AC 2008-1353: SUSTAINABLE NATURAL RESOURCE ENGINEERING

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Sustainable Natural Resource Engineering

Abstract

Natural Resources figure centrally in the understanding of Sustainability and the Professional responsibility of engineers. A teaching approach is outlined that a) utilizes standard Engineering preparation in applied mathematics; b) applies it as a unifying theme across the natural resource field; c) embeds basic undergraduate exposure to ecological and economic concepts; and d) operates via desktop simulation tools accessible to all university students. The approach suggested is related to the new American Society of Civil Engineers (ASCE) Body of Knowledge (BOK2) requirement of Sustainability.

Introduction

Natural Resources underpin all engineering productivity – as source of materials, as environmental media, and as habitat for all living populations including humans. As such they constrain all approaches to sustainability. Understanding their intrinsic dynamics, their unique economics, and their intersection with corporate and governmental agencies, is critical to successful implementation of sustainable engineering. The “triple bottom line” (environmental, economic, social) characteristic of sustainable engineering demands a holistic approach rooted, fundamentally in the Natural Resource interactions with the built, economic, and social environments.

A teaching approach to sustainable engineering based in Natural Resources is described below. It employs the mathematical analysis already familiar to undergraduate engineers and scientists. The resources are sorted into classes by the relevant dynamics. A course-based approach taught at Dartmouth to general engineering students utilizes the mathematics described above plus simulation with simple desktop tools. This course is available in an emerging text[i] and software.

This approach largely fulfills the new ASCE Body of Knowledge (BOK2) requirement for sustainability; that innovation is described and examined as part of this presentation. The opportunity to offer this material through Environmental Engineering programs, as part of a Sustainability initiative, will be discussed.

Sustainability – the Vision

The National Academy of Engineering (NAE) convened important symposia in 2004[ii] and 2005[iii] to address engineering and engineering education with a focus on the near-future (2020). Sustainability was highlighted prominently:

> *An even greater, and ultimately more important, systems problem than homeland security is the 'sustainable development' of human societies on this system of ultimate complexity and fragility we call Earth.* (Vest.[iv])

Related**,** ASCE convened a summit of leaders of the profession in 2006. The vision expressed at the summit reinforces the NAE and related themes[v]:

> *Entrusted by society to create a sustainable world and enhance the global quality of life, civil engineers serve competently, collaboratively, and ethically … as stewards of the natural environment and its resources….*

Sustainability – the Word

The first challenge may be terminological[vi]. The word is rooted in the verb 'sustain' which has several senses

To nurture or support (nature sustains man)
To endure (to sustain injury)
To validate or affirm (to sustain an argument)

In the present context, the first two senses are invoked in the transitive sense: man sustains nature, nature sustains man. Both thrive and endure; a systematic, two-way relationship is implied. To reduce this to a one-way relation, is to lose the sense of the closed-system relationship.

At the heart of this relationship are ***Natural Resources***; they underpin all human productivity; authentic human flourishing demands a relationship of stewardship that recognizes their finite nature; the value inherent in the services rendered from them; and the requirements of fairness achieved through professional service.

The ASCE definition is a technical extension of extant definitions:

> ***Sustainability*** *is the ability to meet human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for the future.* ***Sustainable engineering*** *meets* these human needs.

This definition is emphatic about the role of natural resources described above.

Sustainability and the ASCE Body of Knowledge

In 2008, ASCE released the second edition of the Body of Knowledge (BOK2) for Civil Engineers[vii]. Reflecting the Visions of ASCE and NAE, BOK2 *requires* that all Civil Engineers master sustainability:

> ***The 21st century civil engineer must demonstrate*** *an ability to evaluate the sustainability of engineered systems and services, and of the natural resource base on which they depend; and to design accordingly.*

There are specific requirements for both academic undergraduate preparation, and for early-career development; these are summarized in Table 1.

Clearly, the notion of Natural Resources pervades these definitions and requirements.

In addition, Table 1 highlights what is commonly held: that there are aggregate effects of individual activities. Isolated acts that are perfectly benign and sustainable, can be unsustainable when aggregated. There is a scale effect of professional action; and professions need to look at the aggregate effects of their action. The natural time and space scales imposed by natural resources, transcending individual projects and actions, (as well as jurisdictions, lifetimes), imposes a professional burden – to channel individual actions toward sustainable relations with, common property resources[viii].

Lacking this responsibility, “no one is watching the store.” NAE and ASCE are asserting a professional role for engineering in bringing about sustainable use of Natural Resources.

Table 1. Sustainability (from BOK2)

Overview: The 21st Century Civil Engineer must demonstrate an ability to analyze the sustainability of engineered systems, and of the natural resource base on which they depend; and to design accordingly.

