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Research and development for management of water resources: modernizing the teaching of water resources management

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Abstract

Research and development for management of water resources has become increasingly important with growing needs of economic development, scarcities even in developed countries, and global competitiveness that requires valuing water and other environmental resources much more than now and managing them efficiently. Sustainable development requires a good understanding of not only the traditional hydrology but also other fields such as ecology. With increasing complexity, the need for well-trained engineers and scientists in systems modelling and management with the knowledge of hydrological and environmental processes has increased. But, the cream-of-the crop students at universities are diverting to fields other than water resources such as information-related sciences and engineering. Market demands determine salary levels on which we have no control. On the other hand, students in today's computer and multimedia age can be attracted if the dynamism and the challenges of water resources and environmental problems are made accessible to them in an interesting manner. Making the study interesting without losing the time for imparting the academic necessities is an interesting pedagogical problem. Many of the challenging problems that we face in our field requires proficiency in mathematical modeling of various natural processes, numerical methods, optimization, uncertainty analysis, and computing, all used in the design of solutions. We share from our experiences at least one way to modernize the teaching of sustainable water resources management such that many necessary subjects can be taught in a reasonable time to the required depth, and will be useful for modern practices based on computers.

INTRODUCTION

A major objective of teaching is to make students motivated in a given subject that may even require lectures to have some "song and dance" without losing the academic content. There are two extremes that unfortunately do exist in our teaching and textbooks. One is teaching the subject in a dry manner without bringing to the student the excitement of various challenges, tools, and especially its applicability for solving real-world problems. The other extreme being the presentation of the subject in a superficial manner, even if it is interesting and practical, for example, using software packages that requires one to just input the required data and accept its output as "the" solution. The disadvantage of the first approach is turning away good students or at best providing mostly unmotivated students. The danger of the second approach is the shallow understanding a student attains of the methods and solutions even if the student has been happy about the study and is confident about solving problems. Here, we present an approach that hopefully has sufficient depth without sacrificing the characteristics that makes the study of hydrology and environmental systems interesting and challenging.

We found some simple rules to implement our vision: (i) maintaining modularity (decoupled and layered subject areas), (ii) providing the theory of practical methods motivated by a sample realistic problem, and (iii) case studies demonstrating the usefulness of the methods for real-world applications. Because of the large numerical computing required it is hard to teach without recourse to modern computing environments such as MATLAB®, MathCad®, and some other similar non-commercial tools. We use web based interactive learning, computing, and assessment wherever possible. We provide the major topics here and the discussion of the contents of some topics covered will be mentioned latter with examples: (1) Introduction to Systems approach, probabilistic analysis, numerical methods, optimization, and soft computing (based on fuzzy sets, neural networks and genetic algorithms) (2) Deterministic modeling and design (lumped systems and distributed systems), (3) Time-Series analysis, (4) Stochastic dynamic systems (extending Chapter 2 with stochastic information), (5) Data assimilation methods (combines data observations with models), (6) Design and management under uncertainty, (7) Reduced order methods for large scale systems, and (8) Case studies including in sustainable water and groundwater management, ecosystem analysis, and multimedia contaminant transport. Although the topics covered are many, depending upon the given curriculum (for example some include numerical analysis as a core subject and some don’t), the above material can be covered from 2 to 4 semester (each semester about 13 weeks long) courses. More importantly, the use of real (or realistic) problems and the modern graphics based computing methods is expected to keep the students’ interest high. We will also emphasize design, which enhances creativity and keeps the subject interesting. The tools also allow one to experiment and learn both about the problem and the intricacies of the methods thus help develop creativity. Rest of the paper is organized as follows. In the next section we describe first the content aspects especially with respect to the objective of modularization with two examples. The section following that will describe the various aspects of the presentation and then a section on possible courses and lastly the conclusion section.

MODULARIZATION

The use of modularization is to avoid reinventing the wheel and to increase the understanding of various subject areas. We assume that courses (and hence textbooks) that describe the physical or biological processes are separate from courses that are meant to teach modelling for design and management. This is the first assumption of our modularization and fortunately most curriculum today follow this layering. This layering assumes that hydrological processes has been already covered in the curriculum, that is, it is a bottom layer and the next layer on the top is the management layer on which we will concentrate in this paper. We give one example to show how we modularize the subject areas of modelling and management such that much can be done in a streamlined fashion in a shorter time than otherwise possible. Consider in our current curriculum the example of reservoir routing and channel routing using lumped models. A typical textbook may have the following aspects. It describes briefly the differential equation aspect of lumped models, the stage-discharge relationship, one method of routing, for example, the pulse method that is amenable for hand computing, and one computer method such as the Runge-Kutta method. When moving to the section on river routing, the concentration is more on parameter estimation using inflows and outflows of a river reach using say the Muskingum routing. Lastly the Nash model which models the catchment as a cascade of linear reservoirs and a parameter estimation method using the moment method (which is again amenable for hand calculations) and a brief discussion on models that can be used to analyse both parallel and serial combinations of reservoirs and channels. This approach was developed during the days when hand computing was the only calculating method and little understanding existed among engineers of the intricacies of the numerical method. Rarely are these two limitations justifiable today although, increasing the understanding of numerical methods among engineers is an ongoing task and may require some rethinking on the entire engineering curriculum.

Let us discuss in detail how to modularize and improve the contents with regard to the lumped routing models. In most textbooks, in spite of the introduction to the general structure of lumped routing models, that is, the aspect of the continuity equation defined by a differential equation and the stage-discharge described by an algebraic equation, the solution methods have been presented as if they are meant for either reservoir routing and flow routing. The limitations of the solutions method whether it is the pulse method, which is nothing but a trapezoidal method for solving ordinary differential equations or the Runge-Kutta method, are rarely discussed. This of course can be justified due to lack of time. However, the Runge-Kutta method has been developed at least two times in the book, one for the lumped routing and again for the distributed routing which is a waste of time. Therefore, the numerical methods for solving differential equations can be easily moved into a separate module with clear discussions on various methods and their limitations. These are methods that are applicable wherever they are needed, whether it is reservoir routing, channel routing, distributed routing, water quality modelling, ecological modelling, etc.

Secondly, the parameter estimation in these various methods is done in a similar fashion where the common thread is hand calculations. That is, for example, trial and error methods are used for estimating the parameters of the Muskingum model and a moment method for the Nash cascade model. Although both these methods are still valid there are general parameter estimation methods, for example, based on minimizing the sum of normed deviations that are much more suitable for today's computer based office. Once again, in our presentation, we completely remove parameter estimation methods from the presentation of the lumped models, as it has been dealt in other areas as part of numerical methods. This modularization once again helps in reducing redundancy and gives sufficient space to deal with parameter estimation in some detail.

Lastly, the section on parallel and serial network of reservoirs and channels is left weak, a section which is practical and interesting as it is useful for designing, for example, storm water detention systems. On the other hand, to compensate for this, a chapter or a section on some canned software package is given where the emphasis is mainly on explaining the inputs required and some options of the package. Most often the students are taught to use this as a black box. Some of these software packages are hardly updated with current knowledge mainly because of the difficulty one faces in modifying software developed some time ago in an old programming language and dubious software engineering practices. In our presentation, we avoid using canned software and use the knowledge of the student in lumped systems and numerical methods to directly solve this problem. The details of this practice will be explained in the next section. The advantage of this method is the openness and the generality of the methods used to solve design problems, a practice that can be useful for extending this method to other problems as well, for example, water quality modelling (the canned package mentioned above can't do that), ecological modelling etc. without needing to reinvent a solution method every time a new problem is faced. So far we described one example of modularization in the case of lumped deterministic models. Next we will discuss how we modularized with respect to uncertainty issues.

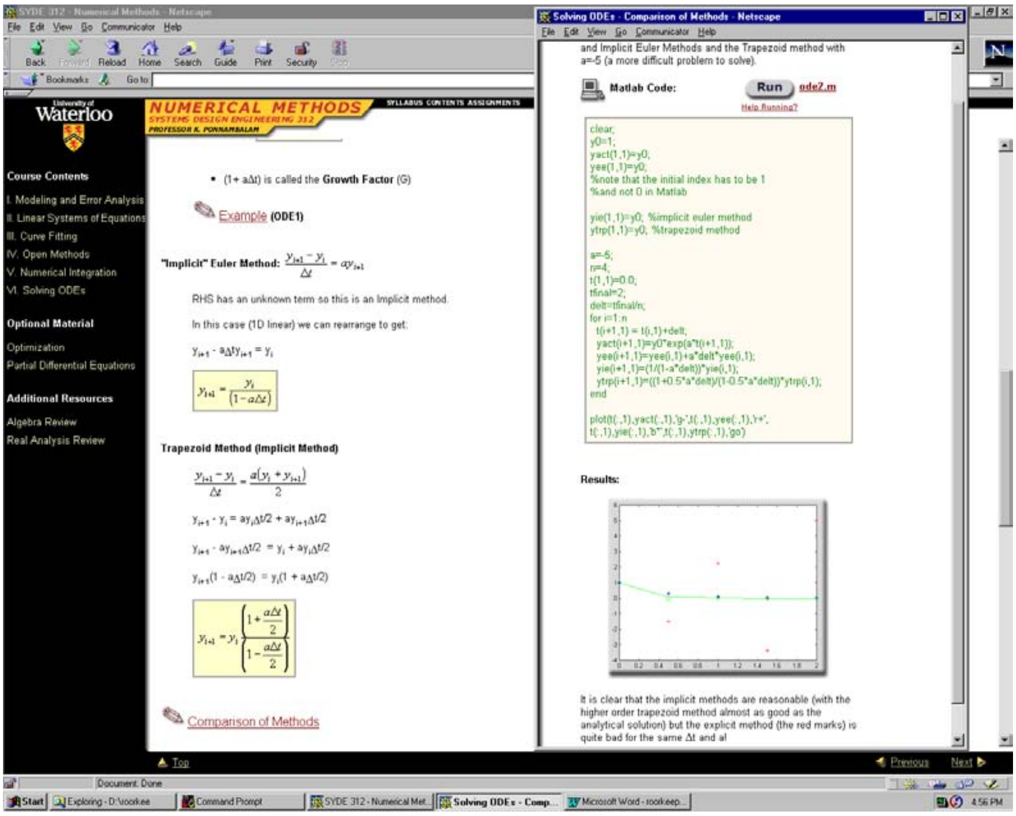
Uncertainty generally means either a variable is stochastic or it is non-crisp (may belong to a fuzzy set) or both. We have kept these two issues separate although there are case studies and example problems where both are used. The fuzzy set theory and its application are discussed in the chapter on numerical methods while the stochastic issues are discussed in three different places where they are appropriate. The introduction section with probabilistic analysis gives a firm background on random variables, statistics, probability distributions, derived distributions, Taylor series based methods for estimating approximate probabilities of functions of random variables and Monte-Carlo simulation. However, the purely and rather staid subject of data analysis of stochastic time series is relegated to a stand-alone chapter on Time-Series analysis. More importantly, the subject of stochastic differential equations involving Ito Calculus is treated separately to give sufficient depth to this somewhat less known field. The major objective of this chapter is to add stochastic information to already known lumped and distributed deterministic systems and to derive their (often numerical only) solutions. The advantages are: (i) algebraic problems with stochastic information is treated by methods in the introduction section, (ii) problems of modelling time-series that do not consider inherent models, whether it be rainfall, evaporation, water quality, is considered in the Time-Series section, and lastly (iii) any differential equation (whether it be in groundwater, water quality or ecology) affected by stochastic uncertainty is considered in the section on stochastic dynamical systems. Uncertainty modelling is also considered in three advanced sections, namely, the section on data assimilation where data observations (often real-time) must be combined with stochastic dynamic models, the section on design and management under uncertainty which combines stochastic modelling with optimization and, lastly, the section on reduced order systems which is an advanced section on reducing the size of the problem solved when considering uncertainty. Because of the modularization we are able to provide a wealth of modern practices in uncertainty modelling and design in a single place without making it too hard to learn. In the next section we will describe our presentation methods where we strive to make the subject easy to learn, interesting, and practical.

PRESENTATION

Students of today have been exposed to computers quite early in their lives. Also, students have seen educational television, much of which is entertaining. In addition, knowledge of real world problems in water and environment is not uncommon due to accessibility to international media. Recently, Internet and web knowledge has also permeated into their day-to-day activities. As mentioned before, the other objective of making the study exciting and modern can be attempted using multimedia devices. We have so far not used any television-based activities, which is good media to bring descriptions of the real-world problems to the class. However, much of our presentation depends on interactive computing including some that are web based. Additional advantage of our presentation is the ability to continually update the writing, lecture notes, and support tools without much difficulty. We will take an excerpt from our presentation that corresponds to the use of multiple components (reservoirs and channels, here) to solve a design problem that one faces often in the practice of urban hydrology, namely, the storm water detention system.

Please refer to the excerpt of Ponnambalam, et al., (2000) in Appendix 1. Because of the modularization, the use of tools such as MATLAB®, equations (models) in standard forms, and well developed numerical methods a reasonably complicated problem reflecting a real-world situation can be solved in an elective level course. The excerpt (some output is not shown here for lack of space) is interactive, that is, while the student reads a text, it is possible to both see the actual computational results as well as experiment with the hyperlinked program that produced the results. Moreover, for easier understanding and modification, the programs are also modularized corresponding to the modules in the solution method. For example, note the software architecture with brief descriptions of the five programs maexdes2, constr, optides2, des2eu, and trinf (with hyperlinks) are shown in a side box for easy access. The program constr is a MATLAB® toolbox program and is often used in the text but is explained in MATLAB®. The rest of the programs that we developed are completely open and corresponds directly with the models and hence can be used to augment the understanding of the mathematics in the models. Therefore, this not a black box approach which we discourage. Experimentation is encouraged and easy to do and furthers the understanding of the problem and the design. Lastly, the experimentation that is impractical by hand calculations is possible with computers making the whole study interesting and allow the students to create their own solutions for any given problem.

While the excerpt in Appendix 1 presents the interactive electronic book, the example in Figure 1 shows how blackboard lecturing can be complimented with Web based interactive notes. Again, for lack of space, we provide just one screen shot with much information but the student can choose and switch between various screens and keep the amount of information under control. Web based interactive notes are similar to blackboard notes, that is, it does not have all the explanations one finds in the electronic book, and is mainly catered towards tutorials, assignment completions, and web based assessment. The MATLAB ® code essentially reflects the openness of our approach, that is, the programs that implement the equations are completely accessible and hence is useful for understanding the mathematics. In addition to learning various subjects, the student is also a given similar exposure to Case Studies of real-world problems thus imparting much confidence in their ability to solve such problems.



- (1+ aΔt) is called the **Growth Factor** (G)

Example **(ODE1)**

"Implicit" Euler Method: $\frac{y_{i+1} - y_i}{\Delta t} = a y_{i+1}$

RHS has an unknown term so this is an Implicit method.

In this case (1D linear) we can rearrange to get:

$y_{i+1} - a\Delta t y_{i+1} = y_i$

$$\boxed{y_{i+1} = \frac{y_i}{(1 - a\Delta t)}}$$

Trapezoid Method (Implicit Method)

$$\frac{y_{i+1} - y_i}{\Delta t} = \frac{a(y_i + y_{i+1})}{2}$$

$y_{i+1} - y_i = a y_i \Delta t/2 + a y_{i+1} \Delta t/2$

$y_{i+1} - a y_{i+1} \Delta t/2 = y_i + a y_i \Delta t/2$

$y_{i+1}(1 - a\Delta t/2) = y_i(1 + a\Delta t/2)$

$$\boxed{y_{i+1} = y_i \frac{\left(1 + \frac{a\Delta t}{2}\right)}{\left(1 - \frac{a\Delta t}{2}\right)}}$$

Comparison of Methods

and Implicit Euler Methods and the Trapezoid method with a=-5 (a more difficult problem to solve).

```
clear;
y0=1;
yact(1,1)=y0;
yee(1,1)=y0;
%note that the initial index has to be 1
%and not 0 in Matlab

yie(1,1)=y0; %implicit euler method
ytrp(1,1)=y0; %trapezoid method

a=-5;
n=4;
t(1,1)=0.0;
tfinal=2;
delt=tfinal/n;
for i=1:n
  t(i+1,1) = t(i,1)+delt;
  yact(i+1,1)=y0*exp(a*t(i+1,1));
  yee(i+1,1)=yee(i,1)+a*delt*yee(i,1);
  yie(i+1,1)=(1/(1-a*delt))*yie(i,1);
  ytrp(i+1,1)=((1+0.5*a*delt)/(1-0.5*a*delt))*ytrp(i,1);
end

plot(t(:,1),yact(:,1),'g-',t(:,1),yee(:,1),'r+',
t(:,1),yie(:,1),'b*',t(:,1),ytrp(:,1),'go')
```

It is clear that the implicit methods are reasonable (with the higher order trapezoid method almost as good as the analytical solution) but the explicit method (the red marks) is quite bad for the same Δt and a!

Figure 1. A screen shot from a web based presentation.

