

Integrated Environmental Modelling: human decisions, human challenges

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Abstract: Integrated Environmental Modelling (IEM) is an invaluable tool for understanding the complex, dynamic ecosystems that house our natural resources and control our environments. Human behaviour affects the ways in which the science of IEM is assembled and used for meaningful societal applications. In particular, human biases and heuristics reflect adaptation and experiential learning to issues with frequent, sharply distinguished, feedbacks. Unfortunately, human behaviour is not adapted to the more diffusely experienced problems that IEM typically seeks to address. Twelve biases are identified that affect IEM (and science in general). These biases are supported by personal observations and by the findings of behavioural scientists. A process for critical analysis is proposed that addresses some human challenges of IEM and solicits explicit description of (1) represented processes and information, (2) unrepresented processes and information, and (3) accounting for, and cognizance of, potential human biases. Several other suggestions are also made that generally complement maintaining attitudes of watchful humility, open-mindedness, honesty and transparent accountability. These suggestions include (1) creating a new area of study in the behavioural biogeosciences, (2) using structured processes for engaging the modelling and stakeholder communities in IEM, and (3) using ‘red teams’ to increase resilience of IEM constructs and use.



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The experiences and education that scientists receive invariably affect their perspectives and create bias. Sarewitz (2004, p. 392) states this reality well in his provocative article on ‘How science makes environmental controversies worse’:

Even the most apparently apolitical, disinterested scientist may, by virtue of disciplinary orientation, view the world in a way that is more amenable to some value systems than others. That is, disciplinary perspective itself can be viewed as a sort of conflict of interest that can never be evaded.

Indeed, Sarewitz (2004) argues that the very act of making choices, and of being sentient human beings, force humans to acquire bias. Scientists and numerical modellers cannot escape this reality. At best, they can try to acknowledge and examine their sources of bias.

After an introduction to the author’s experiential biases and professional background, this paper will discuss the needs and use of Integrated Environmental Modelling (IEM) for the improved management of society’s natural resources and environments. [Our definition of natural resources includes all resources provided by nature, regardless of their biologic, geologic, hydrologic, or atmospheric origins or characteristics.] Following sections will consider the balance between: (1) the

inherent complexity of the integrated transdisciplinary numerical models and tools of IEM, and (2) the simplifications that are required for effective human construction and use of IEM, and that often reflect, or are influenced by, human limitations, biases and heuristics. Several of these human biases and heuristics will be individually recognized and examined. A reference frame, ‘the eye of reality’, will also be introduced that may be useful in thinking about and classifying our human pursuit of knowledge, while keeping in mind our human biases and our related creative intuitions. Lastly, the paper will suggest some ideas and approaches that may help address IEM’s ‘human challenges’, that is, those distinctly human challenges that we need to recognize and overcome to effectively use IEM. Human biases and heuristics are a large part of these challenges.

Some personal experiences and biases

Many of my own biases were formed through my management experiences gained while directing a hydrology research group within the US Geological Survey, and proposing new science directions, for example, in the areas of groundwater studies (Glynn & Plummer 2005; Konikow & Glynn

2013; Plummer & Glynn 2013; Plummer *et al.* 2013), small watershed-basin research and monitoring (Glynn *et al.* 2009), 3D and 4D modelling and visualization (Glynn *et al.* 2011; Jacobsen *et al.* 2011; Pantea *et al.* 2013), and most recently in the domain of the behavioural biogeosciences (Glynn 2014). My perspectives were also formed through some of my research experiences:

- (1) modelling, and attempting to predict, the reactive transport of acidic heavy-metal contamination in groundwaters of the Pinal Creek Basin in Arizona;
- (2) providing geochemical understanding, and scenario and process modelling of oxygen and radionuclide reactive transport in support of performance assessments for high-level nuclear waste disposal in the Fennoscandian Shield in Sweden.

The experiences discussed in this section show the development of my appreciation for the need to more fully consider nature's complexities, as well as the inevitable surprises that nature invariably provides that diminish our hubris as modellers. The surprises and experiences generated a personal set of experiential biases, a set that overlies more innate biases, some of which will be described in later sections.

Combined inverse and forward modelling to assess and reduce knowledge gaps

Glynn & Brown (1996, 2012) used inverse geochemical modelling to deduce the possible sets of reactions that were affecting the chemical evolution of contaminated groundwater at the Pinal Creek site. [Inverse modelling uses observations and data to infer, past or current, process and system information. In contrast, forward modelling assumes process information and a set of initial system conditions and system parameters to predict a future state, see Glynn & Brown (1996, 2012).] The authors also conducted forward reactive transport modelling, using the possible sets of reaction processes obtained through inverse modelling, to examine the resulting migration speed and sequencing of contaminant fronts at the site. They compared these results to the migration of fronts observed at the site, which helped further constrain the sets of potential reaction processes and associated geochemical conditions that applied to the site. Glynn & Brown's (1996, 2012) integration of inverse and forward geochemical modelling helped determine the information that was critically needed to further improve understanding of contaminant transport at the site. The 1996 study provided a basis for further field investigations and numerical

simulations of contaminant transport (Brown *et al.* 1998, 2000). These additional studies added further understanding on the hydrodynamics, reaction mechanisms, and kinetics controlling contaminant transport at the site. They also led the authors to design some *in situ* field experiments to further test their knowledge (Brown & Glynn 2003). '*Lessons learned*' were: (1) *modelling could be used to determine knowledge gaps and to guide field data collection and experiments, and (2) different modelling approaches were highly informative when used synergistically.*

An early surprise

Nature provided a 'Black Swan' surprise (i.e. a high-impact low-probability event, according to Taleb 2007) at the Pinal Creek site, before the completion of the Glynn & Brown (1996) study. An early assumption that the site had relatively steady groundwater flow dynamics was revised in the winter of 1993. Massive flooding over the course of a few months during that winter resulted in water table rises of up to 16 m and a complete reorganization of the usually dry Pinal Creek channel bed with up to 60 m of lateral bank erosion. Critical wells that had been emplaced on the banks were lost, and there was a sudden 'cleanup' or flushing of about a third of the contaminated groundwater system that completely dwarfed the pumping and remediation efforts that had proceeded to date. Site study designs, field investigations and modelling plans were changed by the 1993 event, as were contaminant remediation plans. *Key lesson: catastrophic geomorphic changes (and external forces) can cause abrupt change to groundwater systems and waylay the best-laid plans and the overly narrow, overly static, perspectives of a groundwater scientist, in this case myself.*

A wrong prediction

Nature confounded one of the predictions made by the Glynn & Brown (1996) study. Glynn & Brown (1996) had predicted that pyrolusite (MnO₂) that had been carefully weighed and suspended in research wells emplaced in the contaminant plume would undergo reductive dissolution and loss of material. Instead, the samples acquired mass. A new reactive mechanism discovered through careful laboratory experiments (Villinski *et al.* 2001) was found to best explain the observed gain in mass (Brown & Glynn 2003). *Key lesson: don't get too attached to your 'predictions'.*

Glynn & Brown (2012) provide a 15-year retrospective on Glynn & Brown (1996) and later studies conducted at the Pinal Creek site. Some of

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their key conclusions, pertinent to IEM, are provided below:

Constructing, analyzing and interpreting numerical models, regardless of the type of model (hydrologic vs. geochemical; inverse vs. forward), forces the modeler(s), and hopefully the user(s) of the models, to reexamine and revise their conceptual model and perceptions of the available information. The modelling process forces the modelers and users to assemble, structure, transform, and assess a wide variety of information . . . The studies conducted at the Pinal Creek site illustrate the fact that nature always keeps surprises in reserve for its observers and interpreters. Humility, and frequent testing of assumptions, are needed in modelling nature's systems . . . Given our often limited knowledge of natural systems, it behooves us to model these systems by considering *general* system behavior before interpreting, matching, and predicting *specific* system behavior.

Long-term climate scenarios and performance assessments for nuclear waste disposal

I gained experience relevant to IEM through my work for a small interdisciplinary team of investigators tasked by the Swedish Nuclear Power Inspectorate (SKI) to review extensive investigations conducted by the Swedish Nuclear Fuel and Waste Management Company (SKB) for the Äspö Hard-Rock Laboratory (HRL). The Äspö HRL was studied to assess the potential performance of high-level nuclear waste disposal at 500 m depth in the Fennoscandian Shield. The SKB investigations involved a large group of contractors (i.e. a few hundred) who constructed climate scenarios and examined the many factors that could affect the performance of the waste disposal site over the next 120 000 years. The analyses and performance assessments conducted by SKB were impressive and sophisticated. Milankovich astronomical cycles were used to construct a climate scenario that included the occurrence of three glacial cycles over the next 120 000 years. During two of the cycles, a 2–3 km-high ice sheet was expected to be present on the landscape above the Äspö HRL site. SKB's performance assessments, at least initially, assumed that geochemical conditions were going to remain close to chemical steady state at repository depth. The redox regime was assumed to remain relatively constant: not sufficiently reducing, or sufficiently oxidizing, to cause either sulphidic or oxidative corrosion of the copper canisters used for waste disposal. In particular, a continuous absence of dissolved oxygen in the groundwaters outside the repository was assumed. Dissolved oxygen would have been a problem because of (1) its potential corrosion of the copper canisters and (2) its potential to mobilize radionuclides such as those of U, Tc, Pu and Np, should the nuclear waste become exposed to the

groundwaters. *Key point: SKB performance assessments were IEM constructs that considered both external forcings and internal processes and were detailed in their simulations of complexity.*

Questioning a conceptual model: a small independent team effort

SKI conducted its own performance assessments for a deep repository for high-level waste disposal, the SITE-94 project (Swedish Nuclear Power Inspectorate 1997). The SKI effort was based on the development of risk scenarios constructed after an exhaustive identification of 'features, events, and processes' that could potentially affect the integrity of the disposal site and its ability to keep the high-level nuclear waste products isolated from the human-living environment. Relatively complex and visually impressive 3D hydrodynamic modeling was conducted by both SKB and SKI for their performance assessments and scenario building. Nonetheless, the SITE-94 project showed (Glynn & Voss 1999, Glynn *et al.* 1999) that a scenario that assumed the presence of 2-3 km-high warm-based ice sheets over the Äspö HRL could potentially entail the relatively rapid transport of highly oxygenated glacial meltwaters to 500 m depth, because of the large head gradient and because of low fracture porosity. Observations from the base of the Greenland ice sheet suggested that dissolved oxygen concentrations in the glacial meltwaters, under the base of the ice sheet, could be as high as four to five times the concentrations that would normally be expected under equilibrium with the atmosphere. This possibility disrupted the initial SKB (and SKI) concept scenario of a stable redox regime at repository depth. SKB mounted an extensive research effort to evaluate this possibility. *Lesson learned: despite their sophistication, the performance assessments initially left key assumptions unexamined; an independent team helped point out potential problems.*

Assuming constancy: a recurring problem

Additionally, I conducted numerical simulations that investigated the conditions under which the transport of radionuclides, such as those of Pu and Np, might be reasonably modelled by assuming constant partitioning of the radionuclides between aqueous phases and solid surfaces. The results, applicable to nuclear waste disposal in Sweden (Glynn 2003) and also to radioactive waste at the Idaho National Laboratory in the USA (Nimmo *et al.* 2004; Rousseau *et al.* 2005), indicated that constant partitioning was generally not a reasonable assumption in simulating actinide transport in geological media. *Key point: humans (including*

scientists) are wired, often unreasonably, to seek constancy and simplicity.

A summary of personal lessons

Several lessons resulted from my experiences assessing contaminant transport and nuclear waste disposal issues in Arizona, in Sweden, and later at the Idaho National Laboratory. First, independent analysis by small teams or individuals can be critical in avoiding ‘groupthink’ (Janis 1972) in the development of conceptual models or numerical models. Second, there is no better way of using a model to develop greater understanding of a system than to obtain additional observations and information (but this is not always possible). Third, it is important to keep an open mind for the ‘Black Swan’ surprises and (or) invalidation of assumptions that will invariably occur. *In summary, we have a natural tendency to assume constancy, to simplify and to seek confirmation of our mental models.* Those tendencies can easily lead us into error when trying to model complex, dynamic, systems. Indeed, we may construct highly sophisticated, publicly impressive, numerical models that can nonetheless incorporate problematic simplifying assumptions or preconceptions. When properly utilized, however, structured, interdisciplinary, integrated modelling frameworks may help reduce failures of our human imagination. They can help us organize our knowledge as we gain information and understanding. They can help us uncover process interplays or model sensitivities not previously considered.

What is IEM?

According to Laniak *et al.* (2013, p. 4):

Integrated Environmental Modelling (IEM) is a discipline [that] provides a science-based structure to develop and organize multidisciplinary knowledge. It provides a means to apply this knowledge to explain, explore, and predict environmental-system response to natural and human-induced stressors. By its very nature, it breaks down research silos and brings scientists from multiple disciplines together with decision makers and other stakeholders to solve problems for which the social, economic, and environmental considerations are highly interdependent.

Moore *et al.* (2013) further state: ‘At its most basic level, integrated modelling (IM) is about linking computer models that simulate different processes to help understand and predict how those processes will interact in particular situations.’ The authors add that IEM applies IM to the analysis of environmental problems. The present paper takes a broader view: IEM is needed not only for studies of environmental systems, but also for studies of the natural

resources and of the human activities that are linked to the state of natural and built environments. Despite our innate tendency to do otherwise (Glynn 2014), use and management of natural resources should be integrated, or at least considered, in the simulation of environmental stresses.

Simulation of human activities, and therefore simulation of Coupled Human and Natural Systems (CHANS), requires an understanding of human behaviour, its drivers, commonalities and range of variability in a diversity of social settings (e.g. individual, family, communities, nations) and for a wide range of spatial and temporal scales. My educational and professional background creates a bias towards consideration of biophysical processes above the simulation of human activities and behaviours as might be done in CHANS modelling. *However, my claim here (also in Glynn 2014) is that scientists, including behavioural scientists, often do not consider how human biases and heuristics affect human interactions with, and human study of, natural resources and environments.* This paper focuses on human biases and heuristics that affect the study of natural resources and environments, and therefore the construction and use of IEM simulations – whether or not those simulations also include human and social processes.

Processing integrated information: are computers required?

Computers are not inherently required to construct and use IEM. As individuals, we gather, process, integrate, and act on information and beliefs, often unconsciously. We construct and use a personal form of IEM that is based on a diversity of cognitive inputs, memories and reactions acquired from our past experiences, ingrained social rituals, and innate responses acquired from our evolutionary past. When confronted by unusual events or situations that are not in our experience base or in our genetic code, we often ‘infer’ our responses or actions through logical deduction, induction, or through ‘fuzzy’ analogies to other situations.

Computer models, and other structured and distributable information frameworks, however, can help us share information and knowledge with other people, and can potentially provide greater structure, traceability and accountability for the sources of our knowledge, and ultimately for our actions. In the past, communities and individuals used maps as information frameworks and aids that could help them quickly assess:

- (1) the boundaries, locations, types and quantities of resources and communities (e.g. the oldest ‘modern’ world atlas, the *Theatrum Orbis Terrarum* by Abraham Ortelius, 1570);

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- (2) the temporal trends in those resources and (or) communities (e.g. Charles Minard's 1869 flow map of Napoleon's march through Europe).

Maps have been, and still are, highly successful information frameworks because of their portability, their ability to convey a diversity of information in a highly accessible manner, and because of their ability to segregate information into different levels: the user of a map does not necessarily need to take in all the information presented in the map at once. Instead, the user can choose to access only some elements, while ignoring others, or leaving other elements for a later, more detailed, assessment. Usable simplicity and scalable visualization is a feature of well-constructed maps.

We are now at a stage where the 2D structure of maps, and often their lack of a temporal or dynamic representation of information, are too restrictive. New multi-dimensional, computer-based or web-based, IEM tools are required to help us assess, share and cooperatively use the vast amounts of information that are often available. Proper use of these tools requires consideration of IEM goals and needs, and cognizance of the human challenges and limitations that affect IEM (and much of modern science).

Why is IEM needed? How can it be used?