ASCE embraced sustainability as an ethical obligation in 1996[ix], and Policy Statement 418[x] points to the leadership role that civil engineers must play in sustainable development. The 2006 ASCE Summit[xi] called for renewed professional commitment to stewardship of natural resources and the environment. Knowledge of the principles of sustainability[xii], and their expression in engineering practice, is required of all civil engineers.

There are social, economic, and physical[xiii] aspects of sustainability. The latter includes both natural resources and the environment. Technology affects all three and a broad, integrative understanding is necessary in support of the public interest. Beyond that, *special competence* is required in the scientific understanding of natural resources and the environment, which are the foundation of all human activity; and the integration of this knowledge into practical designs that support and sustain human development. Vest[xiv] referred to this as the primary systems problem facing the 21st century engineer.

The actual life of an engineered work may extend well beyond the design life; and the actual outcomes may be more comprehensive than initial design intentions. The burden of the engineer is to address sustainability in this longer and wider framework.

Individual projects make separate claims on the collective future; ultimately they cannot be considered in isolation. A commitment to sustainable engineering implies a commitment, across the profession, to the resolution of the cumulative effects of individual projects. Ignoring cumulative effects can lead to overall failure. This concern must be expressed by the profession generally, and affect its interaction with civil society.

B: Upon graduation from a baccalaureate program, an individual must be able to *apply* the principles of sustainability[xx] [xii] to the design of traditional and emergent systems (Level **3**)**.** Implied is mastery of a) the scientific understanding of natural resources and the environment, and b) the ethical obligation to relate these sustainably to the public interest. This mastery must rest on a wide educational base[xv], supporting 2-way communication with the service population about the desirability of sustainability and its scientific and technical possibilities.

E: Upon completion of pre-licensure experience and before entry into the practice of civil engineering at the professional level, an individual must be able to *analyze* systems of engineered works, whether traditional or emergent, for sustainable performance (Level **4**). Analysis assumes a scientific, systems-level integration and evaluation of social, economic, and physical factors – the three aspects of sustainability. Achievement at this level requires the “B” achievement described above to be advanced in practice to the analysis level, through structured experience and in synergy with other real works, built or planned. Successful progression of cognitive development in this experiential phase must be demonstrable.

A Curricular Approach

A teaching approach to sustainable engineering based in Natural Resources can be devised for Engineers, taking advantage of the scientific and mathematical skills already demanded of them. As a first principle, we need to avoid adding prerequisites that cannot be found in what is already required.

Analysis of Natural Resources as an integrating theme requires emphasizes on three key aspects:

- The ‘natural’ dynamics of the resource itself, including time and space scales as well as dynamics
- The sense of social value
- The ownership and decision-making regime

The resources are sorted into classes: sterile resources (oil); renewable sterile but degradable resources (water); and living (extinctable) resources (Figure 1). The first two categories are distinctively different; the third category blends dynamics of the first two. A course-based approach taught at Dartmouth to general engineering students uses the mathematics described above – differential equations, algebra, optimization, random numbers -- plus simulation with simple desktop tools – matlab and excel.

This approach largely fulfills the new Civil Engineering Body of Knowledge requirement for sustainability.

	Exhaustible S	Renewable Q
Sterile	Oil	Water
Living	Fish ←	→ Fish

Figure 1. Natural Resources Classification

Sterile, Exhaustible Resources

This is the base case. Several key ideas can be introduced here that are valuable in later cases. A good example is petroleum, for which there is abundant data and concern. A simple depiction of the exhaustion history of petroleum reserves is easily created with a single ordinary differential equation (ODE) in the reserve amount, coupled to a static demand curve and a supply rate decision reflecting the of ownership of the reserve. This system reveals quickly the effect of monopoly versus competitive ownership in a) the market price, b) the market supply and c) the overall resource lifetime. One can explore the effects on depletion rate and time to exhaustion (the ultimate fate of a sterile resource) of various policy options including taxation, nationalization or privatization, interest rate, conservation, and substitution[xvi]. One can enrich the dynamic by adding discovery rate, in which case "Hubbert's Peak"[xvii] can emerge (Figure 2). From there one can explore the roles of price-sensitive discovery, exploration technology, competitive exploration, and various policy incentives for exploration. From this simple set of ODE's, one exposes some basic dynamics underlying the growth of demand, the evolution of substitution, the exhaustion of reserves and the discovery of new deposits. These are all revealed in the dynamic profiles generated, leading to a depiction of Producers' Surplus (Rent) and Consumers' Surplus, over time[xviii]. Since the ultimate fate of the sterile resource is likely to be either exhaustion or mandatory conservation, the tradeoffs among these are readily revealed. Additional interesting policy implications are evident in the time history of Rent and Consumers' Surplus that accrue[xix].

Summarizing: the Non-Renewable (Sterile, Exhaustible) case frames the common conception of natural resources; it is also the source of some common errors. The only choice in this case is how fast to deplete. The depletion period will be brief, during which Consumers' and Producers' surpluses will be generated, and either accumulated as rent, or dissipated. The substitution doctrine tautologically equates the original resource with the accumulated rent and its use toward resource replacement. Various ultimate outcomes include extremes leaving nothing, money, or knowledge of how to get along without the resource.

This is a good case in which to introduce or review basic economic ideas used; and the political economy implied by publicly owned or regulated resources. The mathematics required include Calculus; Ordinary Differential Equations; Linear Algebra and elementary algebraic optimization; computation. The computations can be carried out in common student versions of Matlab and Excel (with the optimizing Solver).

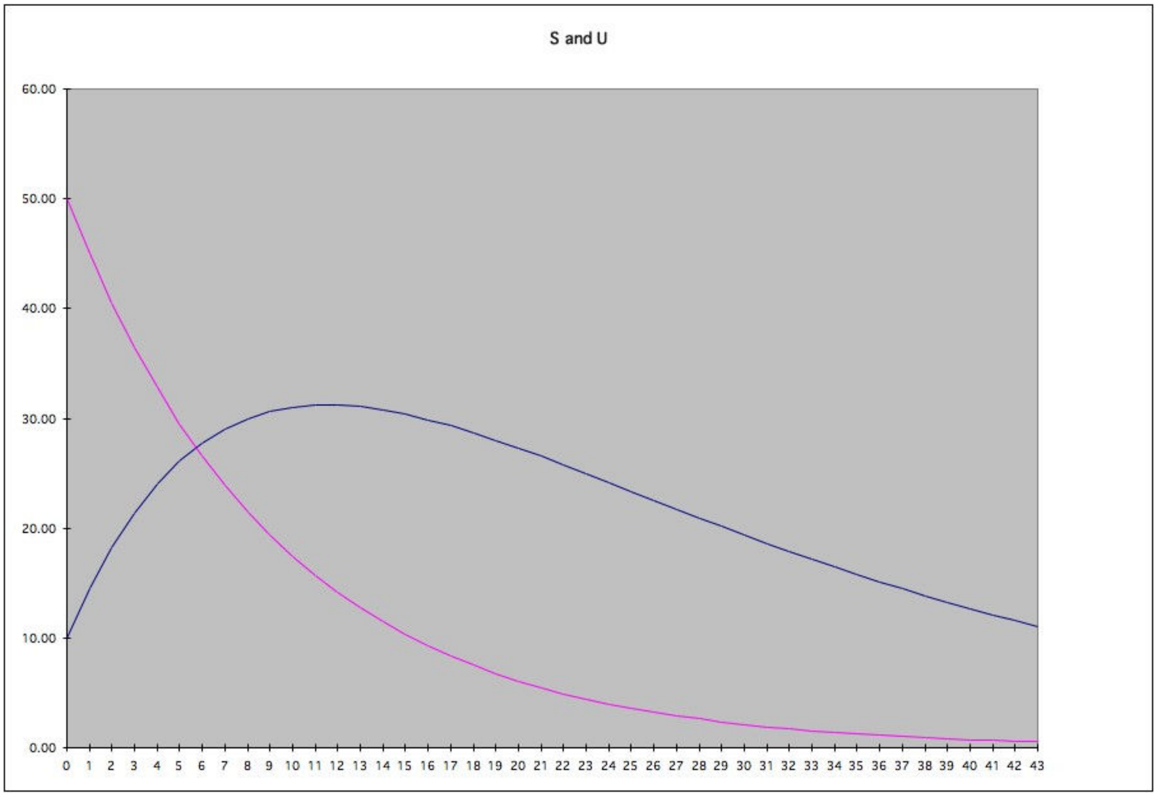

Figure 2. Oil exploration and depletion versus time. S (the proven reserve) peaks as U (the unproven reserve) is drawn down monotonically through discovery.

Living Resources

Building on the dynamic, the idea in this case is to add growth. Unlike the previous case, here we have the possibility of sustainable steady states. In fact there are many, and their discrimination requires an elaboration of a) the nature of the harvesting regime; and b) the ultimate tradeoffs between economic and biological 'welfare'. The first case to consider is the common 'Fisher-Scot-Gordon' fishery with a single biomass variable and a single harvest, and a single harvesting effort variable. Figure 3 illustrates the logistic growth curve.

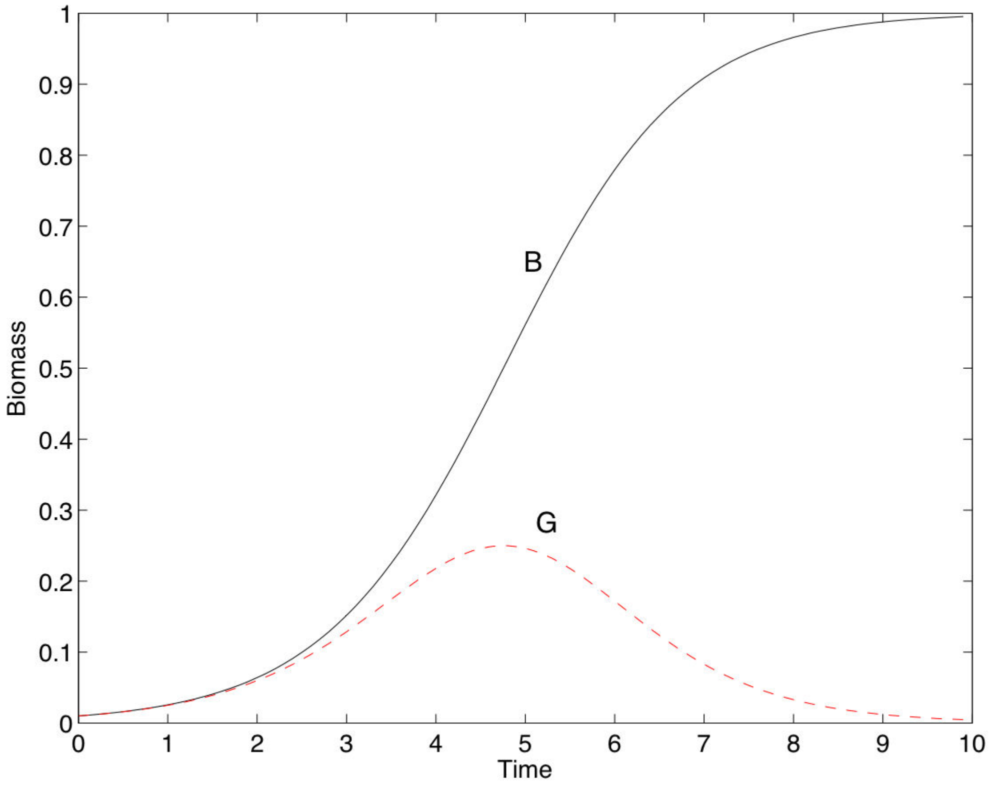

Figure 3. Logistic Growth rate G(B) and Biomass B, versus time in absence of harvesting.

This model depicts the interaction of prey (fish) with predator (fishers). This simple system allows a classic set of equilibria, with monopoly ownership ('controlled access fishery') producing fundamentally different outcomes from the competitive situation ('**open** access fishery'; 'uncontrolled access'). The equilibria possible illumine the importance of harvesting rules in a common-pool resource, and the role played by various political instruments: quotas on harvest, restrictions on gear, licensing of effort, salable permissions (Individual Transferable Quotas). The resulting steady states can be characterized in terms of fish, jobs, public 'rent', and harvest. Many interesting extremes are possible.

Adding dynamic considerations to this case is quite fruitful. To begin with, there is the important consideration of depensation – when at low abundance, increasing harvest rate results in decreasing growth rate, leading to extinction. Avoiding low abundance becomes critical. There is room to explore the mathematical chaos introduced when rates of adjustment become too high; and/or when disturbances to basic processes become prominent. This is a good opportunity to introduce the generation of random numbers in a simulation context and the relations between moments of random inputs and the resultant outputs. The characterization of random influences in such a system is critical, and there is an opportunity to introduce moments, autocorrelation, generating functions, and ensembles of statistically equivalent simulation experiments. Accompanying this introduction is the critical need to discuss extinction and the general consequences of unusual events, where one will only experience a single member of an ensemble of equally likely scenarios. The extinction possibility is especially important when operating at low or depensatory biomass, and/or fast response to random recruitment events. The non-negativeness of all ecological variables is a reflection of the catastrophic irreversibility of extinction.

Figures 4 and 5 illustrate the important consideration of the response time of the fishery. With growth rate a biological given, the human harvesting regime must still be posed as a response of increasing effort when faced with profitability; and vice-versa. Figure 4 illustrates a slow effort response leading to an orderly approach to equilibrium. Figure 5 is a faster effort response. The equilibrium is the same, but the dynamics show boom-bust cycles.

Finally, the maintenance of a standing stock of biomass, and the harvesting of its reproduction, needs always to be balanced against any economic possibility of simple, immediate exploitation. Specifically, if a population is growing slower that money accrues interest, there is an economic incentive to harvest all, put the proceeds into financial investment, and live on the interest with the population extinct. This is readily exposed in the simple mathematics described and makes clear the necessity of political conservation measures in this case if extinction is undesirable. The interest rate in this analysis separates renewable from exhaustible resources – growth rate < r indicates a slow-growing resource will be 'mined' to extinction under simple economic incentives, unless protected.

The above analysis is applicable to 'wild' fishing, where a common pool living resource is 'fugitive' and hard to harvest. There are other related cases where the resource is not fugitive and in fact owned and easily located. Forestry is a classic example; Fish Farming is another. There is a closely related mathematics that makes these fields reachable, typically with adjustments in the nature of the harvesting and appropriate recognition of the ownership regimes involved. All involve the same considerations of balancing harvesting and reproduction rates to achieve sustainable balance. In these cases, it is possible to optimize operations of a fish farm or a managed forest; so there is an opportunity to look at simple linear programming formulations and study their solutions.

This balance is one of constant dynamic adjustment when stochastic disturbances are recognized; and questions of nonlinear stability and size of disturbance become critical, in addition to the simpler question of existence of a steady or attractor.

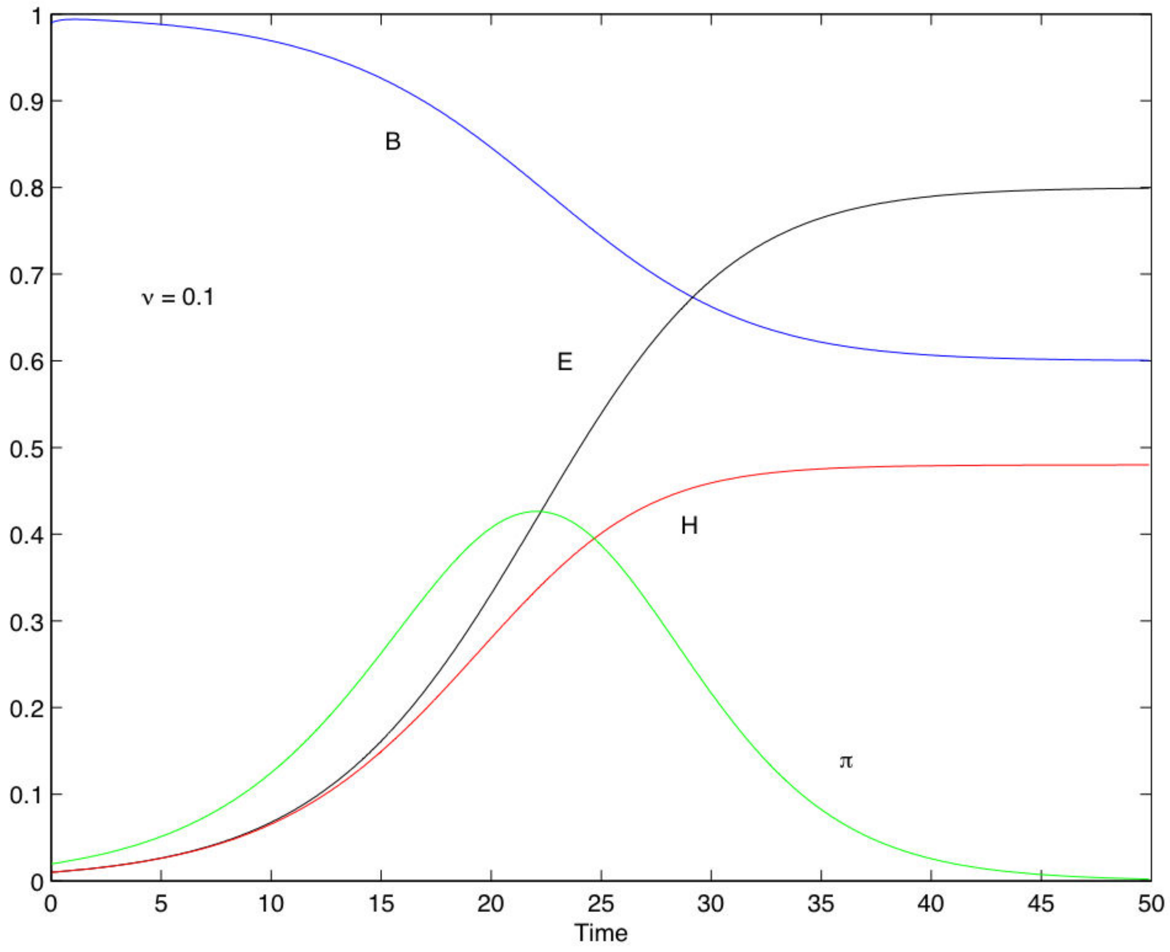

Figure 4. Dynamic Fishery adjustment: B= Biomass, E=Effort, H=Harvest, Pi=Profit.

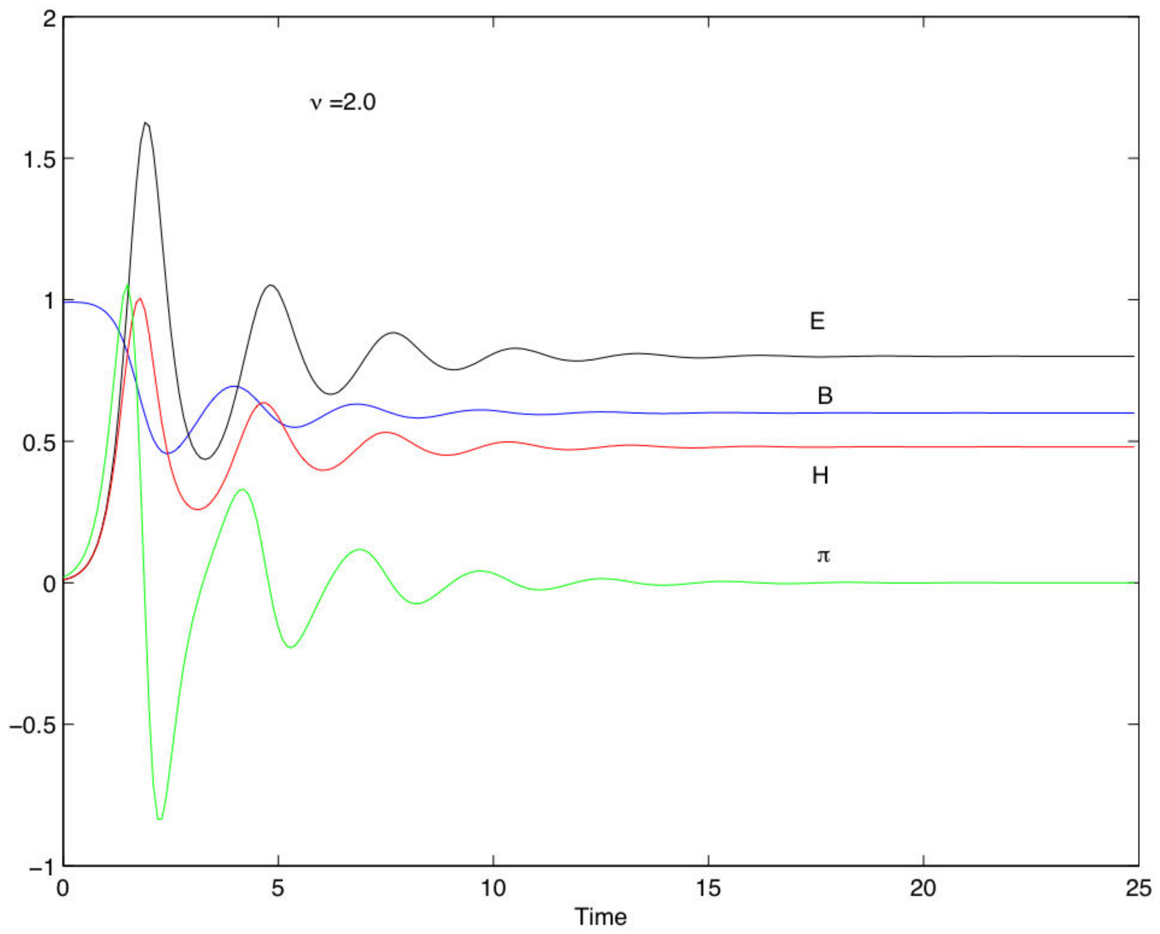

Figure 5. Same as Figure 4, but faster Effort response to profitability. A boom-bust cycle is evident.

This level of analysis can all be achieved with the so-called 'excess biomass' depiction of the natural system. For many populations, it is crucial to distinguish different life-stages, perhaps most importantly the pre- and post-reproductive stages. Adding more state variables and more vital rates (growth, mortality) and stage-specific management options, accomplishes this. Generally, the issues are similar, with the generalizations from one to several dynamic biomass variables. This can be still be done in the context of ODE's, now with many state variables and dynamic modes. A special category can be reserved for the case of "metered models" in which time remains discrete, governed by the seasonal patterns of reproduction. These comprise the analogous mathematical case of difference equations with the time metering having important physical significance. Here we have the opportunity to describe the population in terms eignevalues and eigenvectors of the vital rates (Leslie) matrix; and to discuss the 'stable populatin mode' as an *un*stable mode of an invasive species at low abundance. In these cases a critical requirement is to close the life cycle, such that a population sustains itself via successful reproduction, the surviving offspring constituting 'recruitment' to the population from below. A lively discussion concerns the relation of adult biomass to recruitment rate, and that discussion is particularly important for heavily exploited stocks, habitat loss, and depensatory behavior, with clear management implications.   Understanding recruitment variability is critical and there are several limiting cases of interest.

A special extension of this stage-structured analysis of populations exists in the form of 'cohort models' wherein one commonly accounts for continuous individual development.

The mathematics used: ODE's, simulation, linear algebra, probablility, random number generation, linear programming.

Sterile Renewable Resources

The classic case here is Water. A good departure point is the allocation of a fixed water supply among competing uses. This application exposes some basic steady-state tradeoffs among irrigation, hydropower, navigation, water quality, ecology, and recreation that can be elaborated quite a bit. It leads to the easy generalization of networked hydrology and its management, with the flows and waterlevels in the network being 'allocated' among various uses and subject to various constraints arising in the social-political context. The network constraints are linear and admit multiple feasible states. Optimization can be used to select among them and to study the impact of various formulations of objective. It is important not to confuse the optimization with actual allocation; rather to use it as a study of goals and their implications. A formalization of this in terms of goal programming, in the context of specific river basin network configurations, is very useful. (See the recent compilation of sustainability criterion by Loucks and Gladwell.[xx]) This representation of networked hydrology is readily extended to consider repeated seasonal cycles of water availability, interseasonal storage, agricultural potential, demand and relative value in use.   Generally, this is a classic application of mathematical programming. A theoretical exposure to Linear, Mixed Integer, and Goal Programming is useful. Specific models can be constructed and optimized within the Excel Solver, wholly adequate for instruction at this level.

An extension involves management of reservoirs. The same framework allows one to study power production at a single reservoir, constrained by a hydrological network. This is quickly generalized to systems of 2 or more networked reservoirs. The use of the nonlinear features in the Excel Solver is quite powerful in this case.

Ultimately one resorts to simulation, a classic progression to greater realism.   With simulation one has recourse to a much wider range of features, including nonlinearity and the more elaboration representation of stochastic features –economic, hydrological, and social. A classic study of hydrological timeseries and their synthetic generation is possible at this point, building on the material introduced above.

