Class Meetings: T TH 9:30-11:00
Medford Campus – 196 Boston Ave Suite 2500

Instructor(s): Linda Abriola, TIE Director and University Professor, Tufts School of Engineering
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Annette Huber-Lee, Senior Scientist, Stockholm Environment Institute
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Eric Kemp-Benedict, Senior Scientist, Stockholm Environment Institute,
<eric.kemp-benedict@sei.org>

Office Hours: TBD

Semester Hour Units: 3 SHUs

Prerequisites: prior course in calculus

Course Description: This course focuses on hydrology, water resources engineering, water quality analysis, and systems thinking aspects of water. Students gain a broad understanding of the scientific theories and principles related to processes governing water availability and quality and the practice of applying this theory, along with data and models, to address a range of problems of water resources engineering and management. The course is structured around model applications to case studies, which facilitates exploration of issues related to uncertainty, model complexity, and scale.

Course Objectives: This course will introduce students to essential analytical concepts in water systems. Concepts will be organized around material and energy balances in transport and transformation processes, for both surface and subsurface water. To effectively use the physical water systems concepts, students will apply simple numerical models to solve standard flow and transport problems and will be introduced to core concepts in the study of linked social and physical dynamical systems. They will demonstrate their understanding by applying both general and water-specific systems concepts to a case study in the Mara Basin in East Africa.

Texts or Materials:

Software:
Free download for academic use: Vensim PLE (http://vensim.com/free-download/)
Instructional Software Modules for Environmental Flow and Transport Processes
(requires download of MATLAB software through TTS)
Uploaded software on Canvas

Required Text:
Uploaded readings and lecture notes on Canvas, including Information on the Mara River Basin Project:
https://www.swpwater.org

On Reserve:
Academic Conduct: Each student is responsible for upholding the highest standards of academic integrity, as specified in the Friedman School's Policies and Procedures Handbook and Tufts University policies (http://students.tufts.edu/student-affairs/student-life-policies/academic-integrity-policy). It is the responsibility of each student to understand and comply with these standards, as violations will be sanctioned by penalties ranging from failure on an assignment and the course to dismissal from the school.

Assessment and Grading: The course is separated into four segments: 1) Introduction to Systems; 2) Water Science: Surface Water; 3) Water Science: Subsurface Water; and 4) Water Science and Systems in Practice. The types of assessment by segment are shown in the following table. No exams will be given. Particularly in Segments 1 & 4, students are expected to demonstrate understanding through interactive discussions, in which they apply core concepts to a variety of topics.

Table 1: Types of assessment by course segment

<table>
<thead>
<tr>
<th>INTRO TO SYSTEMS</th>
<th>SURFACE WATER</th>
<th>SUBSURFACE WATER</th>
<th>IN PRACTICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PARTICIPATION</td>
<td>Interactive discussions</td>
<td>In-class responses/discussion</td>
<td>In-class responses/discussion</td>
</tr>
<tr>
<td>HOMEWORK</td>
<td>Readings and exercises</td>
<td>Readings and exercises</td>
<td>Readings and exercises</td>
</tr>
<tr>
<td>OTHER ASSESSMENTS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Grading for the course will be based upon the following distribution:
- Homework 40%
- Final project: 50%
- Class Participation 10%

A passing grade in the course is B- or better. Course grades will be based on the below (subject to revision during the course):

- A  > 94%
- A- 90 - <94%
- B+ 87 - <90%
- B 84 - <87%
- B- 80 - <84%

Instructions for Submission of Assignments and Exams: Assigned readings and exercises must be completed within one week of the assignment. Assignments received after their deadline will not be accepted or graded unless extension is approved in advance. Students who are unable to complete an assignment on time for any reason should notify the instructor by email, text message, or phone call prior to the deadline, with a brief explanation for why the extension is needed.
The final project will have intermediate assignments, with specific due dates. Final projects must be completed and presented during Reading Period.

**Accommodation of Disabilities:** Tufts University is committed to providing equal access and support to all students through the provision of reasonable accommodations so that each student may access their curricula and achieve their personal and academic potential. If you have a disability that requires reasonable accommodations please contact the Friedman School Assistant Dean of Student Affairs at 617-636-6719 to make arrangements for determination of appropriate accommodations. Please be aware that accommodations cannot be enacted retroactively, making timeliness a critical aspect for their provision.

**Tufts WebEx:** Friedman’s on-campus courses may be offered by Tufts WebEx ([https://it.tufts.edu/webex](https://it.tufts.edu/webex)) on days when the Boston campus is closed due to weather or a temporary cancellation issue. Students should expect to be notified by email in the event that class is cancelled and will be provided with the WebEx link for students to use for any remote class sessions. Also, any relevant course slides or materials will be made available on Canvas. The WebEx will be recorded and posted on Canvas when completed. If an on-campus Examination/Presentation was scheduled on a day when the Boston campus is closed due to weather or a temporary cancellation issue, the exam/presentation will be rescheduled for an alternate on-campus class session date.

**Diversity Statement:** We believe that the diversity of student experiences and perspectives is essential to the deepening of knowledge in this course. We consider it part of our responsibility as instructors to address the learning needs of all of the students in this course. We will present materials that are respectful of diversity: race, color, ethnicity, gender, age, disability, religious beliefs, political preference, sexual orientation, gender identity, socioeconomic status, citizenship, language, or national origin among other personal characteristics.

**Course Topics and Assignment Schedule at a Glance:**

<table>
<thead>
<tr>
<th>DATE OF CLASS</th>
<th>COURSE TOPIC</th>
<th>LECTURER</th>
<th>ASSIGNMENTS DUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept 6</td>
<td>Introduction</td>
<td>All</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Introduction to Systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sept 11</td>
<td>Getting started with systems</td>
<td>Kemp-Benedict</td>
<td>Reading: Meadows “Introduction: The Systems Lens”</td>
</tr>
<tr>
<td>Sept 13</td>
<td>Introduction to the Mara River Basin Case Study</td>
<td>Huber-Lee</td>
<td>Reading: Mara River Basin Case Study</td>
</tr>
<tr>
<td>Sept 18</td>
<td>Representing systems</td>
<td>Kemp-Benedict</td>
<td>Reading: Sterman, 4.1 &amp; 4.2</td>
</tr>
<tr>
<td>Sept 20</td>
<td>Systems behavior</td>
<td>Kemp-Benedict</td>
<td>Interpret and draw CLD for water-related systems</td>
</tr>
<tr>
<td>Sept 25</td>
<td>Stocks and flows</td>
<td>Kemp-Benedict</td>
<td>Readings: Sterman, 6.1-6.2.4 Interpret and draw stock-flow diagrams for water-related systems</td>
</tr>
<tr>
<td>Sept 27</td>
<td>Why we misunderstand systems</td>
<td>Kemp-Benedict</td>
<td>Reading: Meadows, chapter 4: “Why Systems</td>
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</tbody>
</table>
Water Science: Surface Water

<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
<th>Author</th>
<th>Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 2</td>
<td>Introduction to water quality modeling and mass balances</td>
<td>Chapra</td>
<td>Reading: Chapra (1997), Chaps 1 &amp; 3</td>
</tr>
<tr>
<td>Oct 4</td>
<td>Reactions I</td>
<td>Chapra</td>
<td>Reading: Chapra (1997), Chap. 2</td>
</tr>
<tr>
<td>Oct 11</td>
<td>Transport</td>
<td>Chapra</td>
<td>Reading: Chapra (1997), Chap 8 &amp; 9</td>
</tr>
<tr>
<td>Oct 16</td>
<td>Heat balances and temperature modeling of surface waters</td>
<td>Chapra</td>
<td>Reading: Chapra (1997), Chaps 30</td>
</tr>
<tr>
<td>Oct 18</td>
<td>Dissolved oxygen modeling</td>
<td>Chapra</td>
<td>Reading: Chapra (1997), Chaps 19 &amp; 20</td>
</tr>
<tr>
<td>Oct 23</td>
<td>Eutrophication</td>
<td>Chapra</td>
<td>Reading: Chapra (1997), Chaps 33</td>
</tr>
</tbody>
</table>