IEM is needed to simulate complex, dynamic systems with multiple processes at multiple scale

Natural resources and both natural and built environments are affected and linked by a complex diversity of processes made dynamic through natural variability, climatic change, population expansion, human behaviour and land-use change. Improved management of resources and environments requires improved understanding of these complex, dynamic, systems. Tools and structured processes are needed that can: (1) help forecast, predict or explore potential system changes, (2) inform policy actions and support decision making, and (3) track impacts of policy actions (or of their absence). IEM provides some new ways to investigate connections, couplings and feedbacks that generally would not be explored in traditional discipline-focused numerical simulations.

Reductionist science and overly simplified models do not suffice

Assuming that resources and environments are not linked, are not complex, and are not subject to

dynamic changes is not a suitable approach to manage the longer term, larger scale, well-being of society (Sterman 2001, 2002). Normal reductionist scientific approaches are insufficient in the face of the complexity and uncertainties associated with natural resources and environments; instead, a 'post-normal' integrative science is needed that acknowledges complexity and helps deal with uncertainty (Funtowicz & Ravetz 1993). Later sections in this paper will expand on these issues, including the balancing of complexity and simplicity.

How can IEM be used?

IEM can help assemble the information that we possess, and the knowledge that we believe to have, in logical, structured constructs (numerical models and databases). IEM can provide a dynamic, adaptive, integrated information framework for the improved management of natural resources and environments. Specifically, IEM can be used to:

- assemble and organize large sets of disparate information, both quantitative and qualitative;
- transform information (e.g. convert, interpolate, extrapolate, integrate, differentiate) to calculate stocks, flows or other system properties;
- design monitoring networks to effectively observe and quantify the stocks, flows, properties or qualities needed for the assessment of natural resources and environments at different scales;
- assess correlations and patterns in observations (i.e. through statistical modelling tools);
- test causality of correlations, suggest testable hypotheses, or help design or interpret field experiments or natural experiments through deterministic modelling approaches;
- explore effects of including or excluding given processes, the equations by which they are represented, the parameters that control them, or the spatial and temporal scales to which they are applied;
- examine sensitivities, thresholds, tipping points, and non-linear behaviours of system processes, representative parameters, boundaries, or system components;
- predict, forecast, or test results of system changes, or explore different scenarios of change.

Generally, IEM can help devise and implement better-considered, more useful, policies to help manage landscapes and natural resources. IEM has the potential to help communities mitigate and adapt to increasingly complex environmental stresses. IEM's complexity arises because of the need to:

- consider, analyse, compile and synthesize multiple types and sources of information;

- interpolate and extrapolate available information across geographic landscapes;
- extrapolate information through time to make forecasts (or hindcasts), or to fill in time gaps;
- transform information into more useful types of information that lend themselves to policy decision making;
- consider and assess assumptions, biases and uncertainties that are inherent in constructed models or information frameworks, and
- assess the potential impact of knowledge gaps and low-probability high-impact events (i.e. 'Black Swans') in a given information framework. Policy decisions and management actions that seemed reasonable at the time of their being taken have often proved problematic later on, usually because longer term impacts, external processes or cascading impacts were not sufficiently considered.

Most of the complexity of IEM comes from the manipulation, analysis, assessment, synthesis and focusing of needed information for IEM construction and use. Additionally, complexities can arise in the processes needed to assess whether IEM-derived policy actions are useful, harmful or need to be adapted to better meet societal needs. For example, adaptive management (Ladson & Argent 2001; Argent 2009; Williams *et al.* 2009; Williams & Brown 2012) and structured decision making have started to be applied in the management of natural resources, replacing 'implement and forget' policy actions, and including stakeholders throughout the policy study and decision process. Adaptive staging, a form of adaptive management, has also been proposed as a potential implementation strategy for nuclear waste disposal (McCombie *et al.* 2003).

Why does simplification remain critical to IEM progress and implementation?

Good management of resources and environments requires (1) getting sufficient information of useful quality and consistency, (2) assembling, transforming and filtering the information to understand it and to help make decisions, (3) getting feedback on the simulated information and on the impact of the implemented decisions, and, most importantly, (4) getting community support for the entire process. Simplification of system complexities and dynamics is needed for many reasons, including the following:

- monitoring and observation systems are restricted by funding and by other practical constraints – not everything can be observed or measured everywhere at any time;

- technology and practical considerations may also limit the acquisition and transmittal of measurements as well as the computer-based processing, archiving and retrieval of information;
- humans have limits (and biases) in their cognitive capabilities, in their abilities to sense, perceive, retrieve and store information, in their abilities to process and transform information into knowledge and in their abilities to act on their knowledge.

Additionally, simplification and shortcuts are essential to human behaviour. 'Fast and frugal' heuristics are evolutionary and experience-based features that, most of the time, provide essential highly efficient guides for human behaviour and decision making (Gigerenzer & Brighton 2009; Marewski *et al.* 2010; Kruglanski & Gigerenzer 2011). Simplifications and heuristics help us avoid the 'paradox of choice' (Schwartz 2004): too much complexity or too many choices can lead to paralysis in decision making.

Lastly, but perhaps most importantly, a commonality of understanding and support is needed at all phases of IEM studies, and especially for IEM-derived decision making and implementation of management actions. A commonality of understanding and support invariably implies that the greater and differing understanding of many individuals gets subsumed to a 'minimum common denominator' of broadly accepted and explainable knowledge. Analogous conclusions, pointing to the benefits of 'small' system dynamics models (i.e. relatively simple and easy to understand), were reached by Ghaffarzadegan *et al.* (2011) in their study on the use of models to address social policy questions.

What are some downfalls or biases related to simplification?

'Simplification' often represents evolutionary adaptation or learned or acquired behaviours that may be expressed as human biases or heuristics. These simplifying biases and heuristics allow human management of complex processes, often with surprising accuracy (Gigerenzer & Goldstein 1996; Gigerenzer & Brighton 2009; Marewski *et al.* 2010). Nonetheless, simplification is not reality, and may be especially poorly suited when confronting modern issues that may have not been experienced or were infrequently experienced in our evolutionary or experiential past (Glynn 2014). Simplification can lead to significant errors of man or of machine, to wrong or misleading simulation results or interpretations, to poor decision making. Human over-reliance on intuitive thoughts and

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reactions can lead to highly biased and ineffective decision making (Tversky & Kahneman 1974; Kahneman 2003a, 2003b, 2011). Similarly, lack of consideration of low-probability high-impact events, i.e. 'Black Swans', can also lead to poor decision making (Taleb 2007).

Poor decision making, at least in the context of a longer term or larger scale perspective, may occur when there is a lack of immediate, sharply distinguished, feedbacks at the level of the individual or of a local (i.e. tightly knit) community; for example, when human decisions or reactions have subtle, large scale or delayed impacts on resources and environments (Sterman 1994). It can also occur when available feedbacks are overprinted by more pressing needs (i.e. more immediate, more local), or by other often irrational considerations (Gilbert 2011). Over-exploitation of common resources (e.g. overfishing, groundwater depletion) is a typical problem that can occur (Hardin 1968; Ostrom *et al.* 2002). Poor choices or judgments may also simply result from poor human cognition of important aspects or processes in complex ecosystems.

Deficient cognition, or lack of cognition, will occur not only because of human memory limitations or limitations of experience. It may also occur because some important ecosystem components are relatively hidden from us (e.g. groundwater, microbes), or because we have natural preferences to track biota or animate entities rather than relatively inanimate entities. I suspect that human cognition preferentially tracks, in decreasing order of importance: (1) oneself, (2) other humans, (3) other biota, (4) physical objects and landscapes. On a parallel track, human cognition is also probably adapted to recognize, in decreasing order of importance: (1) immediate local threats to human security (e.g. aggressive humans or large animals, extreme weather), (2) basic day-to-day resource needs and opportunities (food and water), and (3) the potential of social relations that enable our reproductive success, and help us get respect or esteem. These needs are essential components of Maslow's theory of human motivation or 'hierarchy of needs' (Maslow 1943; Koltko-Rivera 2006).

What are some general human biases that may occur in the application of IEM to ecosystem management?

Our cognitive limitations and adaptive heuristics are responsible for a multitude of human biases that affect the functioning of our minds, our judgments and actions. Here, however, I consider some general human biases that may affect the

construction and application of IEM when seeking to improve management of ecosystem resources and environments. Because I am not trained in the behavioural sciences, some of the biases listed below are speculative, and reflect personal, non-quantitative, observations.

