# Environmental Sustainability for Engineers and Applied Scientists

This textbook presents key approaches to understanding issues of sustainability and environmental management, bridging the gap between engineering and environmental science. It begins with the fundamentals of environmental modelling and toxicology, which are then used to discuss qualitative and quantitative risk assessment methods and environmental assessments of products. It discusses how business and government can work towards sustainability, focussing on managerial and legal tools, before considering ethics and how decisions on environmental management can be made. Students will learn quantitative methods while also gaining an understanding of qualitative, legal and ethical aspects of environmental sustainability. Practical applications are included throughout, and there are study questions at the end of each chapter. PowerPoint slides and JPEGs of all the figures in the book are provided online. This is the perfect textbook on environmental studies for engineering and applied science students.

**Greg Peters** is a professor in the Division of Environmental Systems Analysis at Chalmers University of Technology, Gothenburg, Sweden. Before joining academia, he worked in the urban water sector as a practising environmental engineer. He is the author of many highly cited publications on the quantitative assessment of environmental impacts of water infrastructure, food production, resource consumption and biowaste management. He has served as President of the Australian Life Cycle Assessment Society and as a Lead Author for the Intergovernmental Panel on Climate Change (IPCC).

**Magdalena Svanström** is a professor in the Division of Environmental Systems Analysis at Chalmers University of Technology, Gothenburg, Sweden. She performs research in environmental and sustainability assessment, in particular in the fields of wastewater and sludge management and biobased production, and also in engineering education for sustainable development. She has been a postdoctoral researcher at Massachusetts Institute of Technology and recently taught life cycle assessment as a visiting professor at Brescia University, Italy. She has published a textbook on sustainable development for engineers in Swedish and has been a member of a United Nations Economic Commission for Europe (UNECE) expert group on educator competences in education for sustainable development.

‘This book is a perfect guide for learning how to analyse the problems of natural systems caused by human exploitation, emissions and disturbances. The book analyses the main problems in a scientific way and explains the mathematical models that describe the natural systems. In this way, the book perceives the world from an engineering perspective, but admits that this is a limited perspective, and other disciplines are needed to work towards solutions. It sketches environmental regulation and decision-making. The book is required reading for applied science students and science-driven engineers who are committed to contributing to the grand challenges of our planet.’

*– Karel Mulder, The Hague University of Applied Sciences and Delft University of Technology*

‘Sustainable development – balancing economic and social development with environmental protection – has become a modern paradigm in our technological age. New technological discoveries and product designs are aimed at enhancing human well-being. But they may also give rise to various unwanted “side-effects” that put at risk the quality and longer-term viability of the Earth’s biosphere. Such side-effects induce potential environmental hazards on a local, regional and global scale. Engineers are in the vanguard of those using their skills to mitigate these environmental burdens and improve the quality of life. The present contribution, developed by two experts in environmental engineering and management from Chalmers University in Sweden, provides a guide to the tools that the engineer will need in the twenty-first century to combat ecological hazards. They set out the core elements of environmental modelling and toxicology, alongside methods for risk assessment and product environmental life-cycle assessment (LCA). Multi-criteria decision analysis (MCDA) is then advocated as a vehicle for bringing together the quantitative and qualitative appraisal of diverse impacts. Modern concepts like the circular economy (resource efficiency) and the bio-based economy, that may aid industrial decarbonisation, are described. Importantly, the authors also set out the business and government framework for sustainability assessment, including the ethical issues that will necessitate legal tools and management decision-making. This text deserves to be on the bookshelf of all those engineers and applied scientists who will inevitably face the many environmental and sustainability challenges that will confront our planet in the future.’

*– Geoffrey Hammond, University of Bath*

‘Peters and Svanström have produced a valuable textbook for engineers and applied scientists, one which is both comprehensive and most informative across a range of relevant topics associated with environmental sustainability. They manage to convey to the reader the intricate and interconnected quantitative and qualitative aspects of engineering practice as applied in a sustainability-informed context, in a way that can help develop the critical thinking faculties of both students and professional practitioners. In short, *Environmental Sustainability for Engineers and Applied Scientists* represents a valuable and unique addition to the field, not just in relation to (engineering) education for sustainable development, but as a support for best-practice contemporary engineering education more generally.’

*– Edmond Byrne, University College Cork*

‘A comprehensive textbook with a content of key knowledge essential to understanding sustainability and environmental management. The book will help to bridge the gap between engineering and environmental science. I would strongly recommend the book for both undergraduate and master’s students at technical universities and faculties.’

