USGS

WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Genetic Algorithms for the Control of Sedimentation in River-Reservoir Networks

Focus Categories: SED, M&P, MET

Keywords: Sedimentation, Optimization, Water Resources Planning, Decision Models, Discrete-Time Optimal Control, Reservoir Management, Systems Engineering, Alluvial Rivers, Genetic Algorithms, Sediment Transport Simulation

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Congressional District: 12th District, Illinois

Problem Statement

Alluvial rivers and reservoirs frequently adjust their geometry and conveyance patterns through natural processes of sediment transport. If left uncontrolled, however, excessive scour of a streambed will induce major shifts in boundary geometry and can threaten stability of in-stream structures, such as bridges or underground utilities. Likewise, continued deposition of bed sediment will cause reduced storage capacities in stream channels and in conservation and flood control reservoirs. This decline in storage eventually eliminates the intended capacity for flow regulation and water supply, and reduces the hydroelectric power generation, navigation and recreation benefits that are dependent on reservoir storage. Concentrated accumulation of sediment can also reduce water quality when the transported materials have previously been exposed to and become attached to contaminants, such as those found in some agricultural lands. Although difficult to quantify on a global basis, Mahmood (1987) estimates that reservoirs in particular are losing storage capacity as rapidly as one percent per year and that the annual cost of sediment accumulation has approached $6 billion. Problems associated with excess sedimentation have been evident on a regional basis as well. Consider, for example, Lake Shelbyville and Carlyle Lake on the Kaskaskia River in central Illinois, both of which are operated by the U.S. Army Corps of Engineers, St. Louis District. Preliminary information from the Hydrologic Engineering Division of the St. Louis District indicates that of Illinois reservoirs, Carlyle Lake has been the most effected by sediment accumulation. The Illinois Environmental Protection Agency has labeled water quality in the lake as “fair” and identified runoff and deposition of sediment from agricultural lands and eroded shorelines as causes of pollution (IEPA 1998). Within Carlyle Lake, deposition is occurring at an estimated rate of three times that which was initially expected and will dramatically shorten the useful life of the reservoir (Dyhouse 1998). Subsequently, the geometry and sediment balance of the multi-reservoir river system as a whole will be affected.

Sustainability of rivers and reservoirs is a difficult and costly issue to address after problems have occurred. As an example, it would cost $83 billion to restore Lake Powell on the Colorado River to its original capacity once fully sedimented, assuming a disposal facility would accept the 43 billion cubic yards of dredged material (Morris and Fan 1998). Despite the adverse effects caused by excess sedimentation, there has been minimal effort applied to the development of preventive, control methodologies that limit sedimentation in rivers and reservoirs. In contrast, considerable effort has been focused on developing simulation models that predict sediment movement in alluvial systems. Although these simulators are useful in assessing "what-if" questions concerning bed sediment response for a hydrologic event, they cannot directly solve complex control problems that require decisions to be made. Since channel discharges, or reservoir releases, constitute the most important controllable factor that affects morphology of a river-reservoir network, these decisions involve determination of an optimal reservoir release policy that minimizes the adverse effects of sedimentation for forecasted storms. A general application methodology is needed by reservoir management and planning authorities to efficiently identify short- or long-term optimal reservoir operations that control sedimentation. The methodology should account for uncertainties on parameters such as sediment grain size and transport capacity and contributing runoff to reservoirs. Subsequently, the methodology must attempt to overcome historical gaps between theoretical developments in optimization and practical reservoir management. This proposal focuses on the development of such a methodology that will provide a cost-effective means for sustaining the benefits that regional water resources are capable of providing.

Statement of Research Benefits

This research is unique in its use of natural optimization methods as part of a decision-making mechanism for sedimentation control and in its advancement of optimization models to solve realistic engineering problems. Specifically, benefits of the research have the following aspects:

1. No methodology presently exists that can efficiently identify multiple-reservoir releases that minimize sedimentation while considering the uncertain nature of sediment and hydrologic variables. The results of this research will provide such a methodology that can be used by reservoir management authorities and analysts to control the adverse effects of sedimentation.

2. No previous attempts have been made to evaluate multi-reservoir releases for sedimentation control under conditions of uncertainty. This is

especially unique since the problem posed is a realistic and important aspect of sustainable, productive river-reservoir systems.

3. This will be the first attempt to apply genetic algorithms for solution to the sedimentation problem. Results of this research will reveal important information concerning the general applicability and effectiveness of these natural optimization techniques. There are many other realistic water resources management problems that may benefit and could be solved once the overall solution methodology has been developed and tested.

4. Many previously developed reservoir operation models require simplification of problem size or dynamics and have not been readily adopted by reservoir management authorities due to the complex nature of the model. The proposed research emphasizes use of an established hydraulic and sediment transport simulator into the overall solution approach. As a result, the limitations are only those inherent to the simulation model, and additional problem simplifications are not needed. Furthermore, by limiting optimization data required, those who are familiar with the simulator can use this decision-making tool with minimal additional technical knowledge.

5. The project will benefit the career advancement of a new faculty member and his research efforts, and support a Southern Illinois University student in completion of a graduate degree.

Research Objectives

Rivers and reservoirs cannot be viewed as replaceable resources given the current global environment. As a result, focus should be directed toward adequate decision-making models that promote resource sustainability. The objective of this research is to develop a methodology and computational model for efficiently determining reservoir releases that minimize sedimentation in a multiple-reservoir river network. In this context, the term sedimentation could define total cumulative scour and deposition occurring in an alluvial network, scour and deposition only at specified critical locations in the network, or cost of alleviating the problems caused by scour and deposition. The resulting model will serve as a decision-making mechanism to assist water management authorities in controlling sedimentation and, thus, sustaining river-reservoir systems and their associated benefits.

The sedimentation control problem represents a large-scale, nonlinear programming problem for which there are no explicit solution schemes. The problem can, however, be solved using a discrete-time optimal control approach that is based on a computational interface between simulation techniques and nonlinear optimization methods. This particular optimal control model will rely upon a sediment transport simulation model to solve governing hydraulic and sediment transport constraints and a natural optimization procedure called genetic algorithms to solve the master optimization problem. Uncertainties on sediment characteristics and hydrologic inputs will be accommodated using a chance-constrained formulation of the problem. The model will identify short- or long-term optimal reservoir operations that control sedimentation and will be capable of considering any configuration of a dendritic, single- or multiple-reservoir system. Emphasis will be placed on creating a computationally efficient model that locates a globally optimal reservoir operating policy with a high degree of reliability. Additionally, the optimal control model will incorporate a familiar sediment transport simulator that engineers and reservoir management authorities have previously accepted and will limit additional data requirements beyond that of the simulator. These steps will be taken in efforts to close the apparent gap between theoretical developments in optimization research and practical water resources management.

Research Methods and Procedures

The agenda for the proposed research consists of four major tasks, as follows;

1. Chance-constrained formulation of the network sedimentation problem in accordance with the framework of discrete-time optimal control;

2. Development of a new methodology and computational model for solving the network sedimentation problem;

3. Application of the computational model to both hypothetical and existing multiple-reservoir river systems, and;

4. Assessment of the optimal control model and its applications, and the provision of recommendations for improvements, if needed.

Task 1 - Problem Formulation

For the sedimentation control problem, the matrix of decision variables is represented by stagewise multiple-reservoir releases, and system state variables are reservoir storage levels and bed elevations at identified river and reservoir cross-sections. Although different forms of an objective function will be investigated, a general statement of the reservoir management model is to

Minimize [cumulative scour and deposition in rivers and reservoirs for a simulated event(s)]   (1)

Subject to the following constraints;

(A) <u>Sediment Transport Constraints</u>: These constraints include the governing laws for hydraulic and sediment transport phenomena. They are the continuity equations for water and sediment, the conservation of energy equation, and a select sediment transport capacity equation. These so-called transition constraints describe the stage-by-stage response of the hydraulic network according to an imposed reservoir release policy. Though they are sets of partial differential equations, these constraints can be described generally by a functional relation given as

$$E_{i,t+1} = f_E(E_{i,t}, S_{j,t}, R_{j,t}, t) \quad \text{for all } i, j \tag{2}$$

where $E_{i,t}$, and $E_{i,t+1}$ are bed elevations for river and reservoir cross-sections, i, at discrete times t and $t+1$; $S_{j,t}$ is the stagewise reservoir storage level for reservoir j; and $R_{j,t}$ represents reservoir releases. Evaluation of these relationships, and subsequent determination of stagewise bed elevations, can be performed using an appropriate sediment transport simulation model.

(B) Reservoir Storage Constraints: Continuity of reservoir storage between discrete time intervals must be satisfied and allows for the accumulation or depletion of reservoir storage over a simulated hydrologic period. A general mass balance equation on reservoir storage is

$$S_{j,t+1} = f_S(E_{i,t}, S_{j,t}, R_{j,t}, t) \quad \text{for all } i, j \tag{3}$$

Selection of the hydraulic and sediment transport simulation model must be partly based on its ability to account for changes in reservoir storage. If a one-dimensional steady flow model is chosen, simulation would be traditionally based on conditions where inflow to a reservoir equals its release at each discrete time interval. In an optimal control model, the purpose is to determine a release that is likely to vary from the inflow, and a change in storage is permitted to occur. Therefore, modifications to the simulator may be required to allow for simulation of the quasi-unsteady nature of flow at a reservoir.

(C) Bound Constraints: The remaining constraints are used to define a particular solution space and guarantee feasible reservoir operations. They can be imposed due to physical limitations of the system, such as the maximum reservoir release that can pass a gated outlet, minimum reservoir storage required for navigation, and minimum allocation for water demand, or can be arbitrary limiting parameters imposed by the decision maker. These bound constraints are

$$\underline{R_{j,t}} \leq R_{j,t} \leq \overline{R_{j,t}}$$

$$\underline{S_{j,t+1}} \leq S_{j,t+1} \leq \overline{S_{j,t+1}}$$

$$S_{j,T} = S_{j,target} \qquad (4)$$

where $R_{j,t}$ and $R_{j,t}$ are upper and lower bounds on reservoir releases; $S_{j,t+1}$ and $S_{j,t+1}$ are upper and lower bounds on reservoir storage levels; $S_{j,target}$ represents the target storage level for the terminal storage state, $S_{j,T}$; and T is the number of simulated time intervals.

Parameter uncertainty, to some extent, is inevitable in using a mathematical model to simulate real conditions. For the sedimentation problem, uncertain parameters include sediment size and transport load throughout a hydraulic network and contributing runoff to reservoirs. If the reliability of such parameters is neglected, a mathematically optimal solution may be less than optimal when applied to the real system. To address the nonhomogeneity of these parameters and their impact on decision variables, a chance-constrained formulation will be adopted in the optimal control methodology. Generally, this formulation will require that numerical values assumed by uncertain parameters, and affected constraints, must meet a minimum confidence level. Though probabilistic in nature, the formulation can be transformed to a deterministic equivalent using the mean and standard deviation of the parameter and its standard normal variate corresponding to a desired level of reliability. Statistical data for hydrologic inputs would be provided by the model user. For sediment characteristics, however, this data can be derived through repeated, simultaneous executions of the simulation model using different sediment transport capacity equations.

Task 2 - Model Development

The proposed model formulation is a constrained, nonlinear programming problem that will be solved by a discrete-time optimal control model, written in FORTRAN computer code, that interfaces a sediment transport simulation model with an optimization algorithm. The constrained formulation can be transformed into an unconstrained problem by first applying a penalty function. Such a function is used to penalize the objective function when one or more of the bound constraints are violated, thus eliminating the need for explicit handling of bound constraints. The simulator will be used to implicitly solve the sediment transport and reservoir storage constraints in the nonlinear subproblem. The apparent size and complexity of the optimization problem is reduced since the optimization algorithm does not directly handle the simulator equations and is left only to identify deterministic reservoir release policies, or decision parameters. The master problem of evaluating these optimal releases will be solved using a modified genetic algorithm.

The general methodology will begin with initial conditions, including initial geometry, hydrologic inputs and sediment characteristics, and a user- or computer-generated set of reservoir operation policies, or "populations." Using the simulation model and the objective function, the degree of fitness, or optimality, of each reservoir policy will be evaluated. Select portions of the population with lower levels of optimality are eliminated, and several additional solutions are randomly generated and added to the remaining population. The solutions are next forced to share particular traits in a "reproduction" step. For example, portions of two policies will merge and "mutate" to create a third operational policy. In a cyclic fashion, the simulator will again be executed and used to test optimality of the new population. The process of reproduction, mutation, and evaluation of optimality is continued until an optimal reservoir operation policy is located.

Although an evaluation of accuracy of the more than 45 available sediment transport simulators is not an objective of this project, a qualitative investigation based on history and frequency of use, technical support available, and conclusions drawn by other researchers on model performance can be used to select an appropriate simulation model (Subcommittee on Sedimentation of the Interagency Advisory Committee on Water Data 1988). Though a likely candidate for use is the U.S. Army Corps of Engineer's *HEC-6* sediment transport simulation model (1993), further evaluations may suggest the use of alternative or multiple simulators. Similarly, a thorough investigation of the computational aspects of different types of genetic algorithms and their applications will yield recommendations for developing the optimal control model. During the development of the model, emphasis will be placed on limiting additional data required beyond that of the simulation model alone. This limitation will allow those familiar with sediment transport simulation to use this decision-making tool with minimal additional technical knowledge.

Task 3 - Application

To evaluate the usefulness and capabilities of the methodology in solving the sedimentation problem, the computational model will be applied to two multiple-reservoir river networks. The first of these will be a hypothetical system having a minimum of four reservoirs. To make the application general, the configuration will include reservoirs in both series and parallel. Solution for the case of reservoirs in series will be of particular interest since any release policy implemented at an upstream facility will affect operation at downstream reservoirs. The second application will be based on an existing multiple-reservoir network to demonstrate capabilities of the model in solving real problems. The computational model will be applied to the network consisting of Lake Shelbyville and Carlyle Lake on the Kaskaskia River in central Illinois. Both reservoirs are operated by the U.S. Army Corps of Engineers, St. Louis District, with whom contact has already been made concerning the proposed research. Preliminary information from the Corps of Engineers indicates that Carlyle Lake, Illinois' largest inland lake, is accumulating sediment at rates far beyond that for which the facility was designed. Data gathering and review, establishing geologic, hydrologic, and sediment input information, and evaluation of the most appropriate sediment transport function for the application will be key components of this task.

Task 4 - Assessment

The final task will be to assess the effectiveness of the optimal control model in solving the sedimentation problem. An attempt will be made to answer questions concerning global optimality and parameter sensitivity, including dependence on user- or computer-generated initial release policies. Comparisons to previous research performed by Nicklow (1998) will yield conclusions regarding relative performance and applicability of genetic algorithms to water resources problems. Recommendations for possible future improvements in model formulation, computational procedures, and model modifications, including possible real-time optimal control capabilities, will also be provided.

Related Research

Operating policies for storing and releasing water from a network of reservoirs would ideally be optimized so that a network operates as one system working to achieve a common objective. Often, however, each facility is operated as a separate unit, and reservoir operating decisions are derived using historical rule curves rather than optimal control strategies. As stated by the Tennessee Valley Authority (1974),

"Reservoir operations are still essentially based on so-called rule curves which were developed by multiple objective considerations yet without the benefit of modern system analysis techniques and high speed digital computers. There are indications that significant improvements in water resource management can be achieved by more comprehensive planning and operation procedures using optimization techniques. The annual benefits derived from such improved methodologies may easily amount to several million dollars."

