Developing a Concept of Adaptive Community Learning:
Case Study of a Rapidly Urbanizing Watershed

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ABSTRACT

An iterative approach to working with a community's environmental concerns, at the interface between science and society, is presented. We call this adaptive community learning, within which the principles of adaptive environmental assessment and management are embedded. Handling uncertainty – indeed, gross uncertainty – is integral to our approach. We place our discussion in the context of the evolving foundations of the kind of science needed to address contemporary issues of the environment and sustainability. We then illustrate development and application of our approach in a prototypical case study of managing the quality of Lake Lanier, Georgia (USA), in the face of potentially significant suburbanisation of its watershed. Our primary purpose is to communicate the entirety of the approach as succinctly as possible, without the clutter of the specific results emerging in the several disciplines keyed into the project as a whole.

Keywords: adaptive community learning, cultural theory, environmental foresight, eutrophication, foodweb modelling, inverse methods, sensitivity analysis, stakeholder futures, sustainability science, uncertainty, watershed management.

1. INTRODUCTION

Until recently, managing water quality in a watershed was widely viewed as a matter of installing (and operating) an infrastructure to deal with pollution from industrial and domestic urban sewage. Data on discharges and pollutant loads from a population equivalent, generated or collected from within a government bureaucracy, were used by professional engineers to specify the level of infrastructure that would be necessary for either a final effluent or a section of river to meet a particular chemical composition. This conceptual, and (eventually) literal, transformation of untreated pollutant fluxes into river water of a specified quality was based on scientific principles developed since the early 1900s. From the 1960s onwards they were implemented in an increasingly systematic manner through the mathematical models, optimisation, and decision-support schemes of applied systems analysis (see, for example, [1]). For most of the past century, notably following the advent of the profession of sanitary engineer-ing, the general public had essentially no interest in knowing what these scientific principles might be [2].

We now recognise – and must always (self-evidently) have known – that the river network is defined by the geographical and topographical features of the watershed, hence the movement of water above and below the land surface; that there are people, animals, plants, and vegetation on this surface; and that all the metabolism on, and attributes of, the surface cause materials (many considered as pollutants) to be deposited on it and moved across it by precipitation-induced fluxes of water. Similarly, we can recognise that through the society and economy in which they participate, *people* cause degradation of water quality, *not* the inanimate "population equivalent," or the "some-how people-divorced" wastewater treatment plant of the local, municipal government. This sense of detachment of the person from the problem, which is marked in the urban environment, cannot obtain so readily in the rural environment. There, individual farmers are unmistakably responsible for the distribution and manipulation of the behaviour

of plant and animal communities over the land surface (and thus the degradation of water quality). People too participate much more than previously – in living memory – in *their* aquatic environment, partly because of the growing awareness of man's impact on the environment and the successful restoration of improved surface water quality (devoid, on average, in some places, of significant contamination from the social and economic metabolism of the city). It is they, the people, and their domestic pets, who contract illnesses from contact with the water. It is they who are disadvantaged if the sport fishery, restored through a more complete wastewater infrastructure and thus healthier ecosystem in the lake or river, is threatened in the short-term by a treatment plant failure or in the long-term by climate change, or whatever [3].

In the post-modern idiom,[1] then, it is decreasingly the technocracy of government officials and consulting engineers to whom authority will be delegated to come up with infrastructures, plans and regulations to protect water quality on behalf of the people. Rather, in the coming years, the "democracy" of public participation in this process can be expected to determine the course of watershed management [4]. Indeed, scientists and engineers are increasingly unlikely to be left to their own devices, to be judged by their peers alone. In an era of what Funtowicz and Ravetz [5] have called post-normal science, scientific and engineering works will legitimately be exposed to path-defining scrutiny and review by scientifically and technologically lay persons. Fundamentally, ordinary members of the general public, it has been argued, will determine the adoption of new technologies [6].

In sum, we seek a means of managing community-environment interactions in a manner lying somewhere between "the relatively undisciplined discourse of ordinary language" and "the algorithmic (but incomplete) models of technical policy analysts such as risk assessors or microeconomists" [7]. We acknowledge that the hopes and fears of the community for the future do not remain invariant over time, and that the science base is itself evolving over time; we recognise further that these outlooks of the community will change in the light of interaction with an appropriately articulated view of the evolving science base. Our search is for a process we shall call adaptive community learning.

In this paper we report results from a prototypical case study of a rapidly urbanising watershed – Lake Lanier, Georgia, just to the north of metropolitan Atlanta – where preservation of ecological integrity in the long term is perceived to be at stake. The intensity of development in this particular conurbation can be gauged by the fact that a

wastewater treatment plant, whose price might ordinarily have been some $60 M, has been constructed at a cost of $260 M – because one of the local counties not only draws it water supply from Lanier but is facing the prospect of returning its reclaimed water back to Lanier. We first set out the procedure of adaptive community learning, including a computational scheme for cultivating stakeholder-driven environment foresight, and then proceed to illustrate application of one cycle of the procedure to the Lanier case study. In several respects this study allows us to demonstrate elaboration of the manifesto of Beck [8], on a suitably coherent and challenging problem of immediate, practical significance. More specific results emerging from the several, constituent disciplinary perspectives on this project are in the process of being reported elsewhere.

2. ADAPTIVE COMMUNITY LEARNING AND ENVIRONMENTAL FORESIGHT

We make decisions on the basis of as much relevant information as possible, including information about projected future behaviour: from the consequences of current policy (in the short term) and from the threats to our environment lying just beyond the horizon (in the longer term). We should welcome environmental foresight [9] and ought, therefore, to be engaging in forms of enquiry organised specifically for this purpose [8]. Given a model, and given the assumed meteorological disturbances of the watershed, assumed changes (if any) of land use, and the controls to be installed (wastewater treatment plants, best management practices (BMPs), and so on), it ought to be possible to generate reasonably clear foresight for the short term, over the next few years (for example Rousseau et al. [10]). This, no matter how complicated, is nevertheless foresight in the form of smooth extrapolation from past conditions. Yet policy-makers and the public (especially) tend to be more fearful of the possibilities of nonlinear dislocations and surprises in the future behaviour of environmental systems than of the likelihood of smooth extrapolations of current trends [11]. Indeed, we are really rather creative in imagining what may go wrong [12]. Most of us *are* disturbed by the thought that our environment may yet come to differ significantly from what we have known in our life-times. In the case of Lake Lanier, our survey of stakeholder perspectives reflects just such a pessimism: that things will be worse in the longer term than the more immediate concerns in the shorter term [13]. There are stakeholders taking the decidedly long-term view when they express the hope that their grandchildren will be able to fish for striped bass in the lake, just as they have done.

This making of decisions is not a static thing, however, wherein the participation of the community occurs once and for all during a process itself restricted to a finite period of time [14, 15]. Our challenge, then, is to assess how

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[1]By "post-modern" in this context we wish to acknowledge a declining faith in the usefulness of analytic systems based on the modernist assumption of an "objective" Newtonian world, which can be viewed by detached observers, who are assumed to have no impact on the behaviour of the system they observe and analyse.

community views (on preserving a given piece of the environment) may change over time as a function of iterative interaction with the science base, within the overall framework of adaptive community learning. We know what adaptive management is [16]. In essence, policy therein fulfils two functions: to probe the behaviour of the environmental system in a manner designed to reduce uncertainty about that behaviour, i.e., to enhance learning about the nature of the *physical* system; and to bring about some form of desired behaviour in that system. Adaptive community learning ought both to subsume the principles of adaptive management (so defined) and include actions, or a process of decision-making, whereby the community of stakeholders experiences learning about *itself*, its relationship with the valued piece of the environment, i.e., the community-environment relationship, and the functioning of the physical environment. Just as adaptive management celebrates a prudent measure of experimentation, so does adaptive community learning [7]. The process will be one of "always learning, never getting it right" [17]. In this, the community of stakeholders is interpreted in a much broader sense than merely stakeholders as policy persons/managers. Indeed, the scientifically lay stakeholder is pivotal in the procedure, as will become apparent.

