Thematic Week: Water Economics and Financing

Thematic Axis: Water Markets

Title: Optimization Modelling in Water Resource Systems and Markets

Authors: Jay R. Lund

Department of Civil and Environmental Engineering
University of California – Davis

Abstract:

This paper reviews the application of optimization models to water resource systems and the more contemporary application of system optimization with economic objective functions. Using economic objective functions in water system optimization models provides additional insights beyond traditional technical objectives, and allows model results to be insightful for system policy, planning, design, and operating purposes, as well as water market policies and planning. The CALVIN model of California's intertied water system is presented as an example.

Keywords:

Introduction

There is a long history of formal optimization modeling in water resources engineering and management. Early mathematical optimization dates back to Varlet (1923) for flood control and water supply and Massé (1946) for hydropower operations, with numerical optimization methods dating back at least to Little (1955) in his application of stochastic dynamic programming to hydropower. Most of these applications historically have been to seek optimal operating rules for reservoirs or the optimal sizing and operation of reservoir systems (Yeh 1985, Labadie 2004). While engineering applications of optimization have largely focused on the operation of reservoirs, economists applying optimization have largely focused on finding optimal prices.

Complex societies and economies have evolved and grown in many regions, with water resource infrastructure having been significantly developed. More complex water management problems have arisen that go beyond the optimal operation of a single component or class of water system components (reservoirs or prices). These contemporary water management problems call for a more integrated and comprehensive optimization of water management within a much larger and more diverse economy, and within an institutional structure which is far more de-centralized than traditionally assumed.

Contemporary water management in the developed world is characterized by many potentially conflicting water users and uses, many forms of infrastructure with many water management options, and many water managers. California's water system has hundreds of dams, many dozens of aquifers, tens of thousands of kilometers of aqueducts, and highly diverse water demands ranging from high-valued permanent crops, to low valued annual crops, to residential, commercial, and industrial urban demands, to a host of environmental demands for instream flows, wetlands, and maintaining cool or warm water temperatures depending on the local species of concern. This complex system is managed by a network of interacting institutions, including dozens of federal and state agencies with either project management authority or regulatory authority and about 3,000 local water districts and suppliers with locally-elected leadership and thousands of water contracts among these entities to coordinate water operations. Indeed, water demands are perhaps the most important single component of any functional water system – and these decisions are typically made by millions of sovereign water users each day.

This paper reviews application of optimization modeling to such contemporary water management problems. We begin by briefly summarizing early applications of optimization, mostly for simple single-purpose problems. We then explore the use of more extensive optimization models to help guide thinking, operations, and policies for larger and more diverse problems. We also pay particular attention to the role of water marketing in such systems and uses of optimization modeling for developing policies, plans, and operations which work with water markets.

Applications of Optimization in Water Management

Over more than 50 years, optimization has been applied to a wide variety of water problems. This review will be brief, with a few examples of applications for real-time operations, operations planning, facility planning, and policy-making.

Real-time operations

Real-time operation applications involve the use of optimization to make water management decisions in real operational time-frames, ranging from decisions on which turbines or pumps to employ in the coming minutes to scheduling water releases, diversions, or pumping over hourly, daily, and perhaps weekly time frames. Real-time applications of optimization tend to be mostly for single-purpose operations such as hydropower scheduling or the operation of pumps and storage in water distribution systems. Over these short time-frames, the optimization problem is well-specified and fairly tractable. Many large hydropower systems employ optimization to aid unit scheduling in the face of external price and load fluctuations (Jacobs, et al. 1995). Most use linear programming methods, often making constant-head assumptions for short periods (BC Hydro). Some use is made of dynamic programming for very short term unit scheduling (which turbines to employ) or longer-term operations (Quebec Hydro). Single-purpose real-time optimization benefits from having a well-defined objective for optimization, typically maximizing hydropower revenues or minimizing energy costs for distribution system operations.

