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KEYNOTE

Developing complex environmental modelling skills through project-centric teaching

H.R. Maier [a]

[a] *School of Architecture and Civil Engineering, The University of Adelaide, Adelaide, South Australia*
Email: holger.maier@adelaide.edu.au

Abstract: The use of models to support decision-making is becoming increasingly common in all areas of environmental and natural resources management. However, in many instances, model users are not familiar with modelling basics, potentially leading to misleading and even perverse outcomes. Consequently, there is a need to increase "model literacy" across a range of disciplines. A key to achieving this successfully is to provide an environment that enables students to acquire the relevant skills in a motivating and engaging context, which can be a challenge when dealing with a topic that can be relatively "dry" and complex.

In this paper, details of a course are presented that has been developed and refined over the last 20 years with the goal of enabling students to obtain a deep and nuanced understanding of fundamental modelling principles and how to use models to support decision making in uncertain environments. This is achieved by adopting a project-centric approach that enables students to explore relevant issues in an immersive and engaging environment.

The setting for the project is a river system that is subject to effluent inflows from wastewater treatment plants, as well as inflows of saline groundwater. Models for both of these water quality parameters are needed to quantify the impact of climate change and population growth on dissolved oxygen and corresponding fish health, which are affected by the effluent inflows, as well as salinity and corresponding crop yields and profits. These models are developed in the first two stages of the project, covering a range of fundamental issues associated with model specification, calibration and validation. In the third stage, the dissolved oxygen and salinity models developed in the previous stages are used to assess the impact of climate change on fish health and agricultural productivity and to identify the most suitable mitigation strategies in the form of wastewater treatment and salt interception. Multi-objective optimisation is used to identify the strategies that provide the best trade-offs between reliability, vulnerability and cost and multi-criteria decision analysis is used to identify the solution that provides the best compromise based on stakeholder preferences (Figure 1).

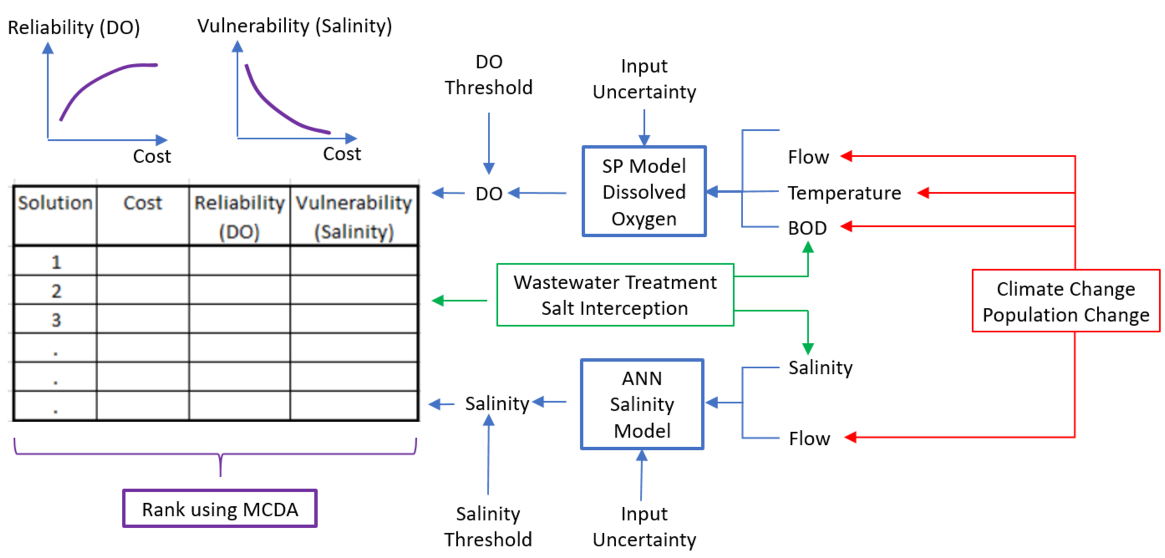

Figure 1. Overview of project

Keywords: *Integrated modelling, integrated assessment frameworks, conceptual model*

