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R. C. Peralta
Utah State University

Ineke M. Kalwij

Shengjun Wu

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Practical Simulation / Optimization Modeling for Groundwater Quality and Quantity Management

Richard C. Peralta, Ineke M. Kalwij, Shengjun Wu
Utah State University, Logan, UT, USA and U.S. Air Force Reserve,
Richard.peralta@usurf.usu.edu, *http://www.usurf.org/units/wdl*

ABSTRACT

Software for mathematically optimizing groundwater management has improved significantly in recent years. The SOMOS code can readily handle large complex plume and water management problems. Most recently, it developed a least-cost $40.82M 30-yr pumping strategy for the 6.58 mile long Blaine NAD plume. That strategy was 19 percent better than the strategy developed simultaneously by an experienced consultant using normal trial and error simulation procedures. The management problem involved 60 stress periods, and well installation and pumping rates that could change every 10 periods. The optimal strategy employed 10 new wells. At a simpler site, SOMOS helped select robust strategies from hundreds of least cost strategies that it identified--all having virtually the same objective function values. For another site, it developed a least-cost strategy for concentration constraints that change with time. A third site demonstrated the need for client-regulator-designer interaction during the design process. It also revealed SOMOS' power in easily modifying posed optimization problem formulations to increase the chance that developed strategies will be acceptable to regulators. Improvements over strategies developed by others using normal trial-and-error ranged up to 50%. SOMOS utility in addressing complicated water resource supply problems is also demonstrated.

INTRODUCTION

Simulation/Optimization (S/O) models include both simulation abilities and optimization algorithms. Simulation might be accomplished by analytical equations, numerical models, or substitutes using a variety of response matrix methods. S/O modeling has been increasing in use for developing management strategies.

For S/O groundwater modeling, the Utah State University Dept. of Biological and Irrigation Eng. (BIE), and the Utah State University Research Foundation Water Dynamics Laboratory, utilize the home-developed SOMOS (Simulation/Optimization Modeling System) software (SSOL & HGS 2001). SOMOS includes Operation Research (OR), Genetic Algorithms (GA), Simulated Annealing and Tabu Search optimization algorithms. Response functions (for OR) and artificial neural networks (linked with GA) are employed as substitute simulators. Peralta (2003) lists abilities of SOMOS, available from above web site.

Peralta (2001) summarizes 6 optimal pump and treat (PAT) strategies BIE developed using SOMOS or its earlier versions. Two of those designs were for existing systems, one was for a partially built system, and three were for desired systems. We do not know whether the optimal strategies developed for existing systems were employed. Our recommendations were employed for the partially existing system at March AFB, and for the three new systems--the CS-10 plume of Massachusetts Military Reservation (HGS, 2000), Norton AFB, and Wurtsmith AFB. According to those involved with the installed systems, all have operated successfully.

The federal Environmental Security Technology Certification Program (ESTCP) recently included SOMOS (Simulation/Optimization Modeling System) within a testing project for three sites. SOMOS yielded improvements of 3% - 50% over strategies developed simultaneously by an experienced consultant using normal trial-and-error methods. SOMOS has also been used for water supply problems, but for those no comparison with trial-and-error methods exists. This paper briefly describes the three ESTCP problems and one supply problem.

SELECTED RECENT SOMOS APPLICATIONS

Blaine Navy Ammunition Depot (NAD) TNT and Solvent Plumes Remediation

This is a spectacular demonstration of SOMOS prowess in optimizing for complex systems (SSOL, 2002a). NAD has plumes of explosives and solvents. The plumes are represented in a 6-layer model having 82 rows and 136 columns. Contaminants were grouped by HydroGeologic so that they could be represented by two plumes. The USU goal was to minimize costs of achieving cleanup to MCL within 30 years, while containing the plumes within containment zones throughout that period (Fig 1). There were 60 stress periods within the 30 years, and wells could be added and pumping rates changed every 5 years. Within four months USU developed a $40.82M least cost strategy, requiring installing 10 new wells. That was 19 percent better than the strategy developed by an experienced consultant for the same problem within the same period. Figure 2 shows the Layer 3 plumes predicted after 25 years of pumping.

