Book Review: “*Effective Parameters of Hydrogeological Models*” May Lead Readers Safely Through the Deep Waters of Uncertainty

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Hydrogeological models are useful tools for understanding complex interactions in hydrogeological systems. Obtaining quantitative hydrogeological predictions allows one to make data-driven decisions. Models have become a widely used tool to deal with various practical and theoretical problems in hydrogeology; however, the difficulty of measuring aquifer properties and the complexity of hydrogeological systems indicate that data measurements and model predictions are subject to significant uncertainty. The second edition of “*Effective Parameters of Hydrogeological Models*” by Vikenti Gorokhovski (2014) (Springer Hydrogeology Series, Hardback ISBN 978-3-319-03568-0, eBook ISBN 978-3-319-03569-7) is an excellent introduction to hydrogeological models and the variety of methods to treat uncertainty surrounding models. The book contains 11 chapters, 68 illustrations with 35 in color. This book is part of the Springer Hydrogeology Series, which seeks to publish a broad portfolio of scientific books for researchers, students, and others interested in hydrogeology.

The book is an updated version of the first edition (2012), also published by Springer as part of the Springer Briefs in Earth Sciences Series. The second edition contains a new chapter on advective solute transport through porous media, which provides a more comprehensive view of the topic. As its title indicates, the book introduces methods to evaluate model parameters that are critical to effective hydrogeological simulations. It is an excellent addition to the existing literature related to model uncertainty analysis, and will be of great value to hydrogeologists, modelers and hydrogeological students, and potentially useful for decision makers, project managers and practitioners. The second edition advances the field of hydrogeological uncertainty analysis in terms of both theory and methodology.

The fact that hydrogeological model predictions are highly uncertain requires critical evaluation of model validity and model performance and this has attracted a great deal of research attention. As Carrera et al. (1993) and Wu and Zeng (2013) have pointed out, three types of uncertainty are involved in hydrogeological modeling: (1) uncertainty associated with

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the selection of adequate conceptual models; (2) uncertainty related to model parameters; and (3) uncertainty surrounding the observation data used in the model and the nature of future stresses. Numerous approaches have been proposed to quantify the uncertainty in hydrologic predictions. However, obtaining simplified and reasonable statistics for model uncertainty is still a challenge for hydrogeologists and statisticians; it has been difficult to reduce or eliminate uncertainty during modeling, although a great deal of work has been done on the issue. This book provides an alternative way of treating model uncertainties, which, in my opinion, is a great contribution to the hydrogeological community.

The book is organized into 11 chapters, one afterword and one abstract which appropriately describes the contents of the book. The book is genuinely multidisciplinary, drawing on hydrogeology, geology, hydraulics, hydrodynamics, statistics, physics, environmental sciences, and even philosophy. Many successful and failed case studies are cited and described in detail in the book. Readers are also provided with a reference list at the end of each chapter (except Chapters 5 and 7) that makes it possible for readers to gain more knowledge on specific topics, although most of these references are two or three decades old. The examples included in the book are simple and easily understood, making it a worthwhile reference for hydrogeologists and students interested in hydrogeology and environmental science. Most importantly, Gorokhovski introduces an alternative way of treating uncertainties in hydrogeological simulations.

- (1) *Introduction* - In this chapter, the author points out that mathematical modeling is a useful and effective tool to obtain quantitative hydrogeological predictions, although these predictions are encumbered by large uncertainties. Gorokhovski uses two simple examples (one is steady-state filtration in an unconfined horizontal aquifer when recharge is absent, and the other is evaluating flux losses from a channel to a drain parallel to the channel) to illustrate that effective model parameters rely on the geological setting and the problems inherent in simulation. Obtaining effective model parameters is an issue during the entire simulation process, as shown by examples where model parameters are assigned with different methods. Gorokhovski also points out in this chapter that estimations of simulation errors and uncertainties are impossible to evaluate without complete information on a particular geological object, but this does not necessarily preclude us from obtaining a simulation-based estimate in some circumstances. We can obtain predictive simulation results by assigning effective parameters to the models. Gorokhovski states at the end of the chapter that we can increase our confidence in the simulation results and make better informed decisions by assigning the most effective parameters to models, even though the uncertainty associated with the prediction is impossible to evaluate. This chapter is well constructed and arouses readers' curiosity on how we can make better informed decisions.
- (2) *Engineering Approach* - It describes the engineering approach that is widely used in hydrogeological investigations. According to the author, engineering approaches may be defined as a kind of deterministic approach with statistical nature for decision making by using probably improvable or even wrong assumptions (Gorokhovski 2014). Sometimes the engineering approach can lead to results that are correct under conditions that have been empirically established. The engineering approach can be successfully applied based on accumulated knowledge and professional experience, which is necessary to provide provable estimates of the uncertainty. The author believes that a great deal of professional experience is a prerequisite for the development of adequate geological models. However, he also lists many cases where the engineering approach failed, even when experts with impeccable credentials were involved. The failed cases mentioned in

this chapter are a reminder that professional experience is valuable for decision-making, but credentials do not always warrant confidence.

- (3) *Geostatistical Approach* - If engineering experience is lacking for a particular project, an alternative method is to estimate model uncertainty with the geostatistical approach discussed in Chapter 3. However, Gorokhovski believes that a geostatistical approach cannot provide accurate estimations of uncertainty, if there are assumptions and postulates that cannot be tested or are simply invalid. He further states that even if the statistical assumptions are valid, the geostatistical formulations may be meaningless, thus requiring discussion on their relevance for the problem at hand before using them. The author discusses some geostatistical assumptions in detail in the following sections of the book, such as ensembles, elements, random sampling, and probability distributions, and lists some simple examples to illustrate his arguments that a geostatistical approach may not permit evaluation of the uncertainty of modeling results because of untested or invalid assumptions. The simple examples are quite interesting and intelligible (Figs. 3.1, 3.2, and 3.3). I especially enjoyed Bertrand's paradox (Fig. 3.3) because it shows that there may be many different solutions to the same question.
- (4) *Model Identification* - Chapter 4 is devoted to discussing issues regarding model identification. It begins with a discussion on incorrectness, which is the typical explanation given when an incorrect model yields misleading results. The chapter continues with a discussion on the regularization of incorrect problems that are prevalent in geophysical and hydrogeological data interpretations. The author believes that model identification is problem-dependent, and effective parameters for one problem may not necessarily be effective for another. The effective parameters may change over time even for the same problem. Gorokhovski illustrates this concept with a simple example in Section 4.3. The parameters of a more complex model and a less complex model are compared in Section 4.4 to emphasize that a less physically sound model can produce a good agreement with observational data as the more physically sound model can do during model calibration. That is to say, the effective parameters used for model identification may lose effectiveness during prediction, because model prediction differs from model identification in many aspects, and model calibration is problem-dependent. The comparison performed in Section 4.4 is quite impressive and allows readers to think deeply about the accuracy and precision of the models and simulations used in their daily research and engineering tasks.
- (5) *Transformation of Geological Objects' Properties into Effective Model Parameters* - The preceding chapters demonstrate why successful calibration of hydrogeological models does not always warrant success in the simulations based on calibration results, and why it is impossible to estimate the uncertainty of the modeling results. I believe readers will be quite likely to ask at this point in the book "How do we obtain successful simulations with the data that is available?" Chapter 5 and the following chapters are dedicated to answering this question. In Chapter 5, the concept and properties of transforming mechanisms are introduced. Transforming mechanisms are a theory proposed for obtaining effective parameters for modeling by taking into account the phenomenon of the problem dependence of model calibrations. Fig. 5.2 is helpful for readers to understand the terms used in transforming mechanisms and their relationships to one another. The example in Section 5.3 illustrates the properties of transforming mechanisms so they are quite easy to understand and is also of great help for readers to gain a deeper understanding of the three properties associated with transforming mechanisms.
- (6) *Examples of Linear Transforming Mechanisms* - This chapter describes a one-dimensional steady-state filtration to a fully penetrating trench as an example, and

illustrates a mathematically easy and detailed derivation of the linear transforming mechanisms. An informative box presents readers with additional knowledge on how to derive Eq. 6.3. Eight cases are described in Section 6.2 and the results are discussed in Section 6.3. These case studies allow readers to become more familiar with transforming mechanism theory. The case presented in Section 6.4 confirms that transforming mechanisms are also problem dependent. Effective parameters obtained for one problem cannot be readily used for another problem. However, there are two small defects in this chapter: (1) the results of case study 6.2.2 are repeated twice (page 78, in the paragraphs above Table 6.2), and (2) the font size of Eqs. 6.25 and 6.26 are inconsistent with the text of the book, and they contain Russian letters.