Water Science: Subsurface Water

<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
<th>Author</th>
<th>Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 25</td>
<td>The subsurface environment, Darcy’s Law, and water balances in subsurface formations</td>
<td>Abriola</td>
<td>Reading: Pinder and Celia, pp 1-27, 52-62;70-85; Assignment: SW-5</td>
</tr>
<tr>
<td>Oct 30</td>
<td>Applications</td>
<td>Abriola</td>
<td>Reading: Freeze and Cherry pp 47-66;</td>
</tr>
<tr>
<td>Nov 1</td>
<td>Mixing mechanisms and chemical transport</td>
<td>Abriola</td>
<td>Pinder and Celia, pp 27-48; 94-102; Domenico and Schwartz pp 358-377</td>
</tr>
<tr>
<td>Nov 6</td>
<td>Applications</td>
<td>Abriola</td>
<td>Reading: Domenico and Schwartz, 472-482; Assignment: GW-1</td>
</tr>
<tr>
<td>Nov 8</td>
<td>Partitioning processes and applications</td>
<td>Abriola</td>
<td>Reading:TBD; Assignment: GW-2</td>
</tr>
<tr>
<td>Nov 13</td>
<td>Microbial transformation processes and applications</td>
<td>Abriola</td>
<td>Assignment: GW-2</td>
</tr>
</tbody>
</table>

Water Science and Systems in Practice

<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
<th>Author</th>
<th>Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 15</td>
<td>Applying system models in practice: methods for engaging stakeholders</td>
<td>Huber-Lee</td>
<td></td>
</tr>
<tr>
<td>Nov 20</td>
<td>Translating stakeholder input into systems models</td>
<td>Kemp-Benedict</td>
<td>Assignment: GW-3</td>
</tr>
<tr>
<td>Nov 27</td>
<td>Preliminary presentation of Mara</td>
<td>Huber-Lee</td>
<td>Presentations by students</td>
</tr>
<tr>
<td>Date</td>
<td>Event Description</td>
<td>Responsible</td>
<td>Session Type</td>
</tr>
<tr>
<td>------------</td>
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</tr>
<tr>
<td>Nov 29</td>
<td>Institutional issues and power dynamics in the representation and sharing of quantitative models</td>
<td>Huber-Lee</td>
<td></td>
</tr>
<tr>
<td>Dec 4</td>
<td>Preliminary presentation of Mara physical and social system models by students</td>
<td>Huber-Lee</td>
<td>Presentations by students</td>
</tr>
<tr>
<td>Dec 6</td>
<td>Strengths and weaknesses of mathematical modeling—from model conceptualization to communication of results</td>
<td>All</td>
<td>In class discussion</td>
</tr>
<tr>
<td>Reading Period</td>
<td>Final presentations of applied systems models</td>
<td>All</td>
<td>Presentations/Final Reports Due</td>
</tr>
</tbody>
</table>

**This schedule is subject to modification at the instructors’ discretion.**

**Detailed Description of Course Topics, Assignment Schedule, and the Learning Objectives for Each Class Session:**

Aside from the introductory lecture, which will provide an overview of the course, the lectures and assignments in this course are designed to address a number of learning objectives. Some of these are specific to a particular segment of the class, while others are shared across segments. They are:

**COURSE OBJECTIVES**

1. Explain and apply core systems concepts
2. Create and interpret system diagrams
3. Anticipate system behavior from structure
4. Understand how people interact with systems
5. Construct material balances on natural waters (surface and groundwater)
6. Understand transport and mixing processes in natural water bodies
7. Quantify chemical transformations and phase change
8. Use energy balances to compute temperatures of natural water bodies (atmospheric-water interactions)
9. Understand and apply simple numerical methods to solve flow and transport problems
10. Apply concepts in an actual transboundary river basin context by combining bio-physical and socio-economic/political factors
11. Communicate results so they are comprehensible to stakeholders and policy makers

In the detailed description for each course session, we refer back to this list.

**Sept 6: Introduction**

Course Overview and Introduction to the Water Environment

**INTRODUCTION TO SYSTEMS**

**Sept 11: Getting started with systems**

*Topics: Defining “systems” and “systems thinking”; examples of systems*

*Contributes to learning objective: 1*
Assignment: Readings: Meadows “Introduction: The Systems Lens”

Sept 13: Introduction to the Mara River Basin Case Study

Topics: Overview of the Mara River Basin in Kenya/Tanzania and the range of issues around water allocation, surface water quality, access to groundwater and the socio-economic and political setting

Contributes to learning objective: 10

Assignment: Readings on the Mara River Basin Case Study (see Canvas)

Sept 18: Representing systems

Topics: Representing systems through networks and causal loop diagrams

Contributes to learning objective: 2

Assignment: Reading: Sterman 4.1 & 4.2

Sept 20: Systems behavior

Topics: Network dynamics: changing relationships, propagation of disturbances; Canonical system dynamics behaviors: exponential growth, goal seeking, S-shaped growth, oscillation, growth with overshoot, overshoot and collapse; Characteristic times and delays, with examples from water-related systems

Contributes to learning objectives: 2 and 3

Assignment: Interpret and draw CLD for water-related systems

Sept 25: Stocks and flows

Topics: Differentiate stocks from flows; the importance of units; identify stocks and flows in water-related systems; flows across networks; stock-flow diagrams

Contributes to learning objectives: 2 and 3

Assignment:

- Reading: Sterman, 6.1-6.2.4
- Interpret and draw stock-flow diagrams for water-related systems

Sept 27: Why we misunderstand systems

Topics: System behavior, human cognition, and planning; Donella Meadows’ tentative list of leverage points, with examples from water-related systems

Contributes to learning objective: 4

Assignment:

- Reading: Meadows, chapter 4: “Why Systems Surprise Us”
- Be prepared to share one example from your own practice or personal experience

WATER SCIENCE: SURFACE WATER

Oct 2: Introduction to water quality modeling and mass balances
Topics: Overview of history of water quality modeling; conservation of mass; mass balance of a well-mixed lake; steady state and time variable solutions

Contributes to learning objective: 5, 6, 9

Assignment: lecture notes review; Reading: Chapra, Lecs. 1, 2, & 3; SW-1: Writing mass balances

Oct 4: Reactions I

Topics: First-order reactions; determining reaction rates; temperature dependence of reaction rates; stoichiometry of reactions; coupled reactions

Contributes to learning objective: 6, 7, 9

Assignment: lecture notes review; Read Chapra, Lecs. 8 & 9; SW-2: identification of reaction rates from laboratory and environmental data; stoichiometry.

Oct 11: Transport

Topics: Advection; diffusion; dispersion; modeling a bay/lake system; vertical mixing and thermal stratification

Contributes to learning objective: 5, 6, 9

Assignment: lecture notes review; Read Chapra, Lec. 30

Oct 16: Introduction to heat balances and temperature modeling of surface waters

Topics: Conservation of energy; heat balances; intro to heat transfer; heat transfer between a surface water and the atmosphere; heat balance of a well-mixed lake

Contributes to learning objective: 8, 9

Assignment: lecture notes review; Read Chapra, Lecs. 19 & 20; SW-3: Model Assignment I: Temperature Modeling

Oct 18: Dissolved oxygen

Topics: Biochemical oxygen demand; Organic carbon decomposition; nitrification/denitrification; gas transfer; steady-state model of oxygen in a well-mixed reactor;

Contributes to learning objective: 7

Assignment: lecture notes review; Read Lec. 33; SW-4: Model Assignment II: Oxygen calibration

Oct 23: Eutrophication

Topics: Introduction to eutrophication, limiting nutrients, phytoplankton kinetics

Contributes to learning objective: 7

Assignment: lecture notes review; Model Calibration Assignment III: Phytoplankton calibration.

WATER SCIENCE: SUBSURFACE WATER

Oct 25: The subsurface environment, Darcy’s Law, and water balances in subsurface formations
Topics: Characteristics of subsurface water bearing formations and classification of water zones - hydraulic conductivity and the influence of fluid and porous media properties on flow

Contributes to learning objective: 5

Assignment: Readings- Pinder and Celia, pp 1-27; 52-62;70-85

Oct 30: Applications

Topics: Boundary conditions, sources and sinks (pumping, evapotranspiration, leakage) one- and two-dimensional applications to the Mara River Basin site –aquifer depletion and river-aquifer interactions

Contributes to learning objective: 5, 9, 10

Assignment: Reading: Freeze and Cherry pp 47-66; GW-1: computation of hydraulic head contours and flow rates

Nov 1: Mixing mechanisms and chemical transport

Topics: Diffusion, hydrodynamic dispersion, influence of velocity and scale on dispersion; conservative tracer transport in aquifers

Contributes to learning objective: 5, 6

Assignment: Readings: Pinder and Celia, pp 27-48; 94-102; Domenico and Schwartz pp 358-377

Nov 6: Applications

Topics: Vertical transport in the soil profile; contaminant transport and surface water-groundwater quality interactions in the Mara River Basin

Contributes to learning objective: 5, 6, 9, 10

Assignment: Reading: Domenico and Schwartz, 472-482; GW-2: Computation of tracer breakthrough curves and profiles

Nov 8: Partitioning processes and applications

Topics: Volatilization; sorption mechanisms; retardation factor; transport and breakthrough profiles in one and two dimensions; equilibrium vs kinetic processes

Contributes to learning objective: 5, 6, 7, 9

Assignment: Readings: TBD

Nov 13: Microbial transformation processes and applications

Topics: Michaelis-Menten kinetics; zero and first order processes; microbial growth and decay; transport subject to microbial decay

Contributes to learning objective: 5, 6, 7, 9

Assignment: GW-3: Computation of reactive contaminant breakthrough curves, mass fluxes, and profiles

WATER SCIENCE AND SYSTEMS IN PRACTICE

Nov 15: Applying system models in practice: methods for engaging stakeholders
Topics: Participatory methods; application of XLRM frameworks in Africa; develop application of XLRM for the Mara

Contributes to learning objective: 4 and 11

Assignment: Readings on Canvas

Nov 20: Translating stakeholder input into systems models

Topics: Qualitative and quantitative approaches to incorporate stakeholder inputs and perceptions; discuss the actual input from stakeholders in the Mara and how elements can and cannot be included into the systems case study model

Contributes to learning objective: 4

Assignment: Actual outputs from the Problem Formulation workshop in August, 2018

Nov 27: Preliminary presentation of Mara physical system models by students

Topics: Focus on the bio-physical components of the system model – how well do they capture processes and ways to improve the representation

Contributes to learning objective: 11

Assignment: Draft presentations

Nov 29: Institutional issues and power dynamics in the representation and sharing of quantitative models

Topics: Power dynamics across borders and sectors; visualization techniques that can make information more accessible across stakeholders; using XLRM techniques to support negotiations around strategies to increase water security

Contributes to learning objective: 4

Assignment: TBD

Dec 4: Preliminary presentation of Mara physical and social system models by students

Topics: Bringing socio-economic and political considerations into a systems model and/or the outputs that can be shared with stakeholders and policy makers

Contributes to learning objective: 10

Assignment: Draft presentations

Dec 6/Reading period: Final presentations of applied systems models

Contributes to learning objective: 11

Assignment: Final presentations

This schedule is subject to modification at the instructors’ discretion.