Operations planning

Operations planning can have two distinct directions, seasonal operations planning and system re-operation studies. Seasonal operations planning seeks to make operational schedules for the coming season, based on forecasts of water availability and water demands, so operations can respond to wet or dry conditions or anticipated changes in demands that might accompany changes in crops prices or environmental conditions. System re-operation studies are longer-term affairs where the operating policies and rules for a system are re-examined and updated to respond to changes in regulatory conditions, regional water demands, and perhaps perceived changes in climate. Applied seasonal operations planning studies have been done by the Corps of Engineers, but simulation remains the most common tool for such problems (Murk and Lund, 1996), outside of hydropower systems. Water purchase decisions are often made in a seasonal operations planning time frame. Several papers develop methods for optimizing water purchases for environmental and urban water purchases (Hollinshead and Lund 2006).

Optimization has found greater use for system re-operation studies (Lund and Ferreira 1996; USACE 1993), although simulation modeling remains central to this activity as well. Re-operation studies also have become more important with increasing need to coordinate activities among diverse elements of large systems, often controlled by different institutions. Several papers discuss optimization of various water market forms in planning long term operation strategies (Jenkins and Lund 2000; Lund and Israel 1995).

Facility Planning

Many early applications of optimization in water resources were for identifying optimal sizes and configurations of reservoir systems. These studies were at a time towards the end of the historical period of major reservoir construction (Luss 1982; Butcher et al. 1969). However, some facility planning aspects remain in contemporary water management, as existing systems are adapted to changes in water demand and supply conditions.

Policy

Optimization models can be particularly useful for examining long-term policies which must operate under sometimes very different conditions from the present, when existing simulation models are likely to work well. Examples include how a water system might operate differently if operations changed to reflect the use of water markets, changes in water allocation policies, changes in climate, integrated water management, dam removal, or major investments (Null and Lund 2006; Tanaka et al 2006; Medellin et al 2007, 2008; Pulido et al 2004; Jenkins et al 2004; Harou and Lund 2008).

Markets and Modeling

Optimization modeling has several advantages and uses in studying water markets. These uses vary with the water marketing problem and the maturity of water market development in a region. Water markets fundamentally change the political and financial relationships among water management institutions in a de-centralized regional system (Pulido et al 2004). Early in the introduction of markets, great policy uncertainty exists regarding the effects of markets on the stability of water systems and the groups which benefit from them (Vaux and Howitt 1984). Planning concerns naturally exist on how operations with markets will affect demands on other water supplies, infrastructure operations, and water deliveries under various hydrologic conditions, particularly droughts (Jenkins et al 2004). Water demand decisions also can change when water markets are introduced (Cary and Zilberman 2002). Ultimately, optimization models can be applied in an operations planning time frame to help determine market participation decisions and how much of which water products available in a market should be purchased under different conditions (Hollinshead and Lund 2006). The major advantage of optimization models in the study of water markets is that they can better represent the more distributed nature of decision-making with markets; their greatest disadvantage is that they often must represent other policy and physical processes in a more simplified way than simulation models.

Simulation and Optimization

Most major water systems worldwide have at least one system model. Often a basin will have several models, with different time scales (hourly, daily, or monthly) and different spatial resolutions to aid with different operational or planning decisions. Usually these are simulation models. There are frequent discussions in the literature of the complementarity of simulation and optimization modeling, particularly for planning and policy purposes (Jacoby and Loucks 1972). For such problems, regional water systems have immense numbers of water management options from which decision-makers can choose. The numbers of alternative combinations of options make examination of most alternatives combinatorially impossible by simulation modeling alone. Even with only 100 binary options which can be either selected or not, there would be $2^{100} = 1.3 * 10^{30}$ potential alternatives to examine by simulation.

Optimization models, which usually require a simpler representation of the system to be mathematically tractable, commonly handle tens of thousands of decision variables (even millions on occasion). This allows optimization models to examine the broad decision-space of integrated water management solutions for those which appear to be most promising. These identified promising solutions can them be tested and refined using more detailed simulation modeling (Lund and Ferriera 1996).

Strategies for Model Development and Use

Various approaches are available for developing models that incorporate water markets as part of more complex water management systems. I would like to highlight modeling which has disintegrated components, modeling with distributed components, and integrated modeling, and discuss the roles of databases in these processes.

It is common to have a variety of models which are loosely linked to provide simulation capability for a basin. These models are often the result of a history of model development in the basin by different interests and agencies. The models are often only loosely coordinated, and could be characterized as disintegrated components of a regional modeling system. Humans are needed to make these models work together; this is not a smooth process, but can inject additional human thought (and expense) into any resulting analysis. Optimization cannot be done in this manner; it is too laborious and slow. But many of the most complex systems can only be simulated in this way, examining very few alternative policies.

The modular development of distributed model components can help rationalize the modeling of complex systems, reducing the need for humans at the interface of modeled processes. Ideally, the distributed component models have well-designed input and output variable sets which allow rational and rapid communications between modules, allowing simulation to be much more easily done, and some forms of optimization (perhaps evolutionary algorithms). The modularization allows model development to occur while the system is being used, with components being improved incrementally to upgrade the modeling system. Alas, this approach is rare, since a river basin rarely has the ability to develop the overarching technical framework and institution needed to design and develop a distributed model system.

Integrated modeling is then all processes to be modeled are combined into a single integrated model. The CALVIN model of California's intertied water system is an example (Jenkins et al. 2004). Traditionally, this type of model has been wonderful for its initially developed task, but has been cumbersome to adapt to the ever-changing analytical needs of real river basins.

The increasing scope and detail of system models of water problems and the rising speed of computing has led us into a new era where models and modeling algorithms are less of a problem than managing the input and output data. Models cover much larger areas in ever greater detail, so models increasingly represent our integrated knowledge and understanding of water systems in far greater detail than an individual can possess. Databases should both store inputs data sets for modeling and contain the documentation, explanation, and origins of these numerical values are important to make these models, and the understanding they represent, something more than a "black box." Databases and models increasingly represent the experience of veterans who have worked with the system and the training-ground of new professionals to a system. Modeling and databases are the textbook for technical people to more rapidly and completely document a system, in much the same way that Frontinus (97 AD) used his treatise on the water supply of ancient Rome to better understand Rome's water supply, as well as to communicate it to others.

Modeling Water Markets in California using Optimization

The CALVIN model of California's intertied water supply system was developed between 1998 and 2001 to examine integrated water management and water markets for California, Figure 1 (Draper et al. 2003; Jenkins et al 2004). It is an economic-engineering optimization model based on generalized network flow programming using the HEC-PRM reservoir system optimization software. Urban, agricultural, and hydropower water demands are economic, based on users' willingness to pay for water delivery and use. Operating costs are also included for pumping, treatment, and urban water quality.

The model contains over a million decision variables for optimizing a wide range of surface water, ground water, pump, treatment plant, recharge, reservoir operation, water conservation, water reuse, and water allocation decisions. The model is usually optimized for monthly decisions over a 72-year period, allowing a range of wet and dry conditions to be considered.

The model has been applied to a wide range of studies of water marketing, integrated water management, climate change, dam removal, conjunctive use, environmental policy, and other issues (Jenkins et al., 2001; Newlin et al., 2002; Draper et al., 2003; Tanaka et al., 2003; Jenkins et al., 2004; Pulido-Velázquez et al., 2004; Null and Lund, 2006; Tanaka et al., 2006; Lund et al., 2007; Medellín-Azuara et al., 2008; Harou and Lund, in press). As an optimization model, it can adapt operations economically to major changes in many aspects of the statewide water system. While this presumes a somewhat unrealistic level of coordination statewide, California's decentralized system does have a fairly good record of cooperation, particularly with the advent of water markets.