The 'temporal insensitivity' bias

Humans are better at representing, understanding and utilizing spatially distributed information than time-distributed information. Spatial distributions seem to be more frequently used, now more than ever with the advent of the internet and our increasingly connected world. Retrieving historical or even older information about past conditions often requires greater effort, or may be impossible. Additionally, the uncertainties (and surprises) associated with forecasts or future scenarios, and the lack of feedback and/or our personal 'lack of skin' in any long-term predictions (beyond one or two generations, i.e. 20–40 years) tend to limit actionable human interest in the distant future. (By 'lack of skin', I mean the lack of a near-immediate, bodily experienced, personal stake.) The longer the timescale of the available (or modelled) information, the lower the degree to which scientists and society are able to easily appreciate, understand and use the information to manage the environment and natural resources. The fields of system dynamics and industrial dynamics have demonstrated the difficulties that human societies have in dealing with systems that have multiple, complex, non-linear feedbacks even on the relatively short management timescales of companies and organizations (Forrester 1968, 1971, 1994). Longer delayed feedbacks make appropriate societal responses even more difficult. Society has generally not understood, or applied, the fundamental reality that our environmental systems and resources (e.g. watersheds, forests, groundwater systems) have a diversity of lagged or delayed responses that range from days to months, years, decades, centuries, millennia and more. The widely varying timescales of ecosystem processes do not generally harmonize with political cycles, or with timescales of societal decision making and feedback. This does not mean that considering long-term ecosystem dynamics is not important, especially when making major societal investments. Following local weather predictions is important to us on a daily basis because it helps us dress appropriately, or tells us of extreme weather events that may be coming towards us. Considering hydrological and climatic variability, or the risk of extreme events, on the timescale of decades to centuries or millennia may also be important if we want to make smart investments in infrastructure

(e.g. installing or removing dams and reservoirs, installing tsunami protection barriers of appropriate height) or in relatively rigid legal compacts between communities or countries (e.g. the Colorado River Compact 1922).

The 'steady-state' bias

This bias is related to the previous one. As we observe the world around us, I believe that we are programmed to seek, and see, stability and simplicity, and to extrapolate current knowledge of active processes and their rates into the future. This makes it easier for us to make decisions in response to short-term imperatives. The historical prevalence of statist-, equilibrium-, or steady-state-oriented perceptions and interpretations of ecosystem processes in the scientific literature (and therefore in management and policy applications) may also partly result from discomfort or avoidance in thinking about our ultimate demise. Improved management of our ecosystems increasingly requires dynamic models, in which steady states may occur and persist for some length of time, and may sometimes recur over longer timescales, but are generally intrinsically unstable because of the many different sources of disturbances or perturbations that can occur, of either natural or human origin (Botkin & Sobel 1975; Botkin 2012). 'Non-stationarity' (Milly *et al.* 2008; Hirsch 2011) and the increasing realization that ecosystems are highly dynamic in all their characteristics and can easily exceed previously considered 'historical ranges of variation', have important implications for the management of our environment and natural resources (Betancourt 2012).

The 'man v. nature' bias

Our sense of exceptionalism often leads us to consider ourselves, and our actions, as removed from the rest of the natural world. 'Natural' systems have been studied and modelled as if they were isolated from human systems and the built environment (Botkin 2000). The concept of the 'independent observer' and the development of the scientific method inherently assume that we are removed from nature. Under many conditions, for example, for small-scale simple systems observed over short time frames, this is not a problem. It is a problem, however, when modelling the larger scale, longer term, integrated processes of complex dynamic ecosystems. Conceptual and numerical models of these systems, and generally of the environment and its resources, have rarely considered the complexity of human behaviour and human decisions, and their full impacts on the environment and its resources. Such models often do not include

humans and their behaviour. This artificial separation has negatively impacted our ability to model and manage the environment and its resources (Force & Machlis 1997; Machlis *et al.* 1997; Machlis & McNutt 2010).

The 'anthropomorphic' bias

Human nature relates best to itself, and commonly seeks to anthropomorphize entities that it does not understand well, including computers and their associated technology (Nass & Moon 2000). Computer 'personalities' that relate to human personalities can be created relatively easily and humans respond socially to technologies (Nass *et al.* 1995). I suspect that integrated models, as complex multi-dimensional dynamic information frameworks, will not escape our tendency for personification, especially if they become accessible to the average person and acquire 'black box' or 'artificial intelligence' characteristics. Their predictions or output may be treated like the prophecies of the Oracle of Delphi: that is, generally held in great respect by many believers, subject to obscure pronouncements that frequently need translation from acolytes and high priests, occasionally amenable to providing additional prophetic details (or more obscure pronouncements) when consulted again with suitable accompanying 'gifts'. It is likely that integrated models will be both shaped and related to as if they were human entities. Hopefully, they will provide a better record of transparency and more widely understood meaning than the Oracle of Delphi. (There is no doubt though that the Oracle was considered by society as a useful source of wisdom and prophecy: she is believed to have been in place for 12 centuries, from 800 BCE to 395 CE; Wikipedia 2015a).

The 'single species' bias

This bias is related to our need for simplicity. Management actions, policies and regulations have often focused on single species, disregarding their interactions or dependencies on other species. Ecosystem management has often ignored the complexities of food webs and focused on individual species, or on a short list of species of interest: threatened and endangered species, 'keystone' species or 'indicator' species. Charismatic species have often received greater study than species that did not appeal as much to the public, or were not as visible (or were not as scary). Less charismatic or less visible species, however, often have great functional relevance in ecosystem processes. As illustrated in the management of sea otters and many other threatened species, ignoring species-species interactions and the need for monitoring and modelling

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multiple populations has often led species management actions astray (Botkin 2012). Despite many studies on large apex predators, the trophic cascades and ecosystem processes that they often control or influence remain areas of much needed study (Ripple *et al.* 2014).

Cognitive perceptions and the 'visible is credible' bias

Vision is such an active sense that it may overwhelm our other cognitive inputs, and possibly also diminish our ability for conscious logical thought (Glynn 2014). Our senses include four other 'classic' receptor senses (hearing, smell, taste, touch or skin sensation), as well as many others, including equilibrioception (balance, acceleration, gravity), proprioception (kinesthetic sense), thermoception (heat flux), chronoception (time), nociception (pain) and other internal 'interoception' and chemoception senses. Vision is a privileged sense that allows near-immediate human response to impactful events. It allows quick assessments of situations. People near us are able to immediately share our visual perceptions. In contrast, other senses (1) involve internal perceptions that are not as easily shared, and/or (2) are associated with greater transmittal delays between emission and reception of the sensory signal (e.g. hearing), and/or (3) require greater time for reception and human processing before action can be taken (e.g. smell). It is no coincidence that vision is a most important sense, especially when it comes to the shaping of human beliefs. 'To see is to believe' is a common human expression. Conversely, the invisible requires a greater effort of belief, or of education and knowledge, and consequently often ends up unrepresented in our mental models, in our conceptual models, and therefore in our numerical models.

Lack of accounting for groundwater processes, and the regulation and management of groundwater and surface water resources as if they were separate resources, are pervasive problems (Winter *et al.* 1999) that, according to Glennon (2002), have contributed to poor management of groundwater resources in several regions of the USA. As another example, integrated environmental watershed models of water, sediment and nutrient inputs to the Chesapeake Bay have, generally, inadequately represented groundwater processes. The models have not accounted for the decadal timescales of groundwater processes (Sanford & Pope 2013), or for the decadal to millennial timescales of sediment processes (Pizzuto *et al.* 2014). As a result, the IEM watershed models for the Chesapeake Bay watershed have, for the most part, ignored the response times required for best management practices and

other efforts to limit sediment and nutrient transport to the Bay.

The 'creeping normality' bias

This is a bias described by Jared Diamond in his study on the collapse of human societies (Diamond 2004). It is also sometimes referred to as the 'boiling frog syndrome' (Wikipedia 2015*b*). Humans are conditioned to respond quickly to immediate, clear and specific risks to themselves and their present communities. Individuals are not conditioned to make decisions that impact them, their descendants, or society in general (present and especially future) in response to diffuse risks. By diffuse risks, I mean risks that are either not perceived or at best perceived as diffuse by individuals because the risks (1) increase slowly or are spread over a longer time-frame, (2) occur at a large spatial scale without clearly noticeable local feedbacks or (3) are buried by uncertainty or variability or diluted by too many other factors affecting human perception. Integrated modelling (IM), in many ways, seeks to upset this conditioned, evolutionary, reality of human perception and response. IM by its very nature seeks to broaden human perception, while still aiming for consequent action. IM often seeks to simulate a greater number or diversity of processes than may be otherwise considered. In many instances, it will provide information that does not relate to immediate and local impacts, or that simulates gradual changes or changes that may be otherwise 'buried away' from human, or at least societal, perception, and therefore from consequent action.