In some engineering programs such as electrical engineering, software engineering, and mechanical engineering it is possible to have many courses which emphasize design bringing out the creativity in students. Students can design and produce their products in a lab or workshop and attain almost instant gratification. But it is hard to replicate that in water resources mainly because of the impracticality of designing small systems. However, computer models and solutions simulate the real-world situation quite well and that is what we advantage of in our presentation. Moreover, elective courses from third year (pre-final) onwards and in the post graduate programs should have at least a minimum of 50% grade allocated to course projects. Typical examinations of about 3 hours long are hardly a place where one can test the creativity of a student. Group projects are also encouraged wherever it is practical and brings out the real-world working atmosphere. In the next section, possible courses for a program in water resources management is presented.

SAMPLE COURSES

We are assuming that a typical undergraduate program with specialization in water resources management will have about 5 elective courses two of which will be processes related courses (for example, one for surface and another for subsurface processes) and here we will not deal with the details of such courses. We present in Table 1 sample syllabi for 3 courses relating to water resources management and also a syllabus for an advanced course at the post graduate level. All include relevant motivational chapters and one or two case studies and is not shown in the table. The names of the various topics we mention can be found in Appendix 2 outlining Ponnambalam, et al. (2000). Each of the courses is approximately 12 to 14 weeks long and can be modified to suit one's own program. Each week is assumed to have 3 hours of lecturing and at least 1 hour of tutorial/computer lab. Students are expected to work up to 10 hours per week outside the class times. These are standard expectations at University of Waterloo's engineering faculty.

Table 1. Sample courses

Course Name	Sections
Deterministic Modelling and Optimization	1.2, 1.4, 1.5, and 1.6; 3.2 and 3.3
Stochastic Modelling and Data Assimilation	1.2, and 1.3; 4.2 and 4.3; 5.2, 5.3 and 5.4
Design under Uncertainty	1.2, 1.3, and 1.6; 6.2, 6.3, and 6.4
Advanced Water Resources Management	1.7; 2.2, 2.3, 2.4 and 2.5; 7.2 and 7.3

At the post graduate level additional courses are expected to be available in remote sensing, geographical information systems, distributed computing, global climate modelling, life cycle analysis and sustainable development, among others.

CONCLUSION

Modernizing a curriculum and the methods of teaching and writing textbooks is an ongoing process. Many computer-based tools are available today for teaching water resources management. The use of these modern tools is also expected to make the study of water resources and management interesting, relevant, and practical. In addition to modernizing the presentation we also suggest updating the syllabi especially in numerical methods, stochastic modelling and optimization. To cover much needed but potentially a large number of subject areas it is necessary to modularize the various topics to avoid repetitions and give us sufficient time. One such arrangement and some possible courses are presented in this paper to start this important discussion.

REFERENCES

Ponnambalam, K., S. Fletcher, and A.W. Heemink, 2000. Design and Management of Water Resources and Environmental Management: A Unified Methodology with Case Studies, Department of Systems Design Engineering, University of Waterloo, Waterloo, Canada.

APPENDIX - 1

AN EXCERPT FROM PONNAMBALAM ET AL. (2000)

Example 3.4 - Designing a Reservoir-Channel Network: Recall Example 3.2. The peak outflow was reduced to 250 cfs using a reservoir whose maximum level raised to about 12.7 ft. In this example the sample problem will be solved using two reservoirs in series with a channel of fixed characteristics (K=2, X=.05) connecting the reservoirs where the reservoir outflow is given by equation (6) and in equation (10) with C=.6. The cost functions are given next:

Cost function for the upstream reservoir:

$$c(h_1) = \begin{cases} 0, h_1 < 5 \\ 3000h_1, h_1 \geq 5 \end{cases}$$

Cost function for the downstream reservoir:

$$c(h_3) = \begin{cases} 0, h_3 < 7 \\ 5000h_3, h_3 \geq 7 \end{cases}$$

In the above cost function the height h_i corresponds to the maximum height (height corresponding to maximum storage) and the cost of channel is ignored. The objective of the design is to minimize the total cost of construction subject to meeting the peak outflow at the down stream reservoir to be less than 250 cfs.