1. INTRODUCTION

The use of models to support decision-making is becoming increasingly common in all areas of environmental and natural resources management. However, in many instances, model users are not familiar with modelling basics, potentially leading to misleading and even perverse outcomes. Consequently, there is a need to increase "model literacy" across a range of disciplines. A key to achieving this successfully is to provide an environment that enables students to acquire the relevant skills in a motivating and engaging context, which can be a challenge when dealing with a topic that can be relatively "dry" and complex. This paper introduces a project-centric, "flipped classroom" approach that has been developed and refined in the Environmental Engineering degree at the University of Adelaide, Australia, for the last 23 years. The course is offered to both undergraduate and postgraduate students.

2. TEACHING APPROACH AND COURSE OVERVIEW

2.1. Teaching Approach

In order to provide context and engage students in their learning from the outset, the course is centred on a realistic project that runs throughout entire course (Figure 2). The project is designed carefully so that it achieves all learning objectives, but does so in a way that is realistic and motivating. The relevant theory needed to complete the project and guidance on how to tackle the project are provided throughout the course via a series of online learning units and modules (Figure 2). By providing relevant theory in the context of the project, students are much more open to receive it. In order to provide students with the opportunity to check whether they have understood all key theoretical concepts, online quizzes are aligned with each theory online learning module. This "flipped classroom" approach is based on Maier (2008) and caters to detailed face-to-face interactions in project design sessions, while also enabling the course to be completed solely online.

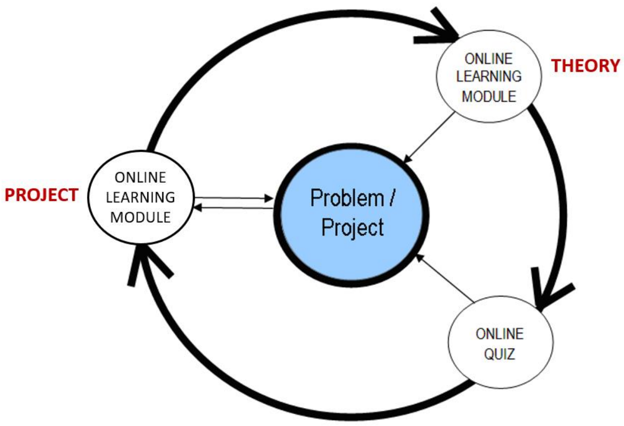

Figure 2. Project-centric approach to teaching (adapted from Maier (2008))

2.2. Project

2.2.1 Overview

The project is centred on the management of the stretch of a fictitious, but realistic, river system (the Williams River) (Figure 3). The river is used as a source of water by irrigators and for domestic and industrial uses in the city of Williamsburg. In addition, it is home to a number of native species of fish, which are considered to be of high ecological value. The stretch of the river of interest is subject to a number of water quality issues, including:

<u>Low levels of dissolved oxygen (DO):</u> There are discharge points for various Wastewater Treatment Plants (WWTPs) that serve a number of townships along the length of the river (Figure 3). This reduces levels of DO, which threatens native fish and invertebrates, can mobilise heavy metals from sediments, can have an impact on recreational water users and increases water treatment costs. The underlying physical processes are well understood and the decay of carbonaceous biochemical oxygen demand (CBOD) and re-aeration are the only processes to significantly impact DO concentrations in the main river channel.

<u>High levels of salinity:</u> There are large inflows of saline groundwater at the start of Reach 12 (Figure 3). The resulting increased levels of salinity at the point where water is extracted to supplement (i) the water supply for Williamsburg and (ii) the irrigation district adjacent to Williamsburg at the end of Reach 12 are the cause of economic losses for domestic, industrial and agricultural water users. The processes affecting salinity concentrations in Reach 12 are not well understood.

The above water quality impacts are projected to become worse as a result of climate and population changes, as these are likely to (i) decrease flow and increase temperature in the river, and (ii) increase domestic,

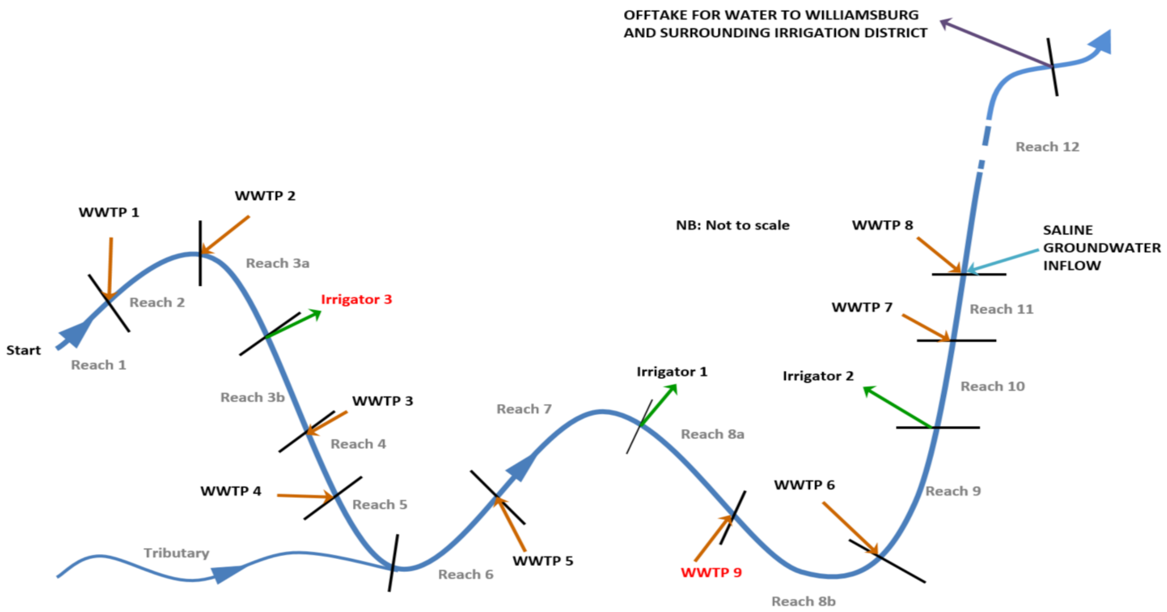

Figure 3. Layout of fictitious Williams River case study

industrial and agricultural water demand and the discharge from the WWTPs (Figure 4). In order to enable this impact to be quantified and the most appropriate responses to be identified, there is a need to develop models that enable the impact of different levels of discharges from the WWTPs on DO levels along the length of the stretch of interest, and the impact of different levels of the saline groundwater inflows on salinity levels at the point where water is extracted for Williamsburg and the surrounding irrigation district (i.e. at the end of Reach 12), to be modelled.

2.2.2 Stages 1 and 2

The development and critical discussion of the DO and salinity models is the focus of the first two stages of the project (Figure 4), including their specification, calibration and validation. As the processes affecting DO are well-understood, DO levels along the length of the river are modelled with the aid of a process-driven, 1-D Streeter-Phelps (SP) model. In contrast, as the processes affecting salinity concentrations in Reach 12 are not well understood, they are modelled with the aid of a data-driven, multi-layer perceptron (MLP) artificial neural network (ANN) model. The use of modelling approaches that have very different conceptual bases enables students to gain a nuanced understanding of which steps of the model development process are generic and which are specific to different modelling approaches. The model development exercises are scaffolded to enable students to explore a number of fundamental model development issues in an experiential manner (Figure 5). Some of these issues include:

- <u>Selection of suitable model type and structure</u>: The use of different modelling approaches enables students to gain a detailed understanding of the relative advantages and disadvantages of the different

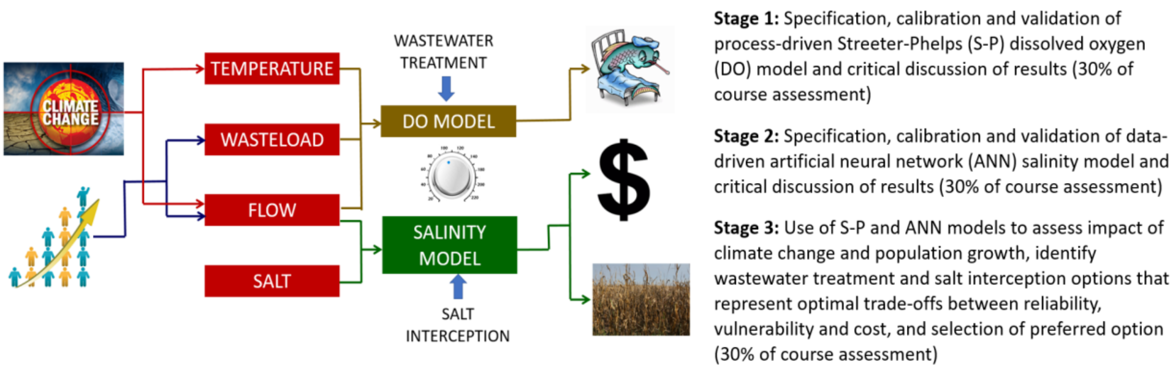

Figure 4. Details of different stages of the project that runs for the duration of the course

approaches. In addition, as the structure of the ANN model is unknown, students gain experience in selecting the most appropriate model structure and potential trade-offs between minimising model error and increasing model complexity.

- <u>Consideration of the properties of the error surface</u>: Conceptualisation of model calibration as the identification of the set of model parameters that corresponds to the lowest point on the error surface (i.e. the *n*-dimensional relationship between changes in the *n* model parameters values determined via calibration and the corresponding value of the selected error metric) enables students to gain a fundamental understanding of the nature of the model calibration process. Students explore methods for gaining an understanding of the properties of the error surface (e.g. degree of roughness, number of local optima) and how these are affected by model type (e.g. S-P or ANN model), model dimensionality (e.g. ANN models with different numbers of hidden nodes) and choice of error metric, calibration data and permissible parameter ranges. This also enables students to explore the issue of parameter identifiability (e.g. equifinality). In addition, students are able to explore how well optimisation algorithms with different explorative / exploitative capacities (i.e. gradient-based methods and evolutionary algorithms) are able to calibrate models with error surfaces with different properties (Figure 5).

- <u>Checking the degree to which the relationship in the data has been captured by the model</u>: Checking model replicative validity enables students to gain an understanding that residual analysis is an important component of model validation and that the methods used are independent of model type.