The 'disciplinary' biases

Biases relating to our disciplinary expertise, or to the social communities or peer groups that we associate with, are plentiful. These associations are generally beneficial in that they help us develop expertise and knowledge in specific areas, and they also provide professional or personal security that we would not have as isolated individuals. However, these associations also have the potential to create biases that can skew our perspectives, our mental models, and therefore the way that numerical models are assembled, interpreted and applied or used. IEM does not escape from these biases, but it does have the potential advantage of bringing in a diversity of perspectives. IM seeks and needs to provide broader and more integrated perspectives for management or policy actions; users of IM must be mindful of using the best possible disciplinary knowledge and expertise, while being very open to different or alternative perspectives. Ecosystems should not be studied and modelled only by biologists with little training in the

physical sciences, or by physical scientists with little training in biology. Definition and quantification of ecosystem functions and services, or assessments of ecosystem health, clearly require the engagement of a broad community. Economic valuation of ecosystem services, or the construction of trading frameworks for various ecosystem crediting plans (e.g. wetland trading, nutrient trading, carbon trading), offer examples of the breadth and depth of interdisciplinary collaboration required for useful applications of IEM. Ultimately, however, broad and diverse collaborations require a core of common understanding, helped by the use of common ontologies and semantics, but also by useful and appropriate simplifications.

The 'dominant stature' bias

This bias reflects the common occurrence where more aggressive individuals, justifiably or not, seek to assert their leadership or dominance, while others, justifiably or not, follow their lead. Relatively similar behaviour can be observed in the leadership/power relationships of wolf packs and ungulate herds. In human gatherings, a widely acknowledged expert or leader may persuade, or subdue, less aggressive participants into accepting an opinion or course of action, sometimes regardless of appropriate justification, i.e. without the requisite level of expertise, knowledge and logical thinking needed from both the leader(s) and the followers. There are excellent reasons for this behaviour in many situations. However, the breadth of reasoned participation required by IEM will generally argue for minimizing, or at least controlling, such behaviour. The 'dominant stature' bias is related to our tendency to follow people who exhibit confidence, even when unwarranted: Chabris & Simons (2010) call this the 'illusion of confidence'.

The 'managed expectations' bias

The 'managed expectations' bias relates to the common need that scientists, policy makers and other professionals have to present their results and conclusions in ways that are more likely to be accepted by their colleagues and/or in a form that avoids jeopardy to their employment (i.e. their security and access to food and other resources, the bottom levels of Maslow's 'hierarchy of needs'). There are probably many psychological factors at play in this general bias, both at the level of the individual and his/her relations with a peer group. To take one well-known example, the 'loss aversion' heuristic (Kahneman 2011) affects our ability to have the most objective judgments. Our high sensitivity to avoidance of potential losses is what causes stockholders to sell their stocks more often than not at

the bottom of a market swing. Similarly, weather newscasters often announce with great confidence that a major snowstorm is most likely the next day, when the greater probability is that it will not occur. The newscaster (and perhaps also the forecaster) is managing societal expectations, and minimizing personal risk to continued employment, by over-weighting the likelihood of a negative event. Scientists are increasingly expected, beyond their duties, to seek objective knowledge, to be careful communicators of risk and to be sensitive to the management of public expectations. This reality is illustrated by the recent trial and conviction of seven Italian scientists to six-year prison terms because of their insufficient attention to public sensitivities (Cartlidge 2012; Marzocchi 2012; Boschi 2013). Managing expectations and the public's perception to risks and its need to find culprits to blame (or scapegoats: a basic social need according to Girardian anthropology, e.g. Girard 1987) is likely to affect how IEM results are used and presented to a broader public. It also has the potential to affect what science is conducted and presented by scientists.

The 'confirmation' bias

This type of bias, also referred to as 'myside' bias, is one of our most important biases. It allows us to quickly, and often efficiently, pursue or act on our beliefs. It also leads us to use, and filter, observations that seek to confirm our pre-existing mental models or conceptual models, rather than to try to discredit those models (Bacon 1620; Nickerson 1998). Confirmation bias minimizes the 'cognitive dissonance' between our existing beliefs and our behaviours and cognitive inputs: we tend to align our behaviour, and the information that we consider, with our pre-existing beliefs (Festinger 1957). Confirmation bias is likely to mislead us in the design and use of IEM in cases where behavioural responses have not been sufficiently conditioned from feedbacks and experiential learning, gained either earlier in our lives or in the human evolutionary past. We need to be cognizant and vigilant of a natural tendency to indulge in confirmation bias. A conscious effort to disprove or rigorously test our conceptual models, and our constructed IEM frameworks, is needed in our pursuit of improved ecosystem management actions for broad societal benefits.

A polymorphous complexity of human biases and limitations

There is a large literature of knowledge that relates to memory biases, human heuristics, social biases and the limits of our attention and logical thinking. Many of these biases and human limitations have

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been discovered through the examination of human rationality and the boundaries and conditions that affect its application (Simon 1990). Discussions of the many memory biases, cognitive biases and heuristic strategies that commonly affect human thinking and decision making can be found in textbooks such as Baron (2006); reference books such as Stanovich (2010); popular books such as Kahneman (2011), Ariely (2010) and Chabris & Simons (2010); scientific reviews aimed at applications such as medical diagnosis (Anderson 2012) or forecasting (Stewart 2001), and on the internet (e.g. Wikipedia 2015c, d). While biases and heuristics relate to the behaviour of individuals, social forces strongly affect them and end up also controlling the behaviour of social groups. Ariely (2010) gives the example of a small group that goes to dinner together, where each person sequentially orders their preference. He argues that the only person that undoubtedly orders what he or she desires is the first one to place their order. All others are generally affected by wanting to either support ordering decisions already made by others, or differentiate themselves by ordering something different. 'Framing' biases affect our judgments, not only through the company we keep, or the environments and habitats that house us, but also through the way information is presented to us. Even as highly educated individuals, we are more likely to decide in favour of a course of action when told that it has a 70% chance of success, than when told that it has a 30% chance of failure (Kahneman 2011).

Framing ourselves as scientists 'conducting objective science' ignores the frequent subjectivity of our judgments

Such judgments are often called into play, assuming that we are not complete robots and that we serve some purpose beyond that of inanimate computers. Instead of deluding ourselves through an 'objectivity frame', we would be better served acknowledging that we often make subjective judgments in the pursuit of science. *We should strive to discern, examine and understand our biases and subjectivity, and take appropriate countermeasures if needed.* As Stanovich & West (2003, p. 171) state:

People assess probabilities incorrectly, they display confirmation bias, they test hypotheses inefficiently, they violate the axioms of utility theory, they do not properly calibrate degrees of belief, they overproject their own opinions onto others, they display illogical framing effects, they uneconomically honor sunk costs, they allow prior knowledge to become implicated in deductive reasoning, and they display numerous other information processing biases.

Francis Bacon (1620) similarly realized that human minds distort reality when he introduced his classification of the 'idols of the mind': (1) the 'idols of the tribe' that innately affect all human beings; (2) the 'idols of the cave' that distinctively mould individuals (e.g. through their experiences or education); (3) the 'idols of the market place' that reflect the distortions of human communications; and (4) the 'idols of the theatre' that impose falsely constraining philosophies or mythologies. Scientists are not immune from these 'idols of the mind', especially when they remain unperceived and unacknowledged.

The 'eye of reality': a frame for knowledge simplicity, complexity and uncertainty

Human biases and limitations are most likely to affect, by being harder to counteract, our evaluations of uncertain, complex, dynamic systems, rather than our evaluations of simpler systems containing mostly factual, static, information. Finding the right level of simplification or of representation for different systems under different circumstances means estimating the level of unrepresented (or unknown) complexity. In terms of visual artistry, it means not just understanding the 'positive space' occupied by simulation model(s) and associated data, it also means having a reasonable level of understanding of the 'negative space' that is unoccupied by a modelling or information construct, i.e. the assumptions and other simplifications that have been made, the reality that is not represented or simulated.

