, evaluate residuals, split sample testing);
Checking Assumptions ( assumptions in model development process, fundamental and specific assumptions, assumptions in defining closeness, assumption of optimization success, examples of assumptions in HyMod);
Residual Evaluation ( bias, cumulative bias, auto-correlation, remaining predictability, heteroscedasticity, normalized distribution, scatterplots);
Split Sample Testing ( calibration and evaluation periods).

**L22: Review of The Class**

Extra Topics (Based on Time Availability): Random Search, Stochastic Global Search.
MATLAB ASSIGNMENTS

A1: Load & Plot Leaf River Data
Objective: To become familiar with writing and execution of Matlab script files, loading and manipulating data, and creating various kinds of x-y plots.

A2: Program ILLR & Run Simulation
Objective: To become familiar with writing and execution of Matlab programs, by programming a simple dynamical model, loading data and running a model simulation run, and displaying the results using appropriate plots.

A3: Program Nash Cascade & Run Simulation
Objective: To become familiar with writing and execution of Matlab programs, by programming a simple dynamical model, loading data and running a model simulation run, and displaying the results using appropriate plots.

A4: Watershed Simulation, Perturbation Analysis & Manual Calibration using HyMod
Objective: To become familiar with the programming and execution of the lumped Watershed Simulation model HyMod01, perform a simple parameter perturbation analysis and simple manual parameter estimation.

A5: Use RS Analysis & Automated (DSM) Optimization to Calibrate HyMod
Objective: To perform 2-dimensional Response Surface Analyses for parameters of the lumped Watershed Simulation model HyMod01, and to search for “optimal” parameter estimates using the Downhill Simplex Method (DSM).

A6: Time Permitting - Use Global random Search to Calibrate HyMod
Objective: To search for globally “optimal” parameter estimates of the lumped watershed simulation model HyMod01 using a Global Random Search Method.

TERM PROJECTS

P1: End of Term Student Presentation (Powerpoint 10 mins)

P2: End of Term Written Project Report (15 pages)

Guidelines:

Goal: To become familiar with the use of various methods for systems analysis using computer-based dynamic models -- including simulation, parameter perturbation analysis, response surface analysis, parameter estimation by optimization search, and model performance/residual analysis.

Requirements: (A) Select a hydrologic system of interest for which you can develop a simple conceptual model, can represent the dynamical input-state-output behavior using mathematical equations, and can program the code in Matlab. (B) Select an appropriate input-output data set that can be used for model evaluation and parameter estimation.

Project Proposal: Turn in a one page (max) statement of objectives, goals, system/model of interest & data available (within 2 weeks).

Project Execution:
1) Formulate Model: Formulate your conceptual model in state-space form and prepare a systems diagram (identify inputs, outputs, state variables, initial states, parameters, model structure).
2) **Specify Model Structure:** Specify equations for model structure, and choose prior estimates for parameters and initial states. Program the model in Matlab.

3) **Run Initial Simulation:** Run a simulation using input data to drive the model. Prepare plots to graphically compare model responses to data.

4) **Perform Sensitivity Analysis:** Perform both perturbation and simple mathematical sensitivity analyses to model parameters.

5) **Select Performance Evaluation Criterion:** Select one or more criteria for evaluation of model performance. Justify your choice of criteria.

6) **Prepare Response Surfaces:** Prepare 2-D response surfaces for selected model parameters.

7) **Calibrate Model:** Calibrate the parameters of your model via optimization.

8) **Evaluate Performance:** Evaluate the calibrated model performance.

9) **Evaluate Uncertainty:** Evaluate uncertainty of model predictions.

**HANDOUTS**

- **H1:** Definitions of Important Terms
- **H2:** Mathworks Learning Matlab 7
- **H3:** Mathworks Learning Simulink 6
- **H4:** Introduction to Matlab (to accompany the PowerPoint lectures)
- **H5:** Guidelines for Written Reports
- **H7:** Term Project Instructions
- **H8:** Steps to Add a New Model to the Toolbox
- **H9:** Sample Response Surfaces
- **H10:** Hoshin’s Matlab Toolbox and Leaf River Dataset