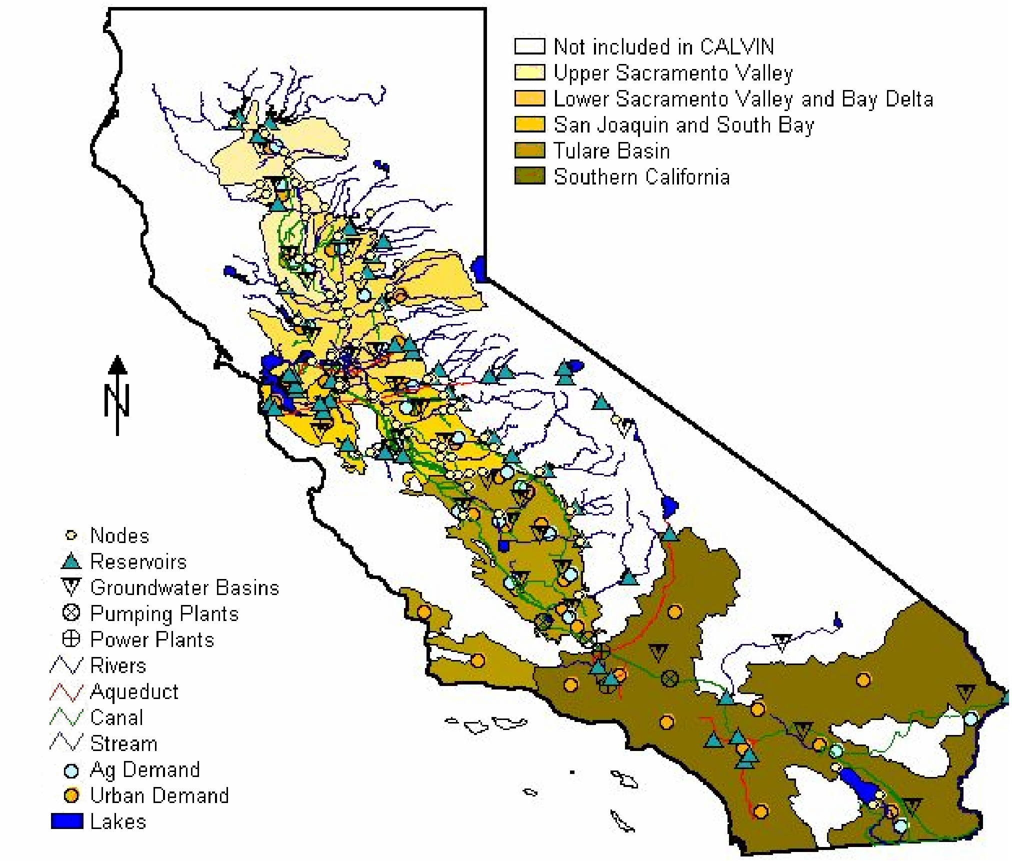


Figure 1: Schematic of CALVIN model superimposed on a map of California

Some Tricky Issues

Optimization modeling of large regional water resource systems faces many tricky issues. These issues do not mark the difficulty or futility of regional modeling, but rather mark that the approach has been successful enough to struggle with details. Most major water systems now rely significantly on simulation modeling capability and there is increasing investigation and use of optimization modeling. Some of these tricky issues often require the modeler to make trade-offs regarding the purposes of the model and available data and representations. These trade-offs then require interpretations and cautions when the model is used outside of its strict and formal range of application, as will be required practically. "All models are wrong, but some are useful," as George Box one wrote, and an imperfect modeling capability is often superior to our unaided intuition when there is no time to build modeling capability better suited to a particular question.

Several of these tricky issues are briefly described below:

Should we model many details of spatial and temporal representation with a simple (fast) mathematical formulation or a rougher representation of the system using a more complex (but slower) mathematical formulation? The CALVIN model includes a relatively detailed representation of California's water system on a monthly time-step, with a wide range of water management infrastructure, operations, and water demand management options – all represented as a simple generalized network flow optimization formulation. With the fast, cheap, and public domain solver comes the limitations of this very simple formulation – perfect hydrologic foresight, inability to include non-convexities, fixed (non-head-dependent) pumping costs, and inability to include in the optimization systemwide hydropower production or other non-network-flow variable of interest. However, models which can address some of these limitations, solved by dynamic programming, genetic algorithms, or other non-linear optimization, could never include the millions of decision variables implied in the CALVIN model.

Groundwater representation always will involve trade-offs. Solution of the detailed groundwater flow (and perhaps quality) equations implies great data and computation requirements. It is simpler and faster to represent groundwater as a surface reservoir underground, with a fixed unit cost for pumping withdrawals and neglecting detailed flows and surface-groundwater interactions.

Economic representation of water demands is essential for water marketing studies. Should long-run or short-run price elasticities of demand be used in representing water demands? Or should more complex representations be included (that impose greater burdens on solution algorithms). Fortunately, uncertainty in demand is usually only important at the margin. For many regional systems, there is little sensitivity of regional results to how urban water demands are represented, since they are so valuable relative to marginal agricultural and environmental demands. Nevertheless, there is room for improving the representation of water conservations and marginal water demands in the urban sector.

Most simple optimization models are "too smart" in having perfect hydrologic foresight. The optimization can see floods and droughts coming and prepare for them unrealistically in advance. While too much is often made of this limitation, it is nonetheless real and sometimes very significant. Simulation models, in contrast, are often "too dumb" in not taking advantage of opportunities that smart water system operators would likely see and take advantage of. There is an inherent trade-off in selecting models which are "too smart" or "too dumb" in terms of hydrologic knowledge, as well as, for water marketing, knowledge of water demands (prices).

Another contrast between simulation and optimization modeling is that optimization models often assume zero institutional viscosity, whereas simulation models often assume zero institutional flexibility. Neither approach is likely to be the case during real droughts or other times of challenge.

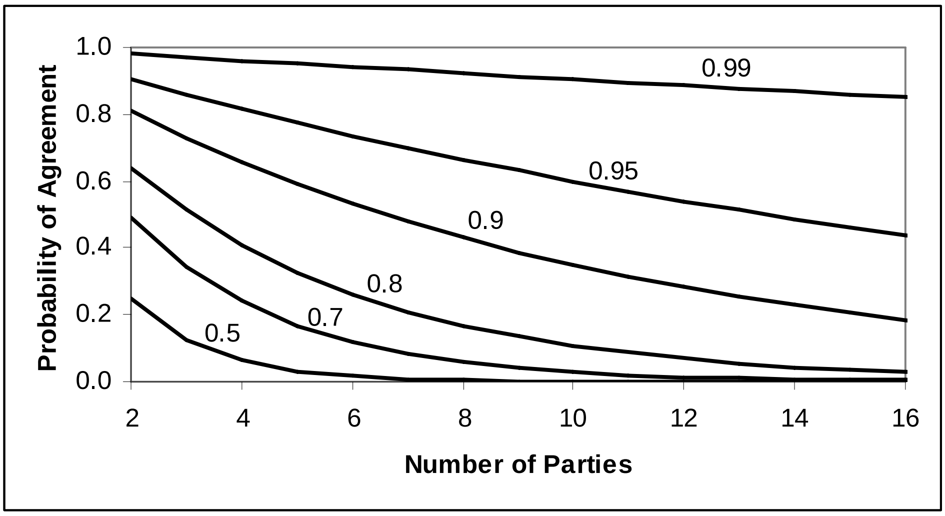
Alas, we must always think about model results.

Mathematics of Markets and Negotiated Consensus

For large water resource systems with many interested parties, it is sometimes said that negotiated or otherwise political solutions are better than market-driven water re-operations. This might sometimes be true, but negotiated and political solutions are often difficult for large de-centralized systems, with many interested parties who have an ability to stall or otherwise prevent timely changes to water management to accompany improvements in the understanding of the water system or external changes such as changes in climate change or water demands.

If n parties must agree to a negotiated solution, and each party has a probability Pa of being agreeable to a given solution, then the probability of all parties agreeing to the solution is Pan. Even parties whose best interests are served by an agreement can have internal political, personal, or organizational reasons for being disagreeable. The mathematics of the probability of an overall agreement under these circumstances appears in Figure 1. The prospects of a purely negotiated solution seem bleak with many required parties, even for high internal abilities of parties to be agreeable.

Figure 1 - Probability that Consensus can be Agreed with Number of Parties and Probability of Agreeability



While markets have many imperfections, they are fairly good at giving many parties an interest in coming to an agreement. Without markets, senior and junior right-holders are in a legal struggle; with functioning markets, newer users with higher valued uses can come to reasonably quick agreement with more senior right-holders, who themselves now have incentives to come to agreement. While not solving all problems of negotiated problem-solving, such markets sometimes can resolve some problems. Where rapid or sustained flexibility is needed with individual parties having incentives to cooperate, markets can be a useful policy instrument.

Mature vs. Immature Markets

Most controversies regarding water markets are where they have not become accepted. This sounds a bit tautological, but is also true in the sense that in regions where water markets have developed, they have become part of the fabric of water management and the operation and regulation of the water system has largely adjusted to and profited from their existence.

California has gone significantly through this type of transition, and optimization models have had a changing role in the course of this development. Vaux and Howitt (1984) were among the first to employ optimization to assess the potential value of water markets in California to reduce the cost of water provision and improve its economic efficiency. Early in the history of major water markets, such analysis was important for policy-making.

However, well-developed water markets are not monolithic, but can take various forms, including permanent sales, long-term sales, spot market sales, and various forms of options (particularly dry-year options). As water markets have become more accepted, modeling has become more sophisticated to include greater representation of infrastructure capacities and operations and how water markets function (Newlin et al 2002; Jenkins et al. 2004; Pulido et al. 2004). In such studies, we can see the larger potential of water markets to help coordinate the many otherwise disparate interests involved in managing most large regional and inter-regional water systems. In many cases, markets change the nature of water management (in a game theoretic sense) such that agencies which previously competed for water now have incentives to cooperate and share water and water operations. Such cooperative behavior often can be seen in economically-driven regional system optimization models (Jenkins et al. 2004).

Finally, optimization models can have a role in aiding potential water buyers and sellers in making water purchase and sale decisions from among a wide range of potential water products. Lund and Israel (1995) present a two-stage optimization model to aid urban water purchasers in selecting amounts of water for permanent and spot-market purchase, as well as the purchase of options and the exercise of options. Hollinshead and Lund (2006) propose a more detailed three-stage linear program for an environmental water account to purchase and sell water over the course of a season as hydrologic, infrastructure, market, and environmental conditions become clearer.

Conclusions

Optimization modeling is becoming more common for water management for policy, planning, and operational decision-making. While still unusual in practice, it offers some distinct advantages when trying to explore novel solution approaches in complex systems or when trying to adapt operations quickly to changing conditions with well-defined objectives. For water marketing, optimization is particularly useful for its ability of better represent the mode decentralized nature of decision-making with markets.

The role of optimization in water market studies varies with the maturity of markets and local conditions. Early in the development of markets, optimization has been useful in policy studies to compare the potential economic value of markets with other water management and policy alternatives. As markets are being developed, optimization models help identify potential market transactions and desirable changes in infrastructure and operations to accompany the introduction of markets. Potential problems and undesirable impacts of markets can also be identified from such model runs. With mature markets, optimization results can help guide operational decisions on water purchases, sales, and water operations in the context of markets.

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