Because of the way we have formulated both the channel routing and the reservoir routing problem in ***Standard Form I***, the above problem can be solved using the following equations (9) and (10) where equations (9) define the differential part and equations (10) define the algebraic part [See also 3.1.3.1]. The equations solved were

$$\begin{aligned} \frac{ds_1}{dt} &= I - O_1 \\ \frac{ds_2}{dt} &= O_1 - O_2 \\ \frac{ds_3}{dt} &= O_2 - O_3 \end{aligned} \tag{9}$$

Equation (9) defines the three differential equations that model the storages in each of the components of the system, namely, upstream reservoir, channel, and downstream reservoir, respectively. The variable I refers to the triangular hydrograph, and the variables O_i refers to the outflows from the three respective components. Because the components are connected in series, outflow from the upstream component is the inflow for the downstream component [See Exercise 3.3 for an alternative design with parallel reservoirs] .

Note that the net input should be in correct units and hence, in the Matlab programs, you will see conversion factors wherever necessary. The outflow functions are given as

$$
\begin{aligned}
&O_1 = CL_1(s_1/43560)^{3/2} \\
&O_2 = as_2 - bO_1, a = \frac{1}{K(1-X)}, b = \frac{X}{1-X} \qquad (10) \\
&O_3 = CL_3(s_3/43560)^{3/2}
\end{aligned}
$$

The initial conditions are assumed as [0 200 0] for the three components, respectively [Why not [0 0 0]?]. To get the head (or storage level) simply divide the storage of the reservoir by 43560. The optimization problem formulated as a nonlinear programming problem (see 1.5.2.3)solved was

$$
\min_{L_1,L_3} c(h_1) + c(h_3)
$$

$$
\begin{aligned}
&\textit{Subject to}: \\
&\max(O_3) \le 250
\end{aligned}
$$

where the peak storage levels h_1 and h_2 and peak outflow O_3 are given by solving equations (9) and (10) with the given initial conditions and parameter values for C, K, and X. The optimal results obtained (for a starting guess of L_1=L_3=10) were L_1=69.1679 ft and L_3=22.5191 ft for K=2 and x = .05 with an optimal cost of 0 and the optimal h_1 and h_3 are 3.97 ft and 6.99 ft respectively. The maximum reservoir height of both reservoirs are much smaller than the 12 ft [Recall: L = 9.18 ft] obtained in the single reservoir design problem above. But this came with longer spillways [No Free Lunch!]. The corresponding Matlab programs are maexdes2.m, optides2.m optdes2.m and optdes2f.m. With this example, you can see the advantage of formulating the reservoir and channel routing in a standard manner (equations 9 and 10) that facilitate the use of other ready to use packages for solving differential equations and optimization quite easily. Note that this problem has at least one another optimal solution (meaning 0 cost!) which corresponds to L_1=48.3284 and L_3=24.5446 that can be obtained with a different starting guess!

maexdes2
|
constr
|
optides2
|
des2eu
|
trinf

maexdes2- main program sets initial solution and calls the optimization solver.
optides2 - formulates the objective function and constraint and calls des2eu which solves equations 9 and 10.
trinf - returns a triangular inflow (data).

APPENDIX - 2

TOPICS AND TIME REQUIREMENTS

Introduction (14 weeks)

Motivation
Systems Approach (1 week)
Probabilistic Analysis (3 weeks)
Numerical Methods (3 weeks)
Sensitivity Analysis (1 week)
Optimization (3 weeks)
Soft Computing (3 weeks)

Analysis of Time Series of Data (4 weeks)

Motivation
Hydrologic Time Series of Data as Stochastic Processes (1 week)
Time Series Modeling Principles (1 week)
Multisite ARMA models (1 week)
Synthetic generation of time series for simulation studies (1 week)

Deterministic Modelling and Design (4 weeks)

Motivation
Lumped Input-Output Model (2 weeks)
Distributed Models (2 weeks)

Stochastic Dynamic Systems (6 weeks)

Motivation
Lumped Models (4 weeks)
Distributed Models (2 weeks)

Data Assimilation Methods (4 weeks)

Motivation
Parameter estimation (1 week)
Kalman Filtering (2 weeks)
Parameter estimation in stochastic systems (1 week)

Design and Management under Uncertainty (5 weeks)

Motivation
Stochastic Programming and Chance-Constrained Methods (2 weeks)
Approximation Methods (2 weeks)
Stochastic Dynamic Programming (1 week)

Reduced Order Methods for Large Scale Systems (5 weeks)

Motivation
Data Assimilation (3 weeks)
Aggregation-Decomposition in Optimization (2 weeks)

Case Studies (4 weeks)

Surface Water Management
Groundwater Management

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