Formulation 1

Minimize Present Value of Cost, Including:
- capital costs of new extraction wells ($400K), treatment ($1.0K per gpm), and discharge piping ($1.5K per gpm),
- fixed cost of O&M ($115K), and sampling ($300K annually),
- variable cost of electricity for well operations ($0.46K/gpm), treatment ($0.283K per gpm), and discharge ($0.066K per gpm).

Constraints are (evaluated at the beginning or end of 5-yr management periods):
- system modifications can only occur at the beginning of each management period;
- layers 3-6 cleanup within modeling period (ny=30);
- concentrations above MCL not to exit from Containment Zone;
- 350, 700, 1050 gpm pumping limits on wells screened in 1,2 or 3 layers;
- no remediation wells in restricted areas, (layer 6, cells with irrigation wells, etc.);
- dry cell constraint

Formulation 3

Minimize the maximum total pumping rate of any management period.
Constraints are the same as Formulation 1, except cleanup is not required, and the maximum number of new extraction wells is 25.

Figure 1. Significant Blaine NAD Optimization Problem Formulations

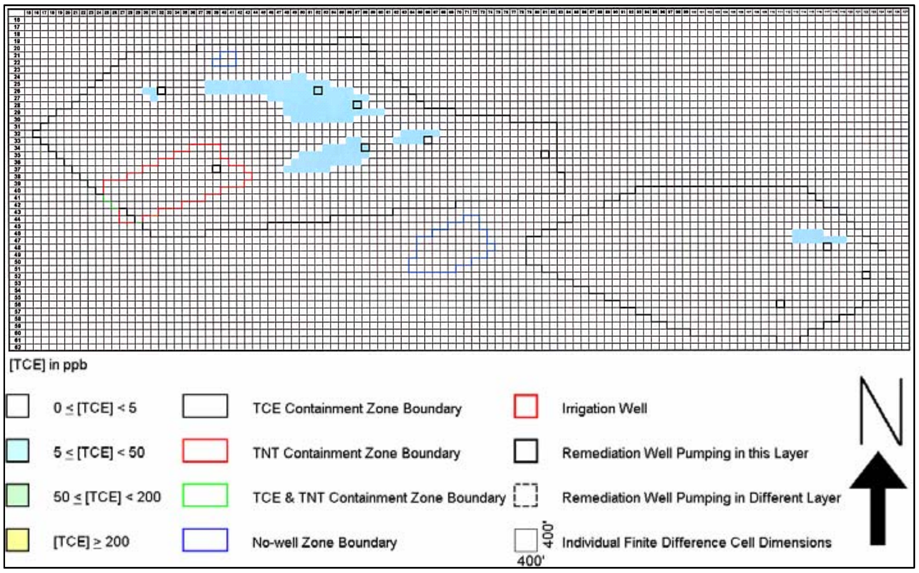

Figure 2. TCE concentrations ≥ 5 ppb in Layer 3 after pumping 25 years

NAD optimization problem Formulation 2 is like Formulation 1 except there is less cost for treated water. The optimal strategy for that formulation is the same as for Formulation 1. Figure 1 shows the optimization problem of Formulation 3. The optimal USU Formulation 3 strategy has a 2139 gpm maximum pumping rate, 26 percent better than that developed by a consultant using trial-and-error. Continued running yielded a 2123 gpm strategy several days later.

Umatilla Army Ammunition Depot (UAD) TNT and RDX Plumes Remediation

For UAD, the Formulation 1 goal was to minimize the cost of achieving RDX and TNT plume containment immediately and eventual cleanup (Figure 3). The site included 132 rows, 125 columns, 5 layers, and has