As human beings, we may distinguish ourselves from other animal species through our propensity to derive abstract simplifications and symbolisms of reality. Although these abstract 'simple' constructions can sometimes lead us astray (Stanovich 2013), our mental models and conceptual frames provide essential guides, often unconsciously used, for our thinking and behaviour. Figure 1 illustrates what I call the 'eye of reality', a reference frame that may be useful in thinking about and classifying our human pursuit of knowledge. My frame depicts information that is:

- (1) known to be known, or that can at least be easily, logically or factually determined; or
- (2) known to be unknown – information that is indistinctly sensed or perceived or that is not easily available or determined; or
- (3) part of the 'unknown unknowns' – unknown information that we may really need but that we do not even know that we need.

The terminology of knowns and unknowns referred to above was presented by Donald Rumsfeld, US Secretary of Defense, at a news briefing

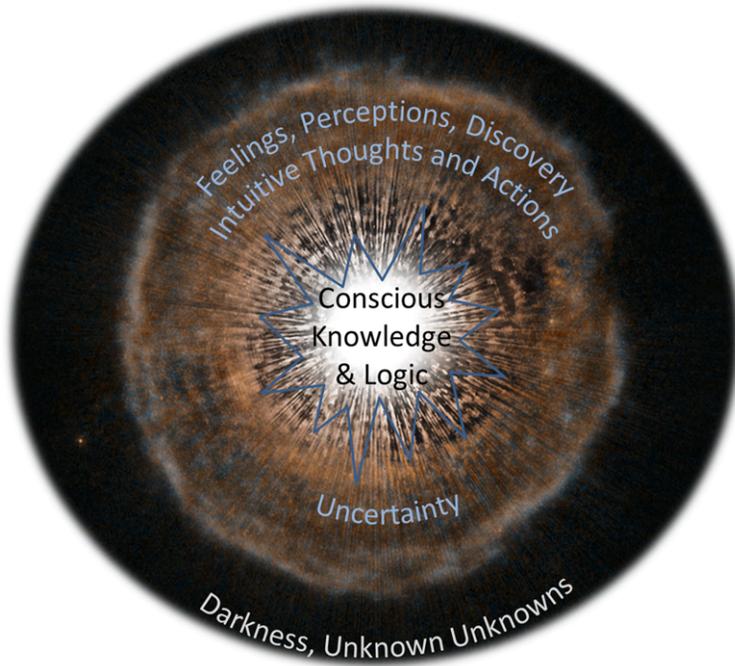


Fig. 1. The 'eye of reality': a representation of knowledge, perceptions, uncertainties and unknowns based on a photograph taken from the Hubble Space Telescope by the National Aeronautics and Space Administration (NASA) of an exploding Red Giant star, a dying unstable star that periodically 'blows a bubble', a nearly spherical shell of gas (http://www.nasa.gov/multimedia/imagegallery/image_feature_2302.html). Image used by permission from NASA (http://www.nasa.gov/audience/formedia/features/MP_Photo_Guidelines.html).

in February 2002 (Wikipedia 2015e). However, there are many antecedents to Rumsfeld's pronouncement going back all the way to the saying 'I know that I know nothing', i.e. the Socratic Paradox, attributed to Plato's accounts of the Greek philosopher (Wikipedia 2015f), which may in turn have originated from the Oracle of Delphi (Wikipedia 2015g).

The white core at the centre of the image represents the most objective and factual knowledge (or information) that we either have or can obtain relatively easily, for example, by quantitative monitoring of our resources and environments, or by applying the scientific method in its strictest form (Popper 1959, 1972), i.e. by seeking to refute a single hypothesis at a time through experiments or logical deductions. 'Normal' (as opposed to 'post-normal') science is part of this white core.

The irregular, star-shaped, blue line around the white core in Figure 1 represents the fact that we all make choices (often unconsciously) as to what hypotheses to test, what properties or entities to notice, observe or quantify, what expertise or fields of study to pursue, what minds to prod. Often our decisions, conscious or unconscious, are made on

the basis of vague perceptions, feelings or intuitions about what might be profitable pursuits in our seeking to explore the 'known unknowns', the speckled and striped brownish area in our diagram. This area of gaseous and increasingly unsubstantive materials represents our decreasing base of knowledge and perceptions as we move away from our white, most factual, core of information. Last but not least, the outer black area in the diagram represents the 'unknown unknowns', the dark matter that we can perhaps reduce through experience but, by definition, that we can never uncover (at least in the immediate).

How can our 'eye of reality' frame be used to address the human challenges of IEM? There are no easy, universal solutions. I would argue that explicitly recognizing and better defining the partitions between the three areas of knowledge are essential, as are attempts to recognize and analyse our human biases, limitations and heuristics that influence our judgments and actions, and invariably also affect our intuitions and creative thoughts. These intuitions and creative thoughts serve as whispered introductions to the 'known unknowns', and possibly eventually to the 'unknown unknowns'.

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Effectively using these ‘whispers’ requires cognizance and understanding of our human biases and limitations, their evolutionary, individual and/or societal origins, and a comparison with the issues and systems at hand. This understanding is critical. Are the ‘whispers’ helpful and appropriate in evaluating or thinking about a particular issue or system? Or do they need to be counteracted?

Addressing the human challenges of IEM

Devising methods and processes to address the human challenges of IEM, and the complexities and uncertainties of the studied systems and issues, is a major area of study. I can only provide initial suggestions that may be helpful in addressing these challenges, beyond the first steps, which are to take greater, explicit, cognizance of human biases and behaviours and to use appropriate knowledge frames, such as ‘the eye of reality’ discussed above.

Appropriate simplicity, adaptive compensations

The efficiency of simplicity is compelling. Simplicity breeds clear understanding by a large community, efficiency of study and minimization of short-term costs. Management and policy actions are generally not taken if a simple enough understanding cannot be achieved by a non-specialist community. Integrated modelling will necessarily breed complexity. The success of IEM is dependent on its ability to model complex and multiple processes; but it is also strongly dependent on being able to reduce that complexity into simple enough descriptions and processes that can be clearly understood by a large community, and that will therefore lead to implementation of reasonable management and policy actions.

The downside of simplicity is that it includes and/or engenders human (or technical) biases, oversights or errors that may need to be compensated for. Adaptive management, sometimes simply called ‘learning by doing’, theoretically provides an iterative way to evaluate information, outline expectations and take actions in the face of uncertainty and complexity, while allowing for later modifications of the actions taken or policies developed as more information and knowledge accrue. As pointed out earlier, adaptive management supported by IEM can improve the management of our natural resources and environments. Adaptive management is not a panacea that will be suitable for all types of situations (Norton & Reckhow 2008; Craig & Ruhl 2014). It will not be a suitable strategy for situations where follow-through monitoring, evaluations and adaptive actions are unlikely. Ethical

or legal reasons can also prevent its use. Adaptive management (and the use of IEM) may also fail in managing systems that have lagged or highly non-linear responses, that have too high a complexity or unobservable causative drivers and feedbacks, or that have threshold responses from which there may be no recovery.

Structured processes to address complexity

The intrinsic complexity of integrated modelling is unavoidable. It requires adequate understanding and simulation of a wide diversity of processes studied (or monitored) by a wide diversity of communities. It involves simulation of a web of interdependent cascading processes that sometimes have threshold behaviours or other non-linear behaviours, and where the importance, or lack of importance, of any given process in the simulation may be something that varies depending on system conditions, spatial and temporal variations, and the consideration (or lack thereof) of other processes. The key to addressing and managing this complexity is to structure, layer, compartmentalize and abstract it in a scalable manner (i.e. simplify it). There are multiple reasons for doing this, which include not only the technical traceability, accountability and use of IEM, but also our fundamental human needs for appropriate and scalable simplicity in visualizing, understanding and sharing the information and knowledge provided by IEM amongst a user community. Additionally, structured complexity and scalable simplicity/abstraction may help quicken understanding and response to unanticipated impacts from decisions or actions taken as a result of an IEM process.