Over the last two decades, significant advances have been made through reservoir operation studies and the application of operations research techniques to water resources problems. Yeh (1985) and Wurbs (1993) provide a comprehensive review of recent management models that have incorporated optimization into their development. The models are aimed at a variety of objectives that range from hydropower generation and water supply, to recreation, fish and wildlife enhancement, and flood control. Though they are important contributions, none of these models are designed to address the network sedimentation problem.

Carriaga and Mays (1995a, 1995b) were the first to address a version of the sedimentation problem by interfacing a differential dynamic programming algorithm with the widely used sediment transport simulator, *HEC-6 Scour and Deposition in Rivers and Reservoirs* (U.S. Army Corps of Engineers 1993). Models created as part of that research considered only sedimentation occurring in a single downstream river reach receiving waters from one reservoir. The interfacing, or optimal control, approach between a simulation model and an optimization algorithm leads to a solution methodology that does not require simplification of problem dynamics or size. This advantage is a result of the simulator, rather than the optimizer, being designated to handle the nonlinear relationships that govern system performance. Similar interfacing approaches have been used in other areas of water resources engineering, including groundwater remediation (Chang et al. 1992, Culver and Shoemaker 1992) and estuary management (Li and Mays 1995).

To solve the sedimentation problem for more general applications, Nicklow (1998) developed an optimal control methodology that interfaced a successive approximation linear quadratic regulator algorithm with a sediment transport simulator. The methodology considered simultaneous operation of multiple reservoirs and incorporated sediment movement within both rivers and reservoirs into the formulation of the problem. The different models developed relied on either a finite difference model or HEC-6 to describe the sediment transport dynamics within the hydraulic network. Application of the models to both hypothetical examples and the Yazoo River network in Mississippi demonstrated that the approach could be effectively used to control sediment scour and deposition. Conclusions, however, revealed a need for reduced computational time, improved reliability in locating globally optimal reservoir operation policies, and inclusion of parameter uncertainty concerning sediment characteristics and hydrology into the problem formulation. The methods in this proposed project will differ from earlier attempts in sedimentation control in that genetic algorithms will be used for constrained control of sediment scour and deposition in both the rivers and reservoirs of a multiple-reservoir network. Reliability issues concerning sediment properties and discretized hydrologic inputs will be addressed using a chance-constrained formulation.

A genetic algorithm is a probabilistic global optimization technique based on the mechanics of natural selection and genetics (Holland 1975). Analogous processes of reproduction, crossover, and mutation are applied to decision variables encoded or characterized, typically using binary strings. The algorithm is designed to produce “populations” of solutions whose “offspring” display increasing levels of optimality (Goldberg 1989). By using genetic algorithms, Otero et al. (1995) devised a methodology for optimal management of freshwater runoff into estuaries. Several applications of the algorithms have been made for improving the design of water distribution systems (Reis et al. 1997, Simpson et al. 1993, Savic and Walters 1997). The technique has also been used in the calibration of rainfall-runoff models (Ndiritu and Daniell 1996) and for generating efficient watershed management policies (Harrell and Ranjithan 1997).

Some of the advantages of using genetic algorithms to solve large-scale nonlinear optimization problems are that they can be used with continuous or discrete parameters, require no simplifying assumptions about the problem, and do not require computation of derivative information during the optimization (Haupt and Haupt 1998). All too often in the solution of complex control problems, the nonlinear dynamics and size of the original problem are simplified as to not exceed the solution capabilities of the optimization algorithm. For the proposed research, unfortunately, these simplifications would lead to only mere estimates of optimal operational policies. Furthermore, in large problems like the sedimentation problem which involve many partial differential equations, the avoidance of time-consuming derivative computations makes these optimization algorithms more attractive than common gradient-based optimization methods. Finally, genetic algorithms employ global sampling methods and have been shown throughout the literature to locate global or near global optima for complicated problems with a high degree of reliability.

Information Transfer Plan

A review of the optimal control methodology, results of applications, and recommendations for improvement will be disseminated to the water resources community through conference presentations and publication in a peer-reviewed journal.

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