*– Fredrik Gröndahl, Royal Institute of Technology, Stockholm*

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# Preface

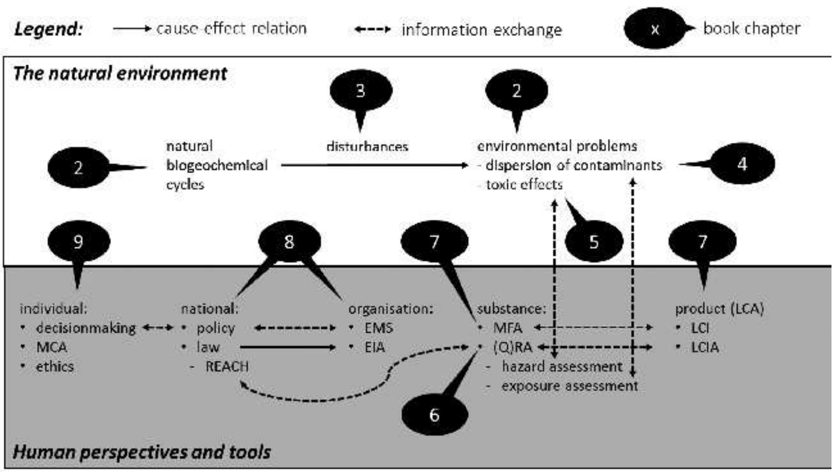
The first question a potential reader might ask is: ‘Why this book?’ Before deciding to make the effort of writing this book, we had to ask ourselves the same question. Our short and surprising answer was: we looked but we could not find a suitable alternative. We meet hundreds of students each year and were challenged to find them a book that is both quantitative and holistic. We wanted a book that built on the basic mathematics and chemistry that most engineers and applied scientists have by their second year of university. (Rigorous high schools may take students to the same level in some countries.) But we expect our students to develop a holistic perspective on environmental management, so we also wanted a book that was broad in the sense that it includes but also goes beyond environmental science, to encompass environmental information tools, ecological issues, law, decision-making and ethics. After fruitful discussions with Cambridge University Press and useful feedback from some anonymous reviewers of our initial plan, this book is the result.

This is not a book on technical design of engineering interventions (air filtration systems, wastewater treatment plants and so on). Plenty of other books are available to introduce environmental technology solutions. Instead, the intent here is to introduce the reader to ways in which we can scientifically describe the environmental problems that need solving, to help the reader to understand some of the management tools that exist for companies and governments that want to solve them, and to choose between alternative solutions. Of course, ‘sustainability’ is a very broad word, and a wide variety of professionals are working towards it. This book is not intended to educate biologists, ecologists, sociologists, political scientists or other professionals in their core skillsets, but we acknowledge that professionals like these also have important contributions to make to environmental management. We hope this book will help engineers and other applied scientists to broaden their core skills and communicate with people of other professions.

We would like to acknowledge some of the many people who have helped to make this book possible; educators who have collaborated with us and inspired this work include Sara Heimersson, Hanna Holmquist, Stuart Khan, Stephen Moore, Kathleen Murphy, Gustav Sandin Albertsson and Peter Thor. Robin Harder deserves particular thanks for his collaboration with Greg Peters on teaching materials to the Chemical Environmental Science course at Chalmers University of Technology, which accelerated the development of Chapter 4. Chalmers’ provision of his time and partial funding for us is gratefully acknowledged.

# Reader's Guide: How Is All of This Connected?

Environmental problems can be viewed from many perspectives, and solutions can be imagined at many levels of detail. It can be hard to visualise how different perspectives fit together. So, to help you understand this book, this reader's guide provides some examples of how different chapters of this book relate to each other. Notice the arrows in the figure indicating cause-effect and informational connections between topics mentioned in the chapters – each of them is briefly explained in the chapter narrative below it.




Chapter 1 provides a general introduction to the book by describing some of the overarching concepts that allow engineers to engage with environmental sustainability from an engineering perspective. An understanding of ecological principles and natural biogeochemical cycles is also foundational because many of the problems we face are caused by natural processes that we have perverted: the natural greenhouse effect is necessary for our survival, but we have intensified it; natural transport and reactive processes in ecosystems can dilute and destroy pollution, but they can also contaminate pristine locations or even make some toxins more potent. So Chapters 2 and 3 describe the natural world and our impacts on biogeochemical cycles. To help to explain how pollution spreads, an introduction to modelling the dispersion of contaminants in the environment is provided in Chapter 4, along with mathematical examples. This is complemented by a more qualitative introduction to toxicology which describes how contaminants are transported in, transformed by and impact on the human body (Chapter 5). These two chapters are critical to understanding the one that follows, because predicting contaminant concentrations in the environment and describing their effects on people and other organisms are critical steps in the process of (quantitative) risk assessment (QRA) (Chapter 6). Risk assessment is a key tool that applied scientists and engineers often use to provide a perspective on the risk posed by substances, but Chapter 6 also introduces qualitative risk assessment methods in relation to the need to manage risk in factory operations.