Another way of keeping complexity manageable and understandable is to build it gradually over time into integrated models, perhaps by building on a series of simple models. Alternatively, a more problematic approach is to reduce complexity, that is, to develop general, highly inclusive, complex models, and to reduce their complexity from the top down. While this approach may lead to significant errors and problems related to a lack of detailed understanding of the models, it has the merit of allowing for the simulation of processes that might not have been accounted for in models built from the bottom up. Modelling results from this top-down approach must be carefully considered to avoid their misuse.

Participatory processes

Education of the scientific community and of the wider public to enable them to achieve a greater

level of comfort and understanding of the capabilities, and limits, of IEM is also needed. Learning may be enhanced through the advent and propagation of new visualization tools, gaming methods and other learning technologies. Perhaps most importantly, education of a wider community can be achieved by encouraging their greater participation in IEM (Voinov & Gaddis 2008; Voinov & Bousquet 2010) in the assembly and use of models to explore and foster understanding of complex systems, or to build scenarios and modelling forecasts (Alcamo 2008; Alcamo & Henrichs 2008; Pahl-wostl 2008). Mediated modelling (Van den Belt 2004), also known as cooperative modelling or participatory modelling, can often provide a useful, structured approach to engage stakeholders and the interested public, together with scientists and other professionals, in helping manage resources and environments. Cockerill *et al.* (2006) provide an excellent account of the strengths and weaknesses of a cooperative modelling project that was used to inform and help select water management options for the Middle Rio Grande (MRG) basin in New Mexico. The cooperative modelling simulated a wide diversity of hydrological and ecosystem processes, including human infrastructure and the impacts of human activities on the landscape. The model and water management scenarios developed helped gain public and stakeholder understanding of the complex system dynamics in the basin and of the trade-offs involved in different management options. The modelling effort ultimately informed the water management plan developed for the MRG basin in 2004 (MRG Water Assembly 2004).

Lessons from a painting: structuring community interactions, using new modes of representation, finding the missing, seeking the 'unknowns'

Jakeman *et al.* (2008, p. 4) state:

Modelling should be about the systematic organization of data, assumptions and knowledge for a specific purpose. In the environmental domain the main reasons for modelling are for knowledge generation and sharing in order to inform a decision that could be for operational management or strategic policy development and implementation.

Clearly, human behaviour and judgment enter the process of assembling and using models. Consequently, just as it is important to build structured, scalable simplicity and abstraction in IEM tools and representations, it is also important to structure and systematically trace and account for human and social interactions during the assembly and use of IEM. These human and social interactions are inherently complex. They include: (1) stakeholder

engagement and learning processes; (2) the accounting and management of multiple perspectives or human information sources; (3) the creative exploration of individual intuitions or perceptions; (4) the recognition, understanding and possible counteraction of human biases and limitations; and (5) decision trees or other methods to trace the construction, evolution and use of IEM.

We should consider using a greater diversity of media and forms of communication and representation to creatively explore our conceptual models, frames of reference and our simplifications in the pursuit of the 'known unknowns' and the 'unknown unknowns' that ideally should be considered in IEM. Here, I use a painting by the American neo-impressionist painter Maurice Prendergast to illustrate some points about the structuring of community and social interactions and the building and use of integrated models (cf. Fig. 2). *A painting represents an integrated expression of mind, experiences and vision, sometimes conscious, sometimes not; in other words, it has many of the characteristics of an integrated model.* The painting in Figure 2 depicts a colourful community enjoying what looks like a leisurely weekend day in the wonderfully structured city of Venice. The painting shows at least three bridges and a multitude of buildings, located alongside the Venetian lagoon, that share similar architectural designs and height and width constraints while avoiding blandness of uniformity. An analogy can be drawn here with the modular structures and connection standards of IEM. There is a sense of purpose in the movements of the crowd, as most (but not all) people seem to be moving away from the painter, towards some common objective or attractor. The painting, through its depiction of Venice and its ordered community, celebrates the spirit of human enterprise and organization. Can IEM achieve a similar spirit of purpose, enterprise and organization?

Now, what is the missing from the information frame of Figure 2? What is the 'negative space' unrepresented but perhaps defined by the painting? The incomplete outline of a person in the lower right is a symbol of missing information and knowledge. There seems to be a lack of diversity in the social classes, professions, origins and other characteristics of the people represented. Does this mean that the collective knowledge base of the community has an impoverished diversity of perspectives? Does the relative uniformity and beauty of their constructs, buildings and bridges point to an attractive form of groupthink? Would a greater diversity of people and constructions provide feedback mechanisms that could help the community and the city avoid a future tragedy, such as one caused by climate change, sea-level rise, and an overconcentration of people and infrastructure in a vulnerable area?

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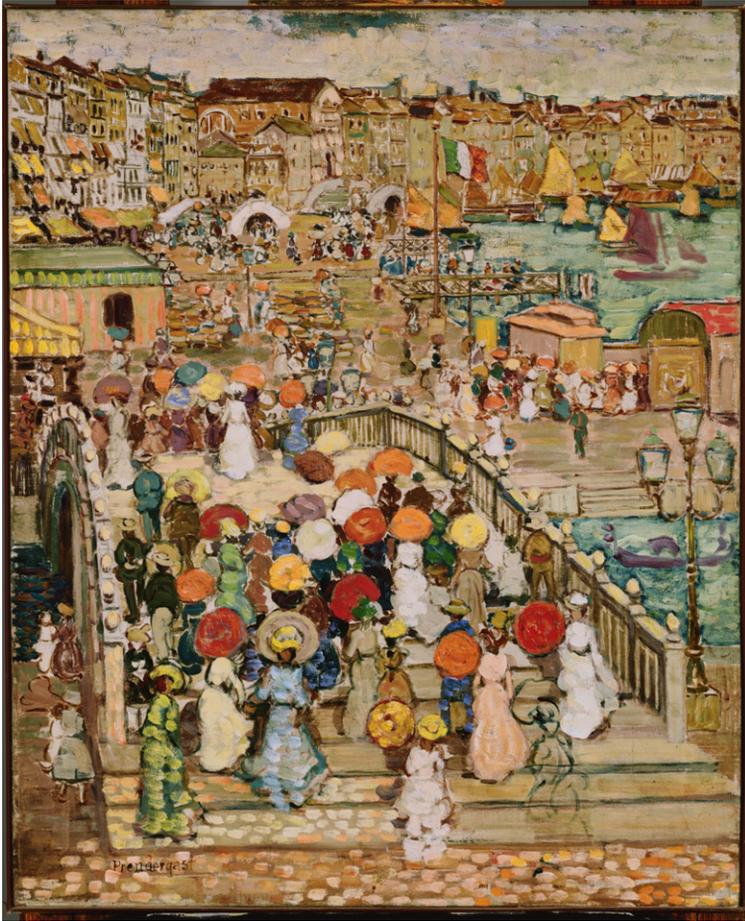


Fig. 2. Maurice Prendergast's (1858–1924) painting of the Ponte della Paglia in Venice. The American post-impressionist painter started the painting during his visit to Venice in 1898–1899 but extensively repainted and completed it two decades later in 1922. Photograph provided, with permission to reproduce it in this article, by the Phillips Collection, Washington DC (http://www.phillipscollection.org/research/american_art/artwork/Prendergast-Ponte_Paglia.htm).

Planning for the future requires understanding past conditions that might have given rise to currently observed realities. Venice developed in marshlands near the sea. The community initially took advantage of the fishing opportunities provided by the lagoon and the marshes, and also periodically sought refuge from Germanic and Hun invasions. As Venice grew in power and infrastructure, so did its commerce and trade. Venice was positioned in an ecotone, an ecologically rich transition area between two biomes. Venice shows man's taming and use of this rich natural ecotone. Because it creates bridges across spatial and temporal scales and across knowledge domains, IEM also has a form of 'ecological richness'. IEM can also serve

as a monument to human enterprise and organization. Both Venice and IEM, however, are susceptible to possible failure, possibly made worse or more catastrophic by initial achievements and by groupthink (Janis 1972). Can/should we provide resilience to our IEM constructs? Providing structured processes, transparent assumptions, shared knowledge, structured communities and inclusive participation is essential, but insufficient in testing for resilience of IEM constructs.