4 management periods (MP) each of 5 years. USU developed many optimal and robust pumping strategies having a virtually identical least cost (present value, 5 % discount) of $1.66M. That is a 23% better than a strategy developed by a consultant using a trial-and-error approach, and 57% better than the strategy being used (which, developed at a different time for different conditions, was expected to cost $3.836M). During the ESTCP competition USU evaluated robustness and identified strategies that were much more robust than others that will cost the same if the deterministic model perfectly represents the physical system (SSOL, 2002c). Of course the model does not perfectly represent the physical system—meaning that an implemented strategy might cost more than expected. A fragile strategy might cost $1.66M over a hydraulic conductivity range of 102-96% of the base hydraulic conductivity field. Outside that range, cleanup is slower and cost-to-cleanup increases dramatically to $2M and higher. Later USU used SOMOS' multiple realization features to develop even more robust and reliable strategies. During the same period that USU developed the first Formulation 1 strategies, USU also developed a Formulation 3 strategy minimizing contaminant mass remaining after 20 years. The USU strategy was almost 50% better than that developed by consultant using trial-and-error (0.20 kg versus 0.38 kg). USU did not think it realistically worthwhile to attempt to further reduce mass by adding additional wells.

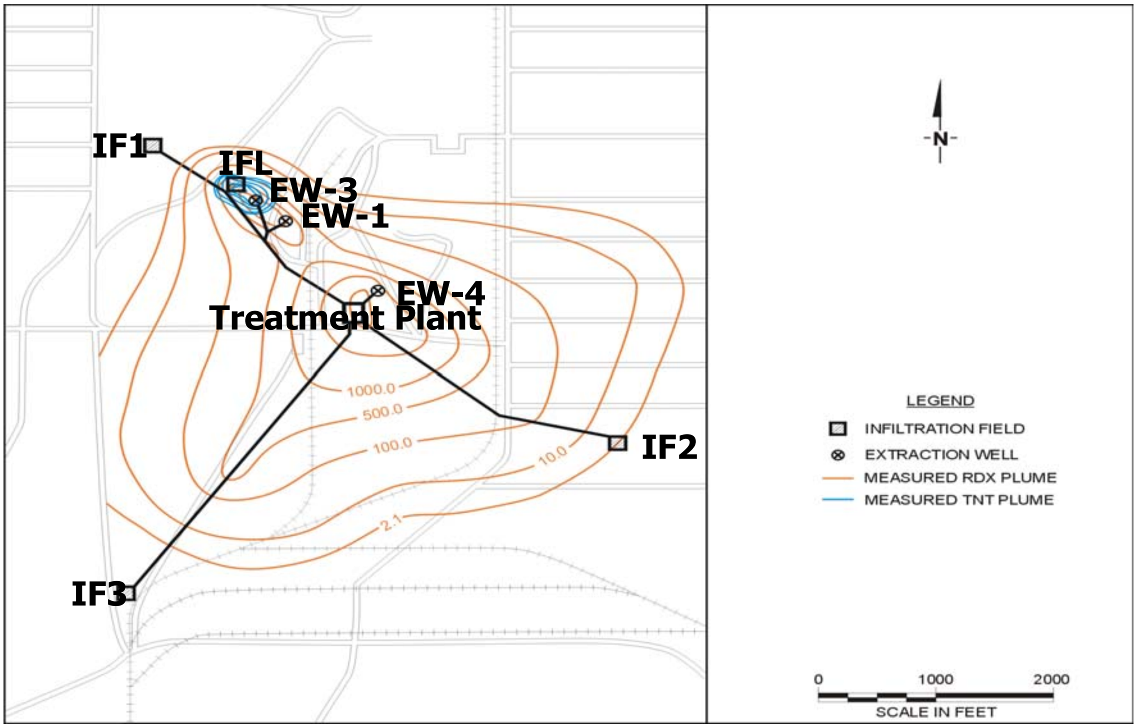

Figure 3: UAD RDX and TNT plumes before pumping

Tooele Army Ammunition Depot (TAD) TCE Plume Remediation

The TAD model includes 165 rows, 99 columns, 4 layers, and has 7 management periods (MP) each of 3 years. TAD formulations were problematic because they were either infeasible (Formulation 3) or could force a design team to choose between producing a design having the best objective function value, or the most desirable design, because these were possibly not the same (Formulations 1 and 2). The project contract prevented design teams from discussing the problem among each other or with the facility. USU opted to aim toward producing what we considered to be the best acceptable designs for the real world.

The assigned Formulation 1 optimization goal was to minