"Optimization tools and principles have made it possible to develop prescriptive models for optimal management of large scale water resources systems, incorporating ubiquitous uncertainties in the prediction of natural processes and the economic impacts."

Optimization Applications in Water Resources Systems Engineering

By Bithin Datta and Harikrishna V.

Introduction
Civil Engineers are involved with the creation, monitoring and management of infrastructural resources, as well as the efficient, economic utilization and management of renewable natural resources like water, including the preservation of its quality. One of the areas of Civil Engineering which really pioneered the use of optimization techniques is Water Resources Systems planning, design, operation and management. Optimization tools are utilized to facilitate optimal decision making in the planning, design and operation of especially large scale water resources systems. The use of optimization tools as the most important component of Decision Support Systems are not confined only to the quantity aspect of water. The mitigation of polluted aquifers in a regional scale, operation of treatment plants and scheduling of effluent discharge in an optimal manner so as to control downstream pollution of rivers and other water bodies, designing of optimal strategies for reservoir releases for water quality augmentation, or maximizing hydropower generation, irrigation water supply etc. are only a few examples of using optimization tools for evolving economically efficient management strategies.

Application of optimization techniques are most exciting, challenging and truly large scale when it comes to the management of water resources systems both in terms of quality and quantity. Of course, it is no doubt true that unless the demand is more than the supply, and the economic value of a resource is considered both in terms of quality and quantity, optimization is more or less meaning less. The economics involved with large scale water resources projects are indeed very complex as it influences the life and future of many sections of the society and different geographical regions in different ways. Then there is the difficulty of correctly predicting future natural processes, which makes the task of making optimal decision based on erroneous forecasts even more challenging. However the applications are enormous in extent and variety. Only a few illustrations are presented here based on the research work carried out by the first author, mainly at I.I.T. Kanpur.

The application of optimization techniques is most challenging in Water Resources Systems area, due to the large number of decision variables involved, stochastic nature of the inputs, and multiple objectives. One important example is the multipurpose planning, design and real-time operation of a system of multiple reservoirs.

Reservoir Planning Design and Operation
The most widespread application of optimization tools is evident in the management and design of reservoir systems, which in a way can be treated as a problem similar to inventory management, with natural uncertainties. Therefore, it is easy to use operation research techniques to address this problem. It has been demonstrated that the development and implementation of an optimal strategy for regional water resources development can result in enormous economic benefits when the planning and design is based on synergistic operation according to a systems concept. In most cases of reservoir operation, the constraints and objective functions are nonlinear. But due to the associated difficulty in computer coding of nonlinear problems and other limitations, the NLP technique has not been widely used. More recently, evolutionary techniques e.g., genetic algorithm (GA), simulated annealing etc. are being utilized...
especially in a linked simulation optimization mode to increase the efficiency and computational feasibility of solving these large scale problems. Very recently, one M.Tech. Thesis under the guidance of the first author developed an externally linked water quality simulation optimization model using GA. The linking mechanism becomes very simple if GA is used instead of gradient based classical optimization techniques. In addition, GA is well suited to locating the non inferior or non-dominated solutions in subsequent generations.

There are other issues which are equally important for both operational models as well as planning models. These are conflicting objectives or purposes of operation, and uncertainties in modeling. The first issue of conflicting objectives is addressed by multiple objective optimization models. The second issue of uncertainties in modeling is very wide in scope and can be addressed partially by improving hydrological forecasting capabilities, and in the case of long term planning models by using the expected value criterion and stochastic optimization. Some of the details related to short term real time operation of reservoirs, reliability, vulnerability and resilience of planning and operation, significance of short term and long term loss or benefit functions are discussed in Datta and Houck (1984), Datta and Burges (1984), and Datta (1993). The role of the quality of stream flow forecast determining the actual economic benefits and losses accrued; even resulting from optimal multiple objective operation of a reservoir system is presented in Figure 1.

Most of the optimization models use some kind of mathematical techniques like Linear programming (LP), Dynamic Programming (DP) and Non Linear Programming (NLP) or their variations. Also each of these techniques can be applied under deterministic assumed conditions or stochastic and uncertain conditions. Often the expected values of the benefits or losses are used as the objective function of the models when stochastic conditions are incorporated. However, as noted in Datta and Burges (1984), the expected value criteria may lead to inefficient “optimal” decisions, and therefore should be used with caution. A typical set of constraints of the optimization model may include mass balance equation, maximum and minimum permissible releases and storage as function of time, penstock or canal system capacity, plant capacity, legal and institutional constraints, and other physical bounds such as demands. The objective function value represents the level of performance of the system for assigned values of the decision variables, often in terms of economic units.

Figure 1. Difference between The sum of Actual Losses and the Sum of Losses Conditioned on Forecasted Flow for optimal Multiple Objective Real time Reservoir Operation(Datta and Burges, 1984)

No doubt, of all the optimization methods LP has found the maximum acceptance due to the associated ease in solution, capacity to solve large scale problems and easily available computer codes. However, LP models are limited to solving models with linear objective function and constraints. However, LP models are extended by incorporating uncertainties in the modeling process in “Chance constrained LP” (Datta and Houck, 1984). Chance constrained LP models incorporating real time stream flow forecasts and the reliability of operation policies were first introduced for real time operation of reservoir system. Dynamic programming based on sequential sub-optimal decisions to obtain an optimal decision is capable of efficiently solving reservoir operation problems with linear or nonlinear separable objective functions and constraints. Many modifications of the discrete
The actual performance of an optimal strategy would depend upon the quality of forecasts for future natural processes like runoff in rivers, and rainfall. Unless the forecasts are accurate and extends sufficiently into the future, the operation policy, although designated as optimal, would only be a Myopic Suboptimal strategy. These important aspects are elucidated in the earlier works of the first author. As mentioned in Datta and Burges (1984) and Datta and Houck (1984), real time forecasts and the associated inaccuracies and uncertainties are most important for operation of reservoir systems. The probability of errors in forecasts also provides a framework for reliability or, risk based operation of reservoirs. Improvement in real time forecasting capabilities or on-line adaptive forecasting can certainly improve the benefits from integrated management of reservoir systems, a fact evident from Figure 1.

Regional Scale Groundwater Pollution and Utilization Management

In a groundwater aquifer, not only the quantity but also the quality of available water determines the purpose for which it can be used. Polluted groundwater is unfit for human consumption or even agricultural use. A judicious planning and development of a spatially and temporarily varying pumping policy can control the extent of contamination in the aquifer. It is possible to develop a time-varying spatial pumping strategy that allocates water according to availability, quality, and demand; and at the same time controls the quality of pumped water. In order to accomplish these two conflicting goals of optimal allocation, and control of contamination, a multiple objective management policy is necessary. Keshari and Datta (1995) presented the development and evaluation of a pattern search algorithm (Hooke-Jeeves), together with the exterior penalty function method for solving a constrained groundwater management model incorporating both the flow and the transport equations. The Powell’s Conjugate Direction method together with exterior penalty function method was also utilized to solve a similar nonlinear constrained groundwater management model.

A two-objective nonlinear optimization model for the management of groundwater withdrawal and
groundwater pollution in a regional scale was presented by Keshari and Datta (1996). This model uses the embedding technique to simulate the flow and the transport processes in the aquifer, thus, eliminating the necessity of externally linking a simulation model with the optimization model. The two different conflicting objectives considered are: (i) minimization of total withdrawal from the entire region over a specified time horizon, and (ii) minimization of the maximum concentration of a conservative pollutant (chloride) occurring in the groundwater. Other implicit objectives that are considered as constraints are the distributions of resulting hydraulic heads in the aquifer.

Graphical representation of typical optimal solutions showing the optimal spatial pumping distribution resulting from the obtained optimal groundwater quality management strategy, the optimal spatial distribution of hydraulic head in the aquifer resulting from the pumping strategy, are shown in Figures 3 and 4, respectively.

Datta and Peralta (1986) presented a multi-objective optimization procedure using quadratic programming for developing a regional conjunctive water management strategy for an important rice production area in Arkansas, U.S.A. The objectives considered were: (a) Minimization of the total cost of water use, and (b) maximization of total withdrawal from the aquifer. They also accounted for the opportunity cost due to the loss in agricultural production caused by nonavailability of water. This work is one of the few very important applications of optimization principles for evolving a regional pumping strategy with conjunctive use of surface and ground water for sustainable development in an intensively agricultural area.

Identification of Unknown Groundwater Pollution Sources

An open and challenging problem in groundwater pollution management is the detection of unknown sources of groundwater pollution. Often, groundwater pollution is detected in a
water supply well, many years after the source of pollution causing the contamination in the aquifer has become active. Often the sources of pollution are clandestine disposal of pollutants by industries, or leaking underground tanks and pipes. Detection of the source of groundwater pollution is the most challenging task and the essential first step in mitigation of contaminated aquifers. Pioneering work has been carried out on this topic at I.I.T. Kanpur, for conservative as well as radioactive pollutants, under the guidance of the first author.

The aquifer may be polluted due to multiple sources, active at different time periods. The determination of pollution sources using only concentration measurement data in the aquifer is analogous to reconstructing the history of events that have occurred in the aquifer over a time horizon. The identification of unknown pollution sources from the contamination measurement data in arbitrarily located observation wells is an inverse problem, which is generally ill-posed and non-unique.

The first author’s first attempt to solve this most challenging problem before joining IIT Kanpur is reported in: Datta et al. (1989). The methodology developed utilized the pattern learning and recognition capabilities of an optimal statistical classifier using stochastic dynamic programming, as well as an expert knowledge base to solve the identification problem. Mahar and Datta (1997, 2000, and 2001) presented optimal source identification methodologies based on embedded optimization models. Mahar and Datta (2000) considered the transient flow condition. Mahar and Datta (2001) considered simultaneous estimation of aquifer parameters and identification of unknown pollution sources. Recently, Datta and Chakrabarty (2003) proposed the use of linked optimization-simulation approach when the simulation model is externally linked to a classical nonlinear optimization model to solve this source identification problem. This approach is capable of solving very large scale identification problems. Figure 6 shows the schematic representation of a linked simulation optimization approach using gradient based nonlinear optimization technique.

Figure 6. Linked Optimization Simulation (Datta and Chakrabarty 2003).

Singh and Datta (2003, 2004) proposed an artificial neural network (ANN) based methodology, and a genetic algorithm (GA) based linked simulation optimization methodology that would facilitate optimal identification for unknown groundwater pollution sources using concentration measurement data. Each methodology requires a groundwater flow and contaminant transport simulation model to simulate the physical processes in the aquifer system. The GA based simulation optimization approach uses the simulation model for fitness evaluation for the population of potential pollution sources evolved by GA. The flow and transport simulation model is externally linked to the GA based optimization model.

Hydraulic Management of Salt Water Intrusion in coastal aquifers

Another application of optimization tools is the management of coastal aquifers for the control of sea water intrusion. Often, the intrusion of sea water into coastal aquifers due to excessive and uncontrolled groundwater withdrawal renders the entire aquifer saline and unfit for beneficial use. Das and Datta (1999a, b, 2000) presented a number of nonlinear optimization based multi-
objective management models for sustainable utilization of coastal aquifer.

In Bhattacharjya and Datta (2004), a linked simulated-optimization based multi-objective management model is developed for coastal aquifer management. An artificial neural network (ANN) is used to approximate the flow and transport processes in coastal aquifers. A modified form of the Non-dominating Sorting Genetic Algorithm (NSGA) developed in the KANGAL lab at I.I.T. Kanpur (by Dr. Deb and his students) is utilized to obtain the Pareto optimal solutions for the three objective saltwater intrusion management problems, as shown in Figure 7.

Although many other optimization problems related to water resource system are in progress, optimal monitoring network design for detection of pollutants in groundwater aquifers, which involves a mixed-integer programming based chance constrained optimization methodology (Datta and Dhiman, 1996) and another model based on a sequential optimization simulation model (Mahar and Datta, 1997) is well studied.

**Concluding Remarks**

A few illustrative applications of optimization techniques in the planning development and management of large scale surface water and groundwater systems are discussed here. An attempt has been made to present or highlight some of the research works which had been carried out by the first author in this field, especially at I.I.T. Kanpur. For the last one or two decades, Water Resources Systems management is one of those areas which have seen enormous application of optimization tools and principles. In the recent years the emphasis is no doubt sifting to the Environmental aspects such as groundwater and surface water pollution and its control and mitigation. The discussion presented here is only meant to provide a glimpse of possible applications, which are by no means exhaustive. The expectation remains that: actual practitioners in this field would soon benefit from the enormous strides made by the researchers.

**Figure 7.** Pareto-Optimal Solution for Three Objective Coastal Saltwater Intrusion Management, (Bhattacharjya and Datta, 2004).

**References**


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