- (7) *Examples of Nonlinear Transforming Mechanisms* - It describes several examples of nonlinear transforming mechanisms. A homogeneous model for the transient filtration of a two-body object is given as an example, and explicit and implicit finite difference methods are applied to obtain the transforming mechanisms. A comparison shows that effective parameters obtained implicitly vary less than those obtained explicitly. Gorokhovski clearly states that the effective parameters obtained by transforming mechanisms may be physically and/or geologically meaningless, which is acceptable, because the author believes that the aim of any simulation is to get accurate results. This viewpoint may not be accepted by many hydrogeologists, who will argue that physically and/or geologically meaningless values of the geological parameter are not acceptable, even if these parameters are effective in the simulation. However, this method provides another way to view models and predictions, and an alternative way to obtain accurate simulation results. The chapter should prompt a reconsideration of these methods by the hydrogeological community.
- (8) *Evaluation of Transforming Mechanisms* - A two-level modeling approach is presented in Chapter 8 in order to deduce transforming mechanisms. This approach can be used when geological objects and corresponding simulation models are so complex that analytical deductions (introduced in Chapter 6) are impossible. This approach can be applied in a straightforward manner to evaluate linear transforming mechanisms, but will encounter considerable computational difficulties when used to evaluate nonlinear transforming mechanisms. Considering that most hydrogeological problems are nonlinear, this constrains the usefulness of the two-level modeling approach and the transforming mechanism theory. To overcome this defect for the time being, the author suggests the use of regression relationships to obtain effective parameters. I have found that regression is not always a good choice for obtaining effective parameters and in many cases the regression equations are derived only with difficulty. I encourage Gorokhovski and other hydrogeologists to continue this line of research and put forward an effective approach for evaluating nonlinear transforming mechanisms.
- (9) *Inverse Problems and Transforming Mechanisms* - This chapter illustrates how transforming mechanisms can be used to solve inverse problems. In this chapter, Gorokhovski defines inverse problems as applications of simpler models for evaluating properties of more complex ones. The author provides a detailed introduction to explain how to solve inverse problems using linear transforming mechanisms and suggests using geophysical approaches to solve non-linear inverse problems that are mathematically difficult. Contrary to common thinking, Gorokhovski proposes that inverse problems differ from model selection or model calibration, because model selection and calibration are optimization problems that relate to specific models with effective parameters that may not have meaning in physical reality, while the results of inverse problems must be tied to physical reality. I agree with Gorokhovski's differentiation of these concepts. For

example, hydraulic conductivities that originate from a well-calibrated groundwater model may be much larger or smaller than the actual values of the aquifers, indicating that these parameters are only effective for the present model of interest and have no physical meaning, thus they cannot be considered as inverse problems.

- (10) *Advective Solute Transport Through Porous Media* - This is a new addition to the second edition of the book. It describes the weaknesses of the classic convective-dispersive model in which fictitious dispersion coefficients and mean pore water velocities are used that make the model unable to fit the long tails of the observed breakthrough curves. Gorokhovski proposes that hydrodynamic dispersion should be directly included in the simulation. He then gives some examples to show the procedure for simulations with one-dimensional hydrodynamic dispersion corrections. He goes on to suggest methods to gain the parameters such as actual pore water velocities, weights and degradation rate. In this chapter, the author presents a number of equations regarding solute transport, which are quite mathematical. I expected that he would have provided some background on the basic theory of fluid flow in porous media, especially on hydrodynamic dispersion for beginning modelers and hydrogeological students. I recommend that readers consult other books on this subject before reading this chapter.
- (11) *Conclusion* - In this concluding chapter, Gorokhovski stresses the inherent attribute of uncertainty associated with hydrogeological models and simulations, and re-emphasizes that engineering experiences are not trustworthy when they do not actually exist. He states that making effective decisions with an understanding of the uncertainty involved in the simulation estimate is one of the most important issues for hydrogeologists. The author also modestly admits that the transforming mechanisms and the two-level modeling approach described in this book are not the only possible ways or even the best ways to deal with the uncertainty of hydrogeological models and simulations. These new methods do nothing to eliminate uncertainty surrounding simulated results. The author concludes at the end of the chapter by quoting Bridgman's statement that hydrogeological modeling is a science with a considerable bit of art, requiring imagination and boldness. This chapter reminds the hydrogeological community that there is still much to be learned about hydrogeological modeling and that will require imagination, courage and action. The book concludes by encouraging and stimulating enthusiasm in readers to continue pursuing the development of hydrogeological modeling.

Afterword - Readers will also find the Afterword at the end of the book very interesting and worth reading. The eight-page afterword describes the working and publishing experiences of the author in the former Soviet Union and the United States, and compares the education system in the two countries. The author also introduces the purpose of writing such a book on transforming mechanisms, including an explanation of why he wanted to add the new chapter in the second edition of the book.

In summary, this book is well written with concise and clear English, except for a few grammatical and spelling errors. The active voice is used throughout the book; reading is like the author telling stories, making the book intelligible and entertaining. The author does an excellent job of including figures where they are necessary to make a point. In my opinion, this is a good publication and deserves to be read by hydrogeologists and modelers, as it presents an alternative way of dealing with uncertainties in hydrogeological modeling. Vikenti Gorokhovski has done a wonderful job writing this book and I hope he can contribute more to the hydrogeological community in the future. To

conclude, I highly recommend this excellent book to anyone who has an interest in hydrogeology and numerical modeling.

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