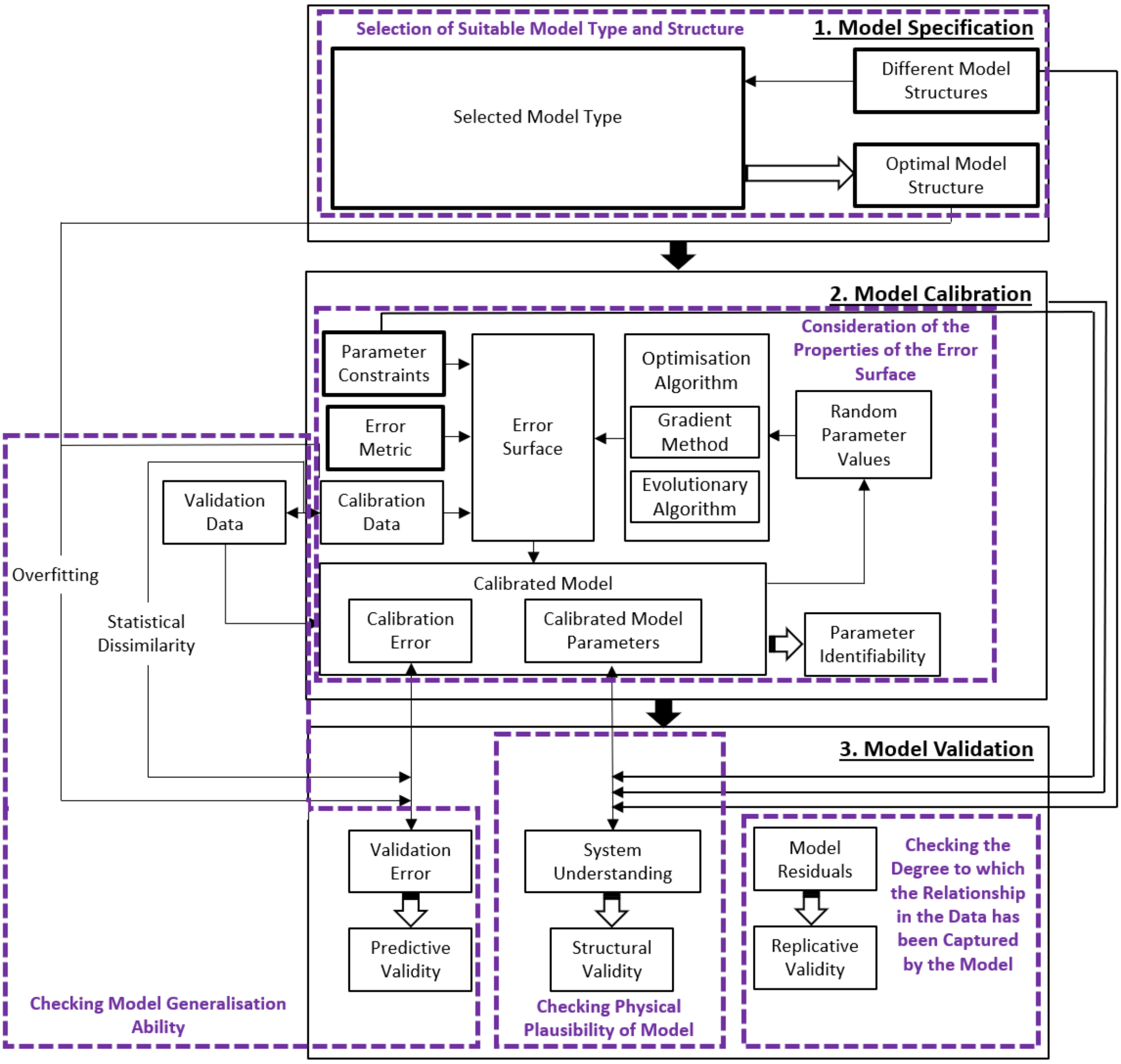

Figure 5. Model development issues explored in stages 1 and 2 of the project

- Checking the physical plausibility of the model: Checking model structural validity enables students to gain an appreciation that the model parameters that correspond to the smallest error during calibration do not necessarily result in the most appropriate model and that there are potential trade-offs between the mathematical optimality of the calibration process and the physical plausibility of the model. The same applies to the selection of an appropriate model structure. This enables students to explore the interplay between data (availability, representation, errors), model complexity, parameter ranges and physical plausibility. Students are also exposed to differences in the methods used to check the physical plausibility of process-driven models, where model parameters have a direct physical interpretation, and those used to check the physical plausibility of data-driven models, where individual model parameters do not have a direct physical meaning.

- Checking model generalisation ability: Checking model predictive validity enables students to gain an appreciation that the process for checking whether a model is predictively valid is identical for different model types. Students also have the opportunity to explore potential causes for any discrepancies between errors on the calibration and validation data. This includes checking the two data sets for statistical dissimilarities, raising awareness about the importance of using appropriate data splitting approaches, and ensuring overfitting to the calibration data has not occurred, which can be a particular problem for artificial neural networks and similar models.

2.2.3 Stage 3

In Stage 3 of the project, the models developed in Stages 1 and 2 are used to quantify the impact of climate and population change on dissolved oxygen, and hence fish health, as well as salinity, and hence crop yields and corresponding profits (Figure 4). In addition, students incorporate uncertainty into the models to enable risk-based performance criteria, including reliability and vulnerability, to be quantified.

Following the impact assessment, students identify the most suitable mitigation strategy, considering different treatment levels at the nine WWTPs to increase DO levels and different numbers of salt interception bores in reach 12 to reduce salinity levels. This involves the use of multi-objective optimisation to determine the combinations of treatment levels at the WWTPs and number of salt interception bores in reach 12 that result in the best trade-offs between reliability, vulnerability and cost (Figure 1). Finally, multi-criteria decision analysis is used to select the preferred mitigation strategy based on stakeholder preferences (Figure 1).

2.2.4 Model Implementation

In order to enable students to focus on the exploration of the various modelling and management issues mentioned in Sections 2.2.2 and 2.2.3, all modelling activities are performed in Microsoft Excel, with all models made available to students. Students have to enter relevant data and information from the design brief and provided data files, but diagnostic tools and plots of key results (e.g. DO profile along the length of the river for the S-P model, model residual plots, relationship between the number of Monte-Carlo samples and the resulting histogram of the generated variable and the corresponding values of reliability and vulnerability) are included in the model spreadsheets provided to students.

The use of MS Excel as the modelling platform directs student focus on the fundamental modelling issues being explored (i.e. looking “under the hood” of models), rather than how they “look from the outside” or how they are developed. The fact that a S-P DO model and an ANN salinity model can all be implemented easily in MS Excel, without the use of Macros, sends a powerful message, as does the fact that the mechanics of calibration (i.e. minimising the cell that contains the model error value by changing the cells that contain the parameter values using the Solver add-in in MS Excel) are exactly the same for the two different models, even though they are conceptually very different.

Although the optimisation algorithms in Solver are fairly simple and computationally inefficient, they enable students to explore the relative ability of different classes of algorithms to solve optimisation problems with different characteristics. The fact that optimisation is used in different contexts (i.e. for model calibration (stages 1 and 2) and identifying mitigation strategies that represent optimal trade-offs between competing objectives (stage 3)) also assists students with generalising the way optimisation problems are formulated and solved.

2.2.5 Assessment

The submissions for the three stages of the project each contribute 30% towards the final course mark (Figure 4), with the remaining 10% corresponding to the online quizzes that accompany the online modules on the underlying theory (see Section 2.3). Each submission requires students to answer a series of questions related to the various fundamental modelling / management issues explored (see Sections 2.2.2 and 2.2.3). Example questions for the calibration component of Stage 1, the development of the S-P DO model, are given in Figure 6a. The corresponding marking rubric, which is the same for all three stages of the project, is shown in Figure 6b, which is based on the SOLO (Structure of Observed Learning Outcomes) taxonomy (Biggs and Collis, 1982). As can be seen, a pass corresponds to a description of the results, a credit to an explanation and critical discussion of the results, a distinction to the use of additional / higher order analysis to gain a deeper understanding of the underlying concepts and a high distinction to the use of external sources to support critical discussion to enable the generality of the results to be established.

Example Questions, Stage 1, Calibration of S-P DO Model:

1. Calibrate DO Model (Unconstrained)
- Which starting positions did you select in parameter space and why? Please think about how the starting positions cover the parameter space (e.g. maximum and minimum values, values in-between these extreme values) and therefore their ability to assist you with finding out what the properties of the error surface are.
- What do the results tell you about the properties of the error surface?
- Do the calibrated values of the parameters make physical sense?

