Economic Engineering of Environmental and Water Resource Systems

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> It would be well if engineering were less generally thought of, and even defined, as the art of constructing. In a certain important sense it is rather the art of non-constructing; or, to define it rudely but not inaptly, it is the art of doing that well with one dollar, which any bungler can do with two after a fashion.
>
> Arthur M. Wellington (1887)

Economic Ideas in Engineering (and Vice Versa)

Economics and engineering are kindred disciplines and have frequently exchanged fundamental ideas over their long history. Modern engineering and economics share common ancestors in the French engineering schools of the late eighteenth century to the mid-nineteenth century (Langins 2004; Ekelund and Hebert 1999; Hayek 1950). The origins of both modern neoclassical (Ekelund and Hebert 1999) and socialist (Hayek 1950) traditions of economics occurred when French engineers tried to determine how to best apply engineering principles to problems of societal importance.

Engineers have always been concerned not only with how to build things, but also with deciding where and how large facilities should be built; and in a more strategic sense, they have become concerned with how to finance facilities (Frontinus 97AD). Benefit-cost analysis methods regarding such problems date back to Navier in the early 1800s; and today's economic view of such problems begins largely with Jules Dupuit (Ekelund and Hebert 1999; Dupuit 1844). Dupuit was a member of the French Corps of Civil Engineers and a graduate of L'École Nationale des Ponts et Chaussees. He is best known in engineering today for the Dupuit assumption in hydraulics, which he developed while working on the sewers of Paris. However, his most widespread intellectual contribution is the idea of "consumers' surplus," which is the economic value of goods and services that consumers receive above and beyond the price to consumers. This idea is at the core of modern microeconomic theory (Dupuit 1844; Ekelund and Hebert 1999). Dupuit developed the idea of consumers' surplus while trying to determine the optimal capacity of a canal, on the basis of its economic benefits and costs. The costs of construction and operation were not difficult to estimate. However, quantifying the economic benefits was (and remains) more difficult.

In the American engineering tradition, despite widespread adoption of French ideas in most areas, economic ideas in engineering undergraduate curricula are largely restricted to what is now traditional engineering economics, with some concerns for optimizing particular facilities (Wellington 1887). However, from time to time, economic ideas have been more broadly applied to system design and infrastructure policies. Since 1936, federal requirements for evaluating the net economic benefits of water-resource projects certainly fall within the Dupuit and Navier tradition of economics in civil works. Academically, the Harvard Water Program (Maass, et al. 1966) and programs at other schools—notably Cornell University and Johns Hopkins University's Department of Geography and Environmental Engineering in the 1970s and early 1980s—have closely tied economics and engineering. It is now commonplace to find economic and engineering traditions rejoined in advanced water-resource engineering education in much of the world, as illustrated by the background, research, and curricula offered by many of the engineering authors in this volume. Expanding on traditional engineering economics, economic engineering emphasizes wider practices of economic principles to support decision making, more flexible and integrated management, benefit valuation, plan design, alternative evaluation, finance, and the design of management institutions (Braden 2000; Griffin 1998).

The present set of papers continues and extends this long tradition of cross-fertilization between economic and engineering thinking in water-resources management and engineering. The simultaneous application of ideas from both fields not only provides insights for understanding and solving water problems but also enriches the two disciplines involved. As water problems become more complex and vexing and require solutions that are well integrated into often-conflicting social and economic objectives, the broadening of ideas for understanding and solving water problems should be especially welcome.

Some major insights into water engineering and management arise from applying economic ideas in several areas, including the following:

- Water demands and forecasts,
- Project finance,
- Design evaluation,
- Economic management tools,
- Contract and agreement negotiation and enforcement, and
- Resolving scale issues in water and environmental system management.

This paper next reviews these areas.

Water Demands and Forecasts

In economic engineering, water demands are not "requirements" or point estimates of "needs" but are functions in which different quantities of water delivery or use have different marginal and total economic values. Dupuit (1853) first stated the economic nature of water demands with the following example.