Red teams storming

As exemplified – so far – by the history of Venice and its frequent flooding, cities and communities

have the potential to grow more resilient and/or to adapt to changes when they are tested by disturbances or perturbations of suitable magnitude. A well-known hypothesis in ecology, the 'Intermediate Disturbance Hypothesis' (e.g. Connell 1978), similarly suggests that smaller disturbances of appropriate intermediate frequency can sometimes, but not always, help avert much bigger catastrophes. This hypothesis is still the subject of significant debate (e.g. Fox 2013; Sheil & Burslem 2013). By analogy, IEM frameworks, and the associated understanding and prediction generated through IEM, may also develop greater resiliency and confidence if they are tested through the efforts of small teams that question or seek to invalidate aspects or assumptions related to a particular IEM effort and its application. Groupthink is the enemy of IEM resilience, honesty and transparency, and of the effort to improve management of resource and environment systems. There are several ways to avoid groupthink in IEM. One way is to set up small groups that compete to achieve some stated IEM objectives. A problem with this approach is that it probably requires metrics of success or of achievement to be made explicitly ahead of the competition, when the end results needed may still be relatively undefined. Another way is to conduct 'in-process reviews' by independent panels that seek to assess and constructively address IEM limitations. In my view, the 'constructionist' expectations mean that these panels may be insufficiently autonomous and insufficiently vigorous in their identification, testing and review of IEM vulnerabilities. A better approach may be to create independent, innovative, highly focused 'red teams' that actively fight groupthink and confirmation bias, and try to 'storm' the IEM construct during its assembly, during interpretation of its outputs or during discussions of its use or applications. 'Red Teaming' is a structured testing approach commonly used to test security processes in military and intelligence operations, or to provide 'alternative analyses' of a given situation (United Kingdom Ministry of Defence 2013).

Behavioural biogeosciences: a new area of study supported by IEM

We are not well adapted to address resource and environment issues that differ from those experienced in our human evolutionary past, and/or that have not provided frequent, sharply experienced feedbacks at the level of the individual, or of a local community. The behavioural sciences can help us understand the extent to which our biases are the result of our evolutionary adaptation to threats and opportunities in our ecosystems. They can tell us when those adaptations may not provide the best solutions to managing our ecosystems

(and ourselves), for example, because the temporal and spatial scales of reference, or the dynamics of change, are outside of our natural adaptive capabilities. The behavioural sciences can help us take cognizance of, and when appropriate compensate for, human limitations in our organized pursuit of knowledge and its applications, including our construction and use of IEM. These limitations extend beyond the biases and heuristics that are discussed in this paper, and beyond the natural, but sometimes inappropriate, prioritizations of our human cognition and attention, as also mentioned earlier. The behavioural sciences can help us understand the useful, but often biased, wellsprings of human intuition, creativity and abstract thought. These are characteristics of our species that help us explore new frontiers of knowledge.

Understanding the full complexity and dynamics of ecosystem processes, correctly assessing their relative importance under different conditions, and therefore their appropriate prioritizations and simplifications during model construction and use, should not be an area of study where only biologists and ecologists participate while primarily focused on biota and on the easily visible. Understanding the dynamic complexity of the physical processes affecting our habitats, our security and our access to water, energy and minerals is equally important. We need to quantitatively monitor those physical processes, and also strive to quantitatively assess or monitor the dynamics of food webs and biotic populations. IEM can provide tools that help organize and maximize our knowledge of the biogeosciences, while also taking into explicit account our human needs, responses and biases. Study of the 'behavioural biogeosciences' needs to become an integral part of IEM.

Expanding our knowledge beyond our current human limitations: some additional thoughts

The suggestions provided above are complementary to what we already know is important in the proper construction and use of numerical models. The construction, interpretation and application of IEM should follow the standards of good modelling practice and scenario building (examples of some excellent reviews are: Alcamo & Henrichs 2008; Crout *et al.* 2008; Schmolke *et al.* 2010; Saltelli & Funto-wicz 2014). *Most importantly, models should be considered as tools for gaining system understanding, rather than revered as providing near-absolute truth(s) once they happen to have been calibrated and tested (i.e. considered 'validated' in some engineering terminology).* Models must also strike the right balance between simplicity and complexity, a balance that will probably vary depending on modelling objectives and available knowledge.

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These principles have been well articulated in several reviews and commentaries on the topic (e.g. Konikow & Bredehoeft 1992; Bredehoeft & Konikow 1993, 2012; Konikow 2011; Voss 2011*a*, 2011*b*; Nordstrom 2012). Models should also reflect a balance between (1) the description of process theory or knowledge and (2) available observations and quantitative measurements. As Kirchner (2006, p. 1) states:

... scientific progress will mostly be achieved through the collision of theory and data, rather than through increasingly elaborate and parameter-rich models that may succeed as mathematical marionettes, dancing to match the calibration data even if their underlying premises are unrealistic.

For IEM in particular, this means that we must put greater emphasis on the most objective part of the scientific enterprise – observations and monitoring – even though we should still use models to help organize available information and decide how, when and where to possibly collect more. Human biases and limitations affect our conceptual models that, together with practical realities, commonly drive our observations and monitoring programmes. Statistical analyses, visualization and other technology tools, when honestly and efficiently used (Tufté 1983, 1990, 1997), may provide useful techniques to help us take cognizance of our biases and subjectivity, whether (1) organizing available information or (2) transforming, agglomerating/reducing or extending information through our models. But fundamentally, improved management of our natural resources and environments through the use of IEM will depend on accessibility to well-characterized, multi-scale, long-term, observations and monitoring (Lovett *et al.* 2007; Keeling 2008; Lins *et al.* 2010). Factual observations and monitoring are critical parts of the white core of our ‘eye of reality’.

Summary comments

Integrated Environmental Modelling (IEM) is needed to help communities better manage the complex and dynamic ecosystems that provide natural resources and form their environments. IEM can (1) help organize and transform basic information (observations, quantitative measurements), (2) complement (or test) existing knowledge, and (3) sometimes provide new knowledge or insights that can help society manage its resources and environments. To be understandable, and therefore usable, by a broad community, IEM will always involve simplifications. Those simplifications will sometimes be consciously made, and sometimes will be unconsciously decided. This paper has provided

examples of a diversity of human biases and heuristics that may also affect how IEMs are assembled, interpreted and applied.

Essentially, there are three steps that are needed at every stage of the IEM construction, interpretation and application process.

- First, all available information and knowledge needs critical examination. In artistic terms, this corresponds to examining the ‘positive space’ occupied by our knowledge base.
- Second, conscious, critical examination is required, to the extent possible, of what is not included in an IEM construct or application. This can be thought of as examining the ‘negative space’ of the IEM construct and application.
- Third, IEM developers, interpreters and users need to take active cognizance, to the extent possible, of the inherent human biases and heuristics that may have (1) affected their definitions of positive and negative space, or (2) influenced their information and knowledge base and, consequently, any modelling constructs and uses.

There will always be ‘unknown unknowns’ that surprise or confound IEM developers and users. The three-step process suggested here seeks to decrease the number of surprises, while maintaining an attitude of watchful humility. Several other specific suggestions may help address the human challenges of IEM. These include:

- (1) testing/auditing model predictions and management policies through an adaptive management iterative process, when feasible;
- (2) using structured processes – such as progressive complexity and/or progressive model reduction – to test for appropriate simplicity, and to maximize understanding and transparency of IEM constructs and use;
- (3) participatory modelling to engage a diversity of perspectives, and grow stakeholder and expert understanding and use of IEM;
- (4) developing structured processes to systematically account for human behaviour (including human biases) and social interactions, and to maximize effective use of IEM for larger scale, longer term issues, i.e. for problems that humans are not naturally adapted to address;
- (5) using creative forms of communication and representation to explore intuitions, conceptual models, simplifications and transient frames of reference, in the pursuit of the ‘known unknowns’ and the ‘unknown unknowns’;
- (6) soliciting ‘red team’ raids at all stages of IEM construction and use to elicit greater critical thinking, and avoid (or at least control) group-think and confirmation bias;

- (7) forming a new area of study in the 'behavioural biogeosciences' that melds the knowledge of behavioural scientists with that of biologists and ecologists, and especially with the expertise of physical scientists engaged in the quantitative description and monitoring of ecosystem processes;
- (8) maximizing smart, efficient and honest practices, not only in modelling activities, but also in information gathering (i.e. observations and monitoring) and visualization.

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