2. Calibrate DO Model (Constrained)
- Which constraints did you place on the decision variables and why?
- What are the trade-offs between model error and the physical realism of the calibrated model parameters?

3. Check Impact of Different Error (Objective) Functions
- What is the impact of the two different objective functions used on the characteristics of the error surface?

(a)

	FAIL < 50%	PASS 50-64%	CREDIT 65-74%	DISTINCTION 75-84%	HIGH DISTINCTION 85-100%
Written Responses and Supporting Material	Appropriate figures and tables in supporting information, but lack of description OR Incomplete / inappropriate supporting information	Comprehensive, coherent presentation and description of all required findings, clearly linked to and backed up by supporting information	As Pass PLUS: Comprehensive, coherent explanation and critical discussion of findings, clearly linked to and backed up by supporting information	As Credit PLUS: Use of additional / higher order analysis to support critical discussion of appropriate results to demonstrate deeper understanding of and greater insight into the topic	As Distinction PLUS: Use of external sources to support critical discussion of appropriate results and to demonstrate ability to consider results in the broader context of the discipline, beyond the scope of the current project

(b)

Figure 6. Details of (a) example questions and (b) the assessment rubric for written project responses

2.3. Learning Units, Online Modules and Quizzes

Online modules are provided for all project tasks (Figure 7) and broader learning units are provided for the relevant theory, which typically include online modules (see Maier, 2008b), lecture notes, industry guest lectures (see Maier, 2009) and online quizzes (Figure 8). This enables students to work on the projects at their own pace, reserving face-to-face interaction for exploring issues associated with completing the project.

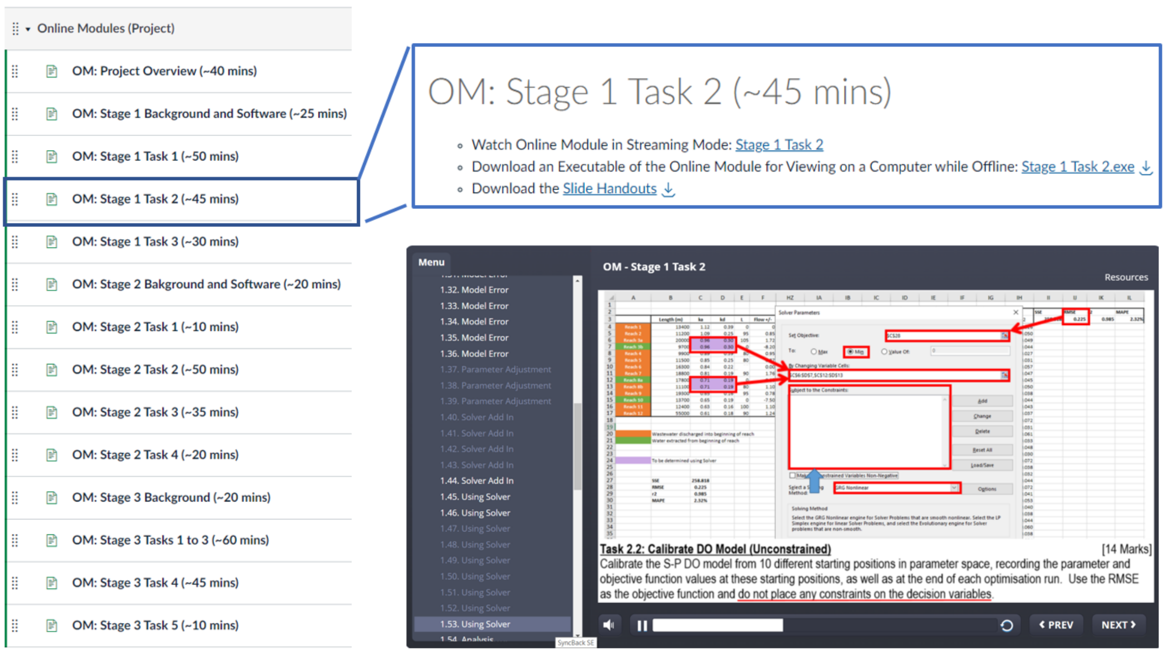

Figure 7. Typical details and layout of project online modules in the online learning management system