2.1. Adaptive Community Learning: The Procedure

The prototypical shell of our procedure involves an iterative, cyclical process entailing the following elements, and largely in this sequence: (i) identifying stakeholder concerns for the future; (ii) developing mathematical models, as maps of the current science base (with all its uncertainties, knowns, partially knowns, and unknowns), to assist in exploring those concerns; (iii) formal, computational assessment of the stakeholder-generated, potential futures; (iv) communicating to stakeholders the plausibility or otherwise of their feared/hoped-for futures; (v) identifying the key scientific unknowns (critical model parameters) on which realisation of the potential future outcomes may crucially turn; and (vi) designing further experimental/field tests to reduce the uncertainty of the key unknowns, in turn to reduce the uncertainty of any forecast future outcomes.

The cycle of this process is completed thus. If, during step (iv), stakeholder fears for the future appear to be groundless, or their hopes not attainable, then in some manner assistance must be provided for their outlooks to be encouraged to move on towards a revised set of concerns, which brings the procedure back again to its first step, ready for another iteration. From the perspective of the scientists participating in the process, they should derive therefrom a set of priorities for the allocation of further scientific effort tailored to the concerns of the community (steps (v) and (vi)). For no environmental problem will there ever be funds sufficient to purchase more science for resolving all the unknowns

possibly germane to the issue at hand. Steps (v) and (vi) are therefore essentially about setting priorities for the scientific agenda, as we continually move into the future. Their outcomes should in due course find their way back into step (ii), into a revised map of the science base (a revised computational model), with which to explore the evolving landscape of stakeholder hopes and fears.

2.2. Environmental Foresight: Computational Aspects

The science base itself does not stand still, as we have said, any more than the continually evolving hopes, fears, and aspirations of the community for the future. We clearly cannot know everything about the structure of the environment's behaviour for the next twenty-five years – certainly not for the biological and ecological facets thereof [18]. It is doubtful too whether we are any longer in a position to "validate" our models in the classical sense of this term [19, 20]. How then shall we deal with our fears of substantial change in the longer-term future, of nonlinear dislocations and unwelcome surprises? What models might we construct and manipulate for this particular purpose? What broader framework of enquiry should be developed and employed to generate the kind of foresight recommended by the US EPA's Science Advisory Board [9]?

There is, without belittling it, the obvious response: an area is to be identified in which scientific data are sparse and/or in conflict and the scientist conducting the enquiry is to submit – to the process of scientific peer review – an opinion on the interpretation of the data as portending some threat to the environment. In other words, the extant historical record gathered within the paradigm of (normal) scientific enquiry is to be examined and interpreted by a practising scientist whose opinion will be judged by other practising scientists. Put cryptically, such a foresight-generating framework taps into the combination of {scientific empirical observations & scientific opinion}. Worthy and necessary though this is, it is not the only thing that could be done. Cast in like terms, our procedure of adaptive community learning – as now defined and as encompassing an alternative line of enquiry – draws upon a combination of {scientific models & stakeholder imagination}. It differs in both elements from that of {scientific empirical observations & scientific opinion}, offering thus a wider search for the possibility of surprises and being undoubtedly eclectic, if unconventional, in the sources of information into which it taps. It has about it a whiff of the public directing upon which issues the torchlight of scientific enquiry is to be shone.

At the computational core of the procedure lies the following. In essence, the "scientific model" must be reconciled with the "stakeholder imagination," in much the same way as we would implement the familiar procedure of model calibration, of reconciling the model with observed

past behaviour [8]. Suppose, then, the behaviour of the given environmental system – in our case the aquatic foodweb of Lake Lanier [21] – can be defined according to the following (lumped-parameter) representation of the state variable dynamics,

$$dx(t)/dt = f\{x, u, \alpha; t\} + \xi(t) \qquad (1a)$$

with observed outputs being defined as follows,

$$y(t) = h\{x, \alpha; t\} + \eta(t) \qquad (1b)$$

in which f and h are vectors of nonlinear functions, u, x, and y are the input, state, and output vectors, respectively, α is a vector of model parameters, ξ and η are notional representations respectively of those attributes of behaviour and output observation that are not to be included in the model in specific form, and t is continuous time. Should it be necessary, spatial variability of the system's state can be assumed to be accounted for by, for example, the use of several state variables of the same attribute of interest at the several defined locations. In this, the vector α can usefully be thought of as a set of tags representing all the knowns, partially knowns, and unknowns in the "scientific model." Suppose further that our empirical experience of the lake's behaviour in the past (t^-) may be expressed as

$$\bar{y}^l \leq \hat{y}(t^-) \leq \bar{y}^u \qquad (2a)$$

$$\underline{y}^l \leq \hat{y}(t^-) \leq \underline{y}^u \qquad (2b)$$

while the hopes and fears of the community for its behaviour in the future (t^+) may be expressed as

$$y_d^l \leq \hat{y}(t^+) \leq y_d^u \qquad (3a)$$

$$y_f^l \leq \hat{y}(t^+) \leq y_f^u \qquad (3b)$$

Here superscripts l and u denote respectively lower and upper bounds on the various domains of behaviour, i.e., those with acceptable ($\bar{y}$) and unacceptable ($\underline{y}$) similarity with the recorded experience of past behaviour (in Equation 2(a) and (b) respectively), and those desired (y_d) and feared (y_f) in the future (in Equation 3(a) and (b) respectively). Equation 2(a) and (b) might typically be complementary and collectively exhaustive, i.e., $\hat{y}(t^-)$ in Equation 2(b) would be anything but that which satisfies Equation 2(a), as here. The same does not necessarily hold for considerations of the future. For example, desired behaviour would usually make reference to some domain quite distinct from feared behaviour, without excluding radically different behaviour, which may (surprisingly) be different from both.

Importantly, in adaptive community learning it is the scientifically lay stakeholders whose imagination of the future is encoded into Equation (3) to become the formal realisation of the "stakeholder imagination." The "scientific model," epitomised by the vector of parameters α in

Equation 1, is thus to be reconciled with these target, future definitions of behaviour. Just as the utility of model calibration lies in the fact that observed past data are a source of knowledge about the behaviour of the system that is maximally independent of theory, as realised in the model, so too here the worth of our approach rests on the authorship of Equations 1 and 3 being likewise *maximally distinct*. Little or nothing would have been learned about the possible threats to our environment were the model of Equation 1 to be reconciled with its self-same author's imagination of the future in Equation 3. We can now see, therefore, how the community of stakeholders can derive from the process a sense of the plausibility or otherwise of their hopes and fears for the future: it will appear formally as something like a probability of entering into the domains of behaviour (y) of Equation 3. The scientists, from their perspective, can derive a sense of the priorities for allocating the limited resources of further scientific enquiry: it resides in the subset of model parameters – labelled $\{\alpha^K(t^+)\}$ – found to be key (as opposed to redundant) in discriminating whether such entry into the feared/hoped-for domains is likely to occur or not.

Much uncertainty formally surrounds this computational procedure. Theory is not utterly secure in environmental science (indeed, far from it, as we have already observed). Wide bounds may attach to the range of values the parameters α may assume in the "scientific model" so that, when realised through Monte Carlo simulation, wide distributions of model-generated outcomes, $\hat{y}$, must be assessed in Equation 3. The domains of the "stakeholder imagination" will themselves also be highly uncertain, with a broad spread of possibilities reflected in the bounds y_d^l, y_d^u, y_f^l, and y_f^u in Equation 3. Our computational approach for accommodating these gross uncertainties [22–24] is based on the concept of a Regionalised Sensitivity Analysis [25–27] extended and modified through a Tree Structured Density Estimation (TSDE) procedure and a Uniform Coverage by Probabilistic Rejection (UCPR) sampling procedure for enabling and strengthening the required multivariate (as opposed to univariate) statistical assessment.

2.3. Sustainability Science

The notion of a "Sustainability Science" – as perhaps a part of post-normal science – is newly minted, or at least a call has recently been made for such a science to embrace the following elements [28]:

> . . . [I]nverse approaches that start from outcomes to be avoided and work backwards to identify relatively safe corridors for a sustainability transition.

> . . . [T]he systematic use of networks for the utilization of expertise and the promotion of social learning.

... [I]n a world put at risk by the unintended consequences of scientific progress, participatory procedures involving scientists, stakeholders, advocates, active citizens, and users of knowledge ...

What has been set out in the foregoing of adaptive community learning and its embedded form of generating environmental foresight (unmistakably an "inverse approach"; [8]) will sit comfortably with these principles. As science goes, thus go engineering and technology, we assert. We may suppose the same sort of strategic changes will begin to determine the use of engineering in developing new technology for integrated water resources management and sustainable development.

3. CASE STUDY

Lake Lanier, located to the north of Atlanta and lying between the development corridors of interstate highways I-75 and I-85, is the single-most important impoundment in Georgia and the subject of intense public and policy scrutiny. Created in 1958 on the Upper Chattahoochee River the lake occupies 15,400 hectares. Its watershed is some 2,704 km^2 in extent, encompassing the foothills of the Appalachian Mountains to the north, and covering a variety of land uses, including significant poultry and pig production, silviculture, and – increasingly from the south – suburbanization. In 1989 land cover in Lanier's watershed was categorized as: open water 6%, forest 77%, urban 3%, pasture 9%, crops 4%, others 1%. By 1997 the urban category had increased to10%, largely at the expense of pasture and crops, which had fallen to 5% and 1%, respectively. Lanier itself is a multi-purpose impoundment, providing hydro-electric power generation, flood protection, drinking water supply, and recreational resources. The growing pressure of these land and water uses on Lake Lanier and its watershed are palpable in a variety of ways: Lanier's water resources are the focus of protracted negotiations among Georgia, Alabama, and Florida over access to streamflows in the Chattahoochee River network (including the Apalachicola and Flint basins); Georgia has been suffering from a drought of several years' duration; 80% of metropolitan Atlanta's water supply is from the surface waters of the Upper Chattahoochee watershed [29]; and the cost of providing wastewater infrastructure in Lanier's watershed, as already observed, may be more than quadruple the norm.^{2} In addition, the state of Georgia is implementing its Total Maximum Daily Load (TMDL) program – for comprehensive watershed management – under an especially tight

Consent Decree Order from the US Federal District Court (Sierra Club et al. vs. EPA).

3.1. Cultivating Stakeholder Imagination: Survey and Workshop

Exactly how one identifies "stakeholder concerns for the (longer-term) future" and then translates them into the quantitative form of Equation 3 is not straightforward. To begin with, the identities of the stakeholders must be apparent; and choosing to establish a dialogue with a representative sample of them should avoid being elitist, if it is to be rigorous [4]. If the broadest possible span of potential futures is to be explored, the kind of perspective an individual adopts on the man-environment relationship can be especially important. Thompson [31] has argued that a member of his "egalitarian social solidarity" will view Nature as ephemeral: any disturbance, no matter how small, may plunge the system (Lake Lanier, here) into a wholly undesirable and unfamiliar pattern of future behaviour. And we have argued that such a perspective – in which (in effect) the map of the science base assembled in the individual's mental model of the behaviour of the given piece of the environment may be highly tenuous, and future outcomes deduced from barely plausible, possibly bizarre future circumstances (see, for example, [12]) – may be just what our stakeholder-driven means of generating environmental foresight needs [8]. For in spite of all our mathematical models and their forecasts, we are continually surprised by what may actually come to pass.

But through what vehicle, within what engaging and supportive social matrix, can these and other individuals be encouraged to express the consequences of their fertile imaginations? Hitherto we have experimented with just two devices: a survey [13] and a "Foresight for Lanier" workshop [32]. The survey, while serving several other purposes, was designed expressly with the foregoing analysis of stakeholder-generated futures in mind. Its goal was to elicit the bounds for the behaviour definitions of Equation 3, where specification of these bounds would yet ideally be maximally untainted by any prejudices of those assembling the map of the science base to be incorporated into the model of Equation 1. In spite of the substantial effort invested in its design, the survey proved to be flawed: on the first account, it turned out that the bounds for Equation 3 would ultimately have had to be specified by the project's scientific personnel (the authors of the model); and second, less fatally, all the indicators of the future vulnerability of Lanier's water quality were found to be of more or less equal concern to respondents.^{3} They placed (pathogenic) bacteria

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^{2}This ballooning of costs has come in part from the insistence of local stakeholders on a "failure-free" infrastructure [30]; this notwithstanding, the permitting process for its discharge to the lake has still become the subject of major litigation and, at times, acrimonious debate.

^{3}Further manipulation of the survey data, in particular, a search for empirical evidence of three of the five social solidarities embraced in Thompson's [31] interpretation of Cultural Theory, reveals a greater variety of relative priorities amongst the given concerns for a large sub-sample of respondents [13].

as their priority, assigned primary culpability for potential degradation to sewage treatment plants, and generally saw the longer-term future (25 years or so hence) as being worse than the immediate future of the next few years [13].

In short, in the spirit of the experimental, prototypical setting of adaptive community learning [7], we learned from the survey that (a) we – the scientists – had *a priori* constrained unintentionally what was to be found of concern to the community and (b) translation from the "language" in which scientifically lay persons perceive their environment to the state variables of a mathematical model is extremely difficult indeed. The foresight workshop, then, sought to avoid the former pitfall and to ease the constraints of the second. It addressed four issues with the 33 members of the community who participated [32]: elicitation of the trends in factors affecting Lake Lanier over the next quarter of a century (essentially the u in the model); expression of stakeholders' personal indicators of the lake's future state (roughly speaking, the definition of x in the model); speculation about the patterns of behaviour of the lake in 2030, in as unbridled a manner as possible; and quantification of these imagined futures in the terms stakeholders themselves had collectively chosen (i.e., the foregoing definition of the elements of x), from both optimistic (y_d^l and y_d^u) and pessimistic (y_f^l and y_f^u) stances.

3.2. Computational Analysis and Outcomes

Computational results from assessment of the reachability of these futures [22, 24] suggest the workshop has proved the more effective vehicle, for the *particular* purpose of generating the kind of environmental foresight described above. Admittedly, problems remain in the means of transforming the ordinary discourse of the community's environmental concerns into the formal technocracy of a computational assessment. But what has been uncovered, from the perspective of the stakeholders, is that their optimistic future is perhaps as much as three times more likely to come to pass than their pessimistic future. Indeed, subject to how one interprets certain probability-like quantities in the numerical analysis, their desired future (Equation 3(a)) is actually a more probable state of affairs than the current conditions in the lake (as reflected in Equation 2(a)). From the assembly of conjectures about the mechanisms governing the behaviour of the lake, i.e., from the knowns and unknowns tagged in the elements comprising the model's parameter vector α, the scientists have found that (tentatively): (i) what might matter most to the reachability of the desired future is a better understanding of how phosphorus is released from sediments and propagated along a microbially based food-chain (up to larval fish) in the lower hypolimnetic waters of the lake (the subset of key parameters $\{\boldsymbol{\alpha}^K(t^+)\}_d$); (ii) the reachability of the feared future hinges instead on improving understanding of the release of phosphorus from the sediments, up through

the hypolimnion into the epilimnetic waters and thence along the more conventional phytoplankton-based food-chain ($\{\boldsymbol{\alpha}^K(t^+)\}_f$, which differs from $\{\boldsymbol{\alpha}^K(t^+)\}_d$); and (iii) under the immediate past and present conditions, the internal loading of phosphorus from sediments is redundant, apparently being easily overshadowed by the external input of nutrients to the lake ($\{\boldsymbol{\alpha}^K(t^-)\}$, which is different yet again from either $\{\boldsymbol{\alpha}^K(t^+)\}_d$ or $\{\boldsymbol{\alpha}^K(t^+)\}_f$).

In spite of all the uncertainty surrounding this analysis, the specificity of these results is reassuring. It does not appear that gross uncertainty – including the imprecision of the natural language in which stakeholders perceive their environment – has rendered our computational analysis impotent. We do not appear to have arrived at either the conclusion that all the stakeholders' hopes and fears are equally plausible or that all the scientific unknowns are more or less equally significant. There are pointers to future action, including ones of a rather subtle nature. For if the feared future is likely to be a low(er) probability outcome (relative to the desired future), should we bother to purchase more science in the domain of the phytoplankton-based food-chain, even though this improved understanding could be crucial, in the event, to averting a potentially disastrous, very costly form of future behaviour? The question – a matter of the worth of buying additional information – is well known in classical decision analysis.

4. CONCLUSIONS: TOWARDS THE NEXT TURN OF THE CYCLE

4.1. Scientific Prejudices, Stakeholders, and the Searchlight of Science

The problem with iterative procedures is that they must have a point of departure, which will not be free of prejudice and will almost certainly govern the outcome of this first iteration. Unlike conventional impact assessments, which often remain as isolated one-off events [15], participants in an ongoing adaptive community learning process cannot distance themselves from any failings of an outcome skewed by the prejudices they brought to the first iteration. Yet in a research project of relatively short duration, wherein the procedure, all computational analyses, and subsequent laboratory and field work must be developed and implemented more or less in parallel, it is vital to begin with some rather bold and specific prejudices, especially in respect of those bits of the science base to be tested experimentally (for which substantial planning and appropriate length and timing of observation are required). Enough was known at the outset, in the case of Lake Lanier, for us to recognise a number of potentially key "unknowns": the coupled particulate-solute chemistry of Fe, Mn, Ca, and P; the role of the bottom sediments and their interaction with exchange fluxes between the surface water and groundwater systems; the significance of the microbial loop in the foodweb

[33, 34] and, in particular, the positions of pathogenic micro-organisms in that web; stratification of the lake's water and the behaviour of the Chattahoochee tributary as a submerged jet; and the role of atmospheric deposition of nutrients (notably phosphorus) in epilimnetic primary production.

Our prejudice was to plump for the biogeochemistry of Fe-P interactions on the surfaces of the clay-rich Piedmont soils of Lanier's watershed – and the settling of these particulates through the water column into the lake's sediments – as the key unknown. Our models [22, 35] and our field work [36] reflect this prejudice. Because the structure of the model assembled for the purposes of generating the foresight discussed above has been biased accordingly (it did not address the Chattahoochee as a submerged jet, nor the role of atmospheric nutrient deposition, for example), a healthy dose of scepticism should be cast upon the outcome of sediment-water release of P as a key factor in the potential future behaviour of the lake. We feel vindicated by the results of our field work, nevertheless [36]. They suggest the conventional paradigm of P cycling in lakes, developed historically on the basis of observing systems in northern temperate regions (for example, [37]) is inappropriate for the iron-rich impoundments of the south-eastern United States [38]. Indeed, at the close of this first cycle through the process of adaptive community learning, we – the scientists – are in a position to offer a composite hypothesis for where more science should be acquired in a second iteration.[4]

Caution should not be abandoned, however. According to the results of the survey issued shortly after the start of the project, stakeholders have the greatest concern for "bacteria," i.e., pathogens. These have yet to rise to the status of a state variable (x) in any of our formal mathematical models, although field work has been completed with a view to developing a conceptual picture of their fate in watershed/impoundment systems. The area over which the scientists train the searchlight of science, through their mathematical models, continues to remain disjoint from the areas where the stakeholders would have us direct it.

4.2. Generating Foresight

Foresight comes in far- and near-sighted categories. The one must search for potential surprises, nonlinear dislocations, or structural shifts in patterns of behaviour, in principle, over the longer term [22]; the other is intended to deliver "smooth extrapolation" over a short span, from current conditions [35]. Our focus herein has been on the former. It is akin to a

fishing expedition: embarking with a broad intent to entrap something of significance, not entirely aimless, but with much ground to cover. In this, the design of the net – the model, that is – is crucial. Its extent should be large: a high dimension for both its state variables (x) and parameters (α), to cover a reasonable portion of the potentially relevant science base. Its entrapment mechanism, however, should not be geared to just a specific species (constituent hypothesis), nor its mesh size too fine-grained. Somehow one wants to be able to distinguish between catching a few big fish (the key unknowns, not clearly identified *a priori*), while letting go of the myriad minnows (the redundant bits of the science base).

From the present exercise, the conclusion is that the principles of the method work and the algorithmic extension to the TSDE procedure, in particular, appears to be successful in discriminating key from redundant model parameters in a multivariate setting. Forecasting is not the same as foresight. The outcomes from the modelling exercise in the present instance are not a projection of where the system might come to be at some point in the future. They are rather probabilities of hitting specific, predefined target behaviours and priorities for those key unknowns that should be made better knowns. Our procedure echoes what has been described in the area of climate change as the exploration of "imaginable surprises," derived from "backcasting scenarios from posited future states and/or reconstructing past scenarios in alternative ways to identify events or processes that might happen" [39]. In fact, one can conceive of designing the model with the express purpose of discovering our ignorance, and at the earliest possible juncture [8]. As opposed to the design of a model for forecasting in the *short* term, where the model's structure might be relatively rigid in comparison [35], the foresight process fully expects the structure of the model to evolve with the evolving science base over time in the *longer* term.

4.3. Communication at the Stakeholder-Science Interface

Thomann's work in the early 1960s – on modelling dissolved oxygen behaviour in the Potomac River [40] – was observed some years later by Orlob [41] to have ushered in the "modern era" of water quality management. For much of that era much of applied systems analysis sought to place more of the problem under the rule of formal computational analysis, progressively wringing out the human element from that analysis [1]. This is *not* to say that the human dimension of the man-environment interaction was excluded from the analysis – quite the opposite. Indeed, there is much contemporary interest in placing this dimension at the heart of the computations [42]. Rather, while working increasingly in the clinical world of equations and algorithms, those undertaking the analysis could either remain remote, or

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[4]At the intersection of understanding (a) the detailed interactions between the aquatic Fe and P cycles, (b) the supply of organic carbon for bacterial activity and its influence over the Fe-P interactions, and (c) the influence of phytoplankton populations over these same interactions through highly elevated pH (>8.5) conditions.

become increasingly remote, from ordinary members of the public interacting with their cherished piece of the environment. The applied systems analysis could easily have become a closeted affair, quite separate from the sociology of the problem it addressed. While applied system analysis, we know, is not the same an engineering analysis – nor, by any means, are all applied systems analysts trained originally as engineers – the following is a telling insight. Individuals become engineers precisely because they are poor communicators and cannot relate to society and its political processes [43]. In fact, things may be bad enough for there to be a correlation between those who have chosen to become engineers and the occurrence of autism in their family background (again, [43]).

Irrespective of the arrival of any post-modern era, our case study of Lake Lanier has become fully participatory; a process in which, in the spirit of adaptive community learning, the analysts have come to learn they are part of the problem. Quite apart from the various other aspects of communication with which we have had to deal – across the disparate jargons of conventionally widely separated disciplines, of assessing the quality (validity) of our models as devices for communicating scientific notions across the science-society divide [44], or of translating the natural discourse of stakeholders into the quantitative, numerical requirements of a mathematical model [22, 24] – it has been necessary to come to terms with the fact that the previously imagined neutrality (objectivity) of clinical detachment may be neither possible nor helpful to progress.

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