> the enemy comes, blockades the city, diverts the stream; the inhabitants have now at their disposal only the drops that escape from the works of the enemy or that of a few wells that dry up easily; there is no longer any more for all usages, everyone is more or less deprived; water then has a value. … If the enemy, perfecting its works, succeeds in progressively diminishing the quantity of water that enters the city, its price is going to rise more and more, and one will not care to exchange a liter of it for a diamond.
>
> [Dupuit 1853, translated by Ekelund and Hebert 1999]

Economic representations of water demands are now commonly adopted for understanding and forecasting water demands, as well as for water management, particularly where demand-side responses are important (as they almost always are).

Project Finance

The economics of project finance is embedded in traditional engineering curricula, although engineers are often not acquainted with more recent, innovative, and flexible approaches to capital and operations finance. This limits their abilities to employ these financial means to improve project design and operations.

Design Evaluation

Benefit-cost analysis (BCA), cost-effectiveness analysis (CEA), multiobjective analysis (MOA), and optimization are generally part of advanced water engineering and economics curricula. Less common for engineers are some useful techniques of valuation, particularly environmental value of water in instream and off-stream settings, which are often significant motivators of contemporary water-resource projects.

An essential objective of many water resource developments, from an economic viewpoint, is to be economically sustainable, i.e., to pay back the resources invested and generate a profit within a reasonable time, or justify a long-term or short-term subsidy for noneconomic services. However, other necessary conditions for sustainability exist. Neither the economic soundness of a water-resource project nor its actual operation is sufficient for self-sustainability; they are, however, both necessary conditions (Pearce and Turner 1990). Economic engineering for water resources—which combines economic principles, hydrologic processes and water engineering criteria—appears to be a suitable framework to assist in design and management for sustainability. For example, externality analysis that is based on both economics and hydrology is often useful (Pulido-Velázquez et al. 2006; Marques et al. 2006). Also, for long-term water resources systems analysis, engineering systems reliability criteria should be combined with economic ones (Cai et al. 2002).

Economic Management Tools

A summary of water supply management options commonly discussed in the literature and in practice (Fig. 1) reveals considerably more diversity than what has traditionally been taught in engineering classes. Many of these water management options require an understanding of both economic and engineering principles so that these options can be appropriately implemented and designed into water supply systems.

With this expanding menu of water-supply alternatives comes the challenge of integrating the use of multiple resources in a manner that accomplishes objectives related to cost, reliability and environmental impact. Although strategies involving a diverse portfolio of supply assets are being developed for the water industry (Wilchfort and Lund 1997), this approach has been quite successful within the power sector (Hinz 2003). Diversification has allowed power utilities to reduce dependence on large base-load facilities through increased use of peaking plants and market-based acquisitions (Cope et al. 2001), both of which are employed intermittently to satisfy demand spikes, leading to less surplus capacity in off-peak periods and a corresponding reduction in cost and environmental impact.