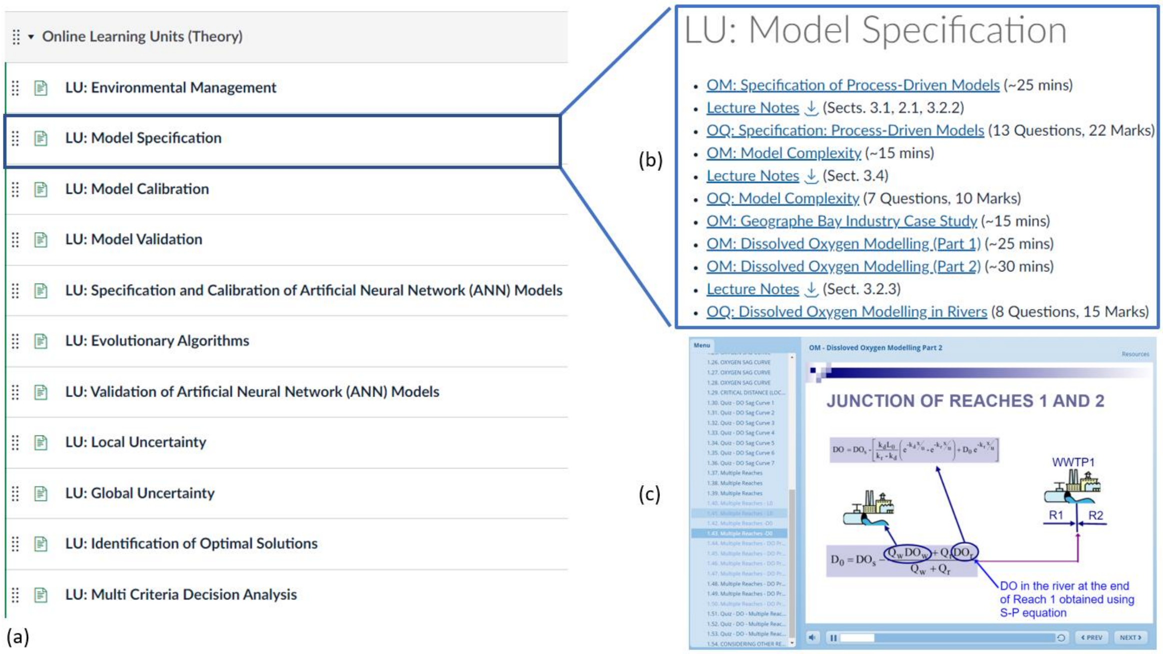

Figure 8. Typical details of layout and format of online learning units in learning management system including (a) list of learning units, (b) layout and content of an example learning unit and (c) example of typical online module that forms part of a learning unit

3. CONCLUSIONS

The use of models is increasing in prevalence, which is a trend that is likely to continue into the future with an increase in system complexity and the ready availability of data and information, as well as an increasing need for transparency and evidence-based decision-making. However, many users of models lack a basic understanding of modelling fundamentals, which increases the chances of the mis-use of models and that decisions are made based on on misleading or incorrect information. This paper presents details of a course that has been developed and refined over more than 20 years to increase basic “model literacy” by engaging students in an immersive, problem-based learning experience. This provides students with the opportunity to explore relatively sophisticated modelling principles in an authentic context, enabling them to develop a high level of model literacy through experiential learning.

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