Another substance-level perspective is offered by material flow analysis (MFA) in Chapter 7, a chapter which mostly takes a product-level perspective of environmental management. An MFA can be thought of as a map of substance flows for a region, whereas producing a life cycle inventory (LCI) is more typically about mapping the supply chain for a product. Some of the same data are used in compiling MFAs and LCIs. LCI is the second step in life cycle assessment (LCA), where the third is life cycle impact assessment (LCIA). LCIA methods for chemical impacts are based on QRA methods. The EU REACH legislation is a good example of risk assessment embodied in legislation, which is one of the organisational and national tools discussed in Chapter 8. If you are ever involved in writing or reviewing the environmental impact assessment (EIA) process for something an organisation wants to build, then the general structure of that EIA will be predefined in the local laws – a legal cause-effect relationship. Many private companies have an environmental management system (EMS), but EMSs are also employed by national governments, among others, and it can be said that Sweden's Environmental Objectives are part of an EMS policy operating at the national level. Ultimately, policy decisions are made by people. The final chapter of the book takes the perspective of people working in organisations and us as individuals, and examines factors that influence decision-making. It also suggests how we can balance environmental and other goals in practice by considering mathematical support offered by multicritera analysis (MCA) and more qualitative ethical principles (Chapter 9).

There is more to this book than just these topics, but hopefully you now have a sense of how some of them are related to each other in the real world. Each chapter comes with some study questions at the end to help you to process what you have read and to extend your understanding into new places and applications not directly covered here.

# Abbreviations

| | |
|---|---|
| AHP | analytic hierarchy process |
| BAT | best available technology |
| BATNEEC | best available techniques not entailing excessive costs |
| BPEO | best practicable environmental option |
| BSL | biosafety level |
| CFC | chlorofluorocarbon |
| CLRTAP | Convention on Long-Range Transboundary Air Pollution |
| CMR | carcinogenic, mutagenic, toxic to reproduction |
| DPSIR | drivers, pressures, states, impacts, responses |
| DDT | dichlorodiphenyltrichloroethane |
| DNA | deoxyribonucleic acid |
| EChA | European Chemicals Agency |
| $ED_{50}$ | effective dose for 50% of organisms |
| EDC | endocrine-disrupting chemical |
| EEIOA | environmentally extended input-output analysis |
| EFA | ecological footprint analysis |
| EIA | environmental impact assessment |
| EIS | environmental impact statement |
| EMS | environmental management system |
| ESA | environmental systems analysis |
| GHS | globally harmonised system |
| H | Henry’s law coefficient |
| HAZOP | hazard and operability study |
| HCFC | hydrochlorofluorocarbon |
| HQ | hazard quotient |
| IOA | input-output analysis |
| $K_{oc}$ | soil organic carbon sorption coefficient |
| $K_{ow}$ | octanol-water partition coefficient |
| $K_S$ | solubility constant |
| LCC | life cycle costing |
| LCI | life cycle inventory |
| LCIA | life cycle impact assessment |
| LCSA | life cycle sustainability assessment |
| $LD_{50}$ | lethal dose for 50% of organisms |
| MAUT | multiattribute utility theory |

| | |
|---|---|
| MCA | multicriteria analysis |
| MCDA | multicriteria decision aid |
| MFA | material flux (or flow) analysis |
| MIPS | material intensity per service |
| NGO | non-governmental organisation |
| NIMBY | not in my backyard |
| NOAEL | no observable adverse effect level |
| NPV | net present value |
| PBT | persistent, bioaccumulative and toxic |
| PCB | polychlorinated biphenyl compound |
| PDCA cycle | plan-do-check-act cycle |
| PER | public environmental report |
| PET | polyethylene terephthalate |
| POP | persistent organic pollutant |
| PROMETHEE | preference ranking organisation method for enriched evaluation |
| QALY | quality adjusted life years |
| QRA | quantitative risk assessment |
| REACH | Registration, Evaluation and Authorisation of Chemicals Regulation |
| RfD | reference dose |
| RoHS | Restriction of Hazardous Substances Directive |
| SLCA | social life cycle assessment |
| SVHC | substances of very high concern |
| UF | uncertainty factor |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USEPA | United States Environmental Protection Agency |
| vPvB | very persistent and very bioaccumulative |