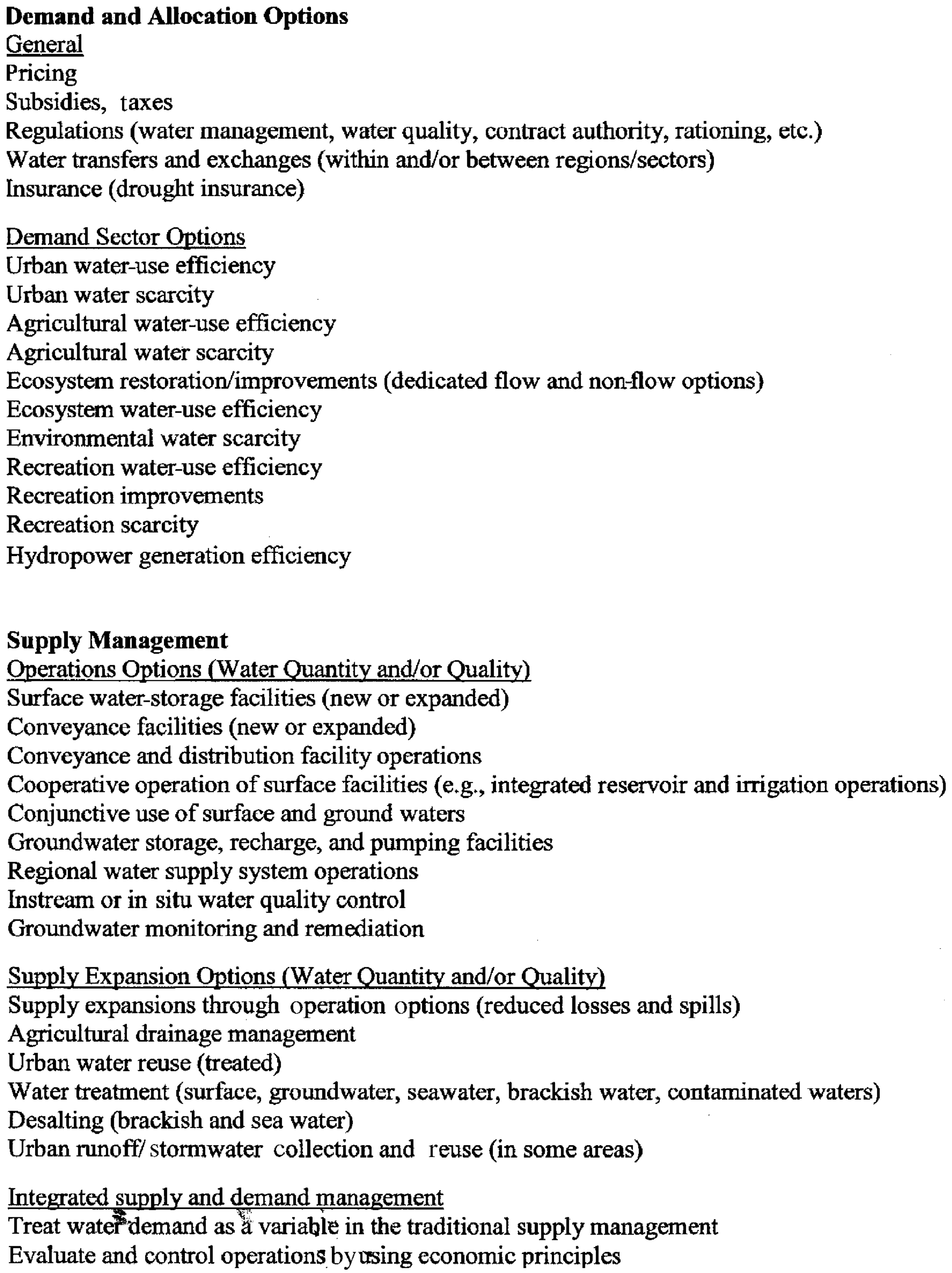
Although some conceptual similarities exist between the circumstances facing the water and power industries, there are also significant differences in the ways that each sector's portfolios are evaluated and managed. For example, both water supply and demand exhibit random variability linked to climatic parameters (e.g., temperature, precipitation), but power supply is controlled by producers. In addition, although water can be stored relatively easily, the costs of transporting it are high; power has essentially the opposite characteristics. Water is also distinguished by different qualities that affect both treatment technology choices and their costs. So, although diversification strategies used in the power industry (and the solution techniques used to identify them) can be referred to for inspiration, the intellectual substance that serves as underpinning for the integrated analysis of water resource systems must be developed independently.

Contract and Agreement Negotiation and Enforcement

Water management is not merely the construction and operation of physical infrastructure. Water-resource systems typically involve several water management, water regulation, and water facility agencies or firms; many private engineering, construction, and operational contractors; and thousands to millions of water users. For a water-resource system to function well, these entities must cooperate, which require incentives for good technical performance and financially responsible behavior. Economics provides a coherent framework for understanding and designing the institutional, contractual, and legal relationships required for a well-functioning water resource system (Fisher et al. 2005). These issues take on growing significance with the increasingly complex financing structures—for example, design-build-operate (DBO), build-operate-own-transfer (BOOT)—used to develop water supply and treatment systems (Hyman et al. 1998), and the range of more sophisticated transfer agreements (e.g., options, leases) available within current water markets (Howitt 1998; Lund and Israel 1995).

Resolving Scale Issues in Water and Environmental System Management

Scale effects bedevil much hydrologic analysis, as well as the analysis and understanding of water-management systems. Economic ideas provide a coherent and solution-oriented approach to understanding and resolving management issues across scales of water users, water districts, watersheds, river basins, and even larger regional, national, or transnational scales. Prices, compen-



Demand and Allocation Options
General
Pricing
Subsidies, taxes
Regulations (water management, water quality, contract authority, rationing, etc.)
Water transfers and exchanges (within and/or between regions/sectors)
Insurance (drought insurance)

Demand Sector Options
Urban water-use efficiency
Urban water scarcity
Agricultural water-use efficiency
Agricultural water scarcity
Ecosystem restoration/improvements (dedicated flow and non-flow options)
Ecosystem water-use efficiency
Environmental water scarcity
Recreation water-use efficiency
Recreation improvements
Recreation scarcity
Hydropower generation efficiency

Supply Management
Operations Options (Water Quantity and/or Quality)
Surface water-storage facilities (new or expanded)
Conveyance facilities (new or expanded)
Conveyance and distribution facility operations
Cooperative operation of surface facilities (e.g., integrated reservoir and irrigation operations)
Conjunctive use of surface and ground waters
Groundwater storage, recharge, and pumping facilities
Regional water supply system operations
Instream or in situ water quality control
Groundwater monitoring and remediation

Supply Expansion Options (Water Quantity and/or Quality)
Supply expansions through operation options (reduced losses and spills)
Agricultural drainage management
Urban water reuse (treated)
Water treatment (surface, groundwater, seawater, brackish water, contaminated waters)
Desalting (brackish and sea water)
Urban runoff/ stormwater collection and reuse (in some areas)

Integrated supply and demand management
Treat water demand as a variable in the traditional supply management
Evaluate and control operations by using economic principles

Fig. 1. Water Supply System Management Options

sations, contracts, and other economic approaches provide a consistent and self-regulating basis for appropriate interactions across such management scales (Hayek 1945).

This Special Issue

This special issue has collected a variety of integrated economic-engineering perspectives on water resource management. Some papers are by economists who address more traditional engineering topics. Others are by engineers, who in the tradition of Jules Dupuit, find that some economic ideas are useful to solve or understand an important problem. The papers deal with a wide variety of problems, ranging from microscale household water conservation decisions (Alcubilla and Lund), to local agency and district policies (Griffin; Brown and Rogers), to large regional scale operations involving many institutions and interests (Kirsch and Characklis; Marques, et al.; Pulido-Velázquez, et al.; Ringler and Cai; Ward, et al.; Watkins and Moser), as well as integrated hydrologic-economic modeling issues (Cai and Wang). Two technical notes highlight specific economic aspects of common facilities (Traviglia and Characklis; Booker and O'Neill). The issues involved cover the wide range of contemporary water-management problems and management actions, from water-use efficiency and conservation, economic water-demand estimation, water pricing, forecasting, environmental valuation, and conjunctive use of ground and surface waters to more traditional options of reservoir sizing and operations and facility cost estimation. The resulting collection of papers thus exemplifies well the value of combining economic and engineering ideas for diverse applications of advances in water resources management. We hope that others find this collection useful and illustrative of the work remaining to be done.

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