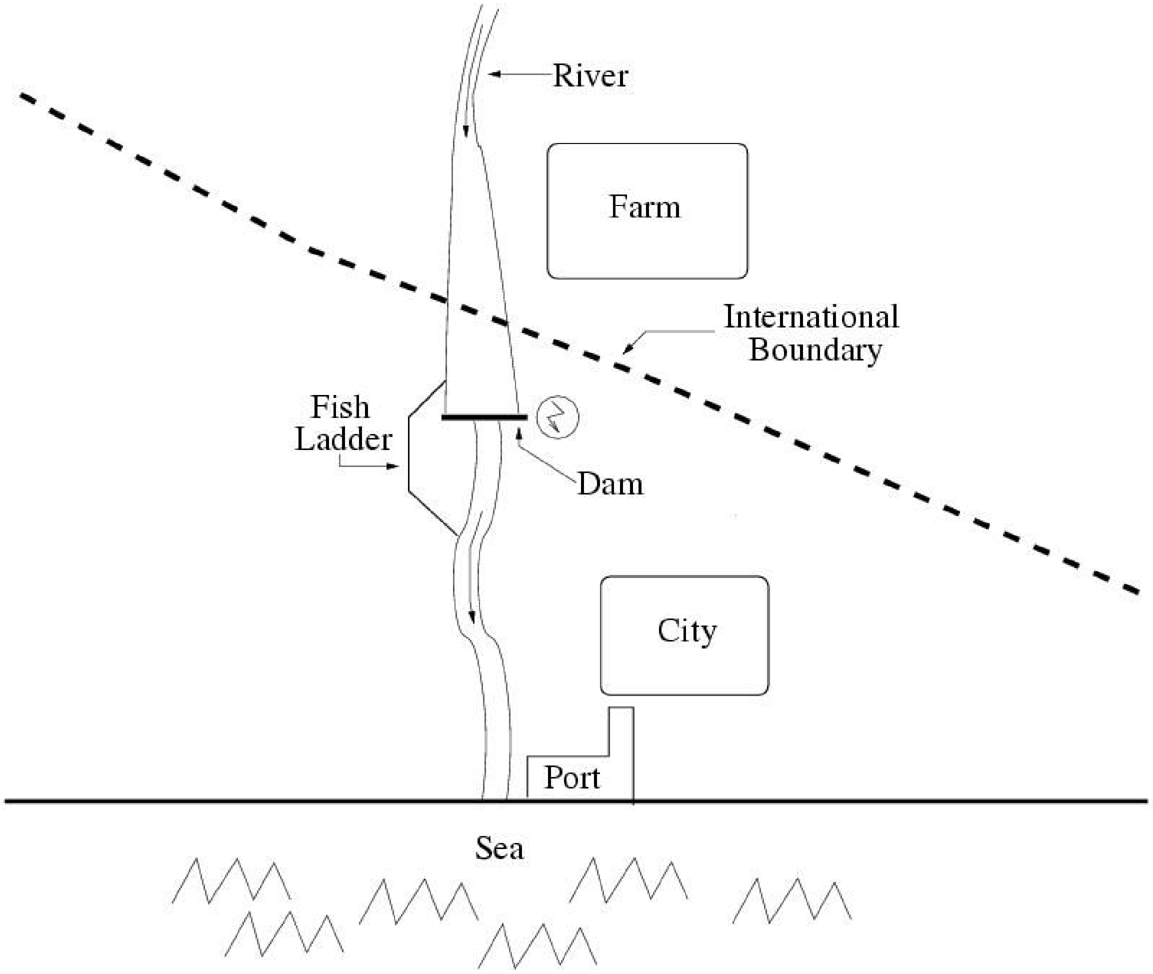

Figure 6 River Basin System

Degradable Resources

Water Quality is the classic case here. Adding water quality to the hydrological network studied above can be done systematically. The classic case of "programming" releases of pollutants into a network, and tracing the water quality response at various locations, is natural at this point. The joint effect of several sources can be represented in a general framework of coordinating joint action to achieve water quality and other aims. The optimization framework allows the exploration of various goals and their affects on outcomes. Goals related to employment, receiving water classification, land use, habitat, low-flow standards, and others are readily accommodated within a Goal Programming (LP) framework. There is a vast literature on this general problem; the possibility here is to introduce the management of pollution sources in the same framework as the management of water flowrates and storages, at the river basin scale.

Modes of Instruction

We have shown a model for a single course for engineering students that satisfies significant portion of the new BOK outcome in Sustainability. This model uses standard engineering (and therefore science) preparation and skill with simple applied mathematics, and the mastery of simple desktop tools in wide use. It has been tested in use at Dartmouth College; the text from that experience is in print and there is a small software archive, web-served. As engineering science at Dartmouth is an undergraduate major parallel to the other sciences, this material is accessible to students in other scientific majors and represents an outreach opportunity for engineering educators.

This is the first model – a single upper-level undergraduate course. A second model addresses the same students but can be packaged in a distributed mode – across the curriculum. To that end, the various applications serve as illustrations of the mathematical ideas in concrete examples: linear algebra; ordinary differential equations; optimization; applied statistics. Bringing quantitative Natural Resource analysis to engineering and science students in standing courses, is a different but powerful method to approach the general problem of Sustainability education. It has the added attraction of bringing classic analysis into very contemporary focus, enhancing the relevance and attractiveness of the topics and skills covered.

Yet a third model addresses a different audience: the graduate professional cohort in MBA, MEM, and MPA degree programs (respectively, Master of Business Administration, Engineering Management, Public Affairs). There is also an emerging "Master of Environment" category[xxi]. Here the integrative, contemporary nature of the material is perhaps most naturally appealing to students; the challenge is rather, to inspire the reintroduction of basic mathematics. The best approach here is to lead with simulation. Students in these categories are typically expected to be productive in this arena; Natural Resources and Sustainability are within their desktop grasp, as are extensive networked data bases and corporate operational sources.

Finally the entry-level, unified treatment described here serves as a gateway to further study. In the nonrenewable category, one might follow the Resource Economics field[xxii]. In the living category, the are multiple paths onward, including bioeconomic studies[xxiii]; fishery management[xxiv] [xxv]; population dynamics[xxvi] [xxvii]; control theory[xxviii]; water resources[xxix]; sustainability science[xxx]; ecology[xxxi]; basic modeling[xxxii]; development studies[xxxiii]; and of course, education[xxxiv] [xxxv]

Conclusion

Sustainability is emergent as a necessary part of engineering. Instruction in it is not optional. A fundamental topic within it deals with Natural Resources. An undergraduate offering can be constructed with natural linkage to extant engineering programs in Civil and Environmental engineering. Such a course can be offered in ways that appeal to other majors, and to professional master's programs. Text and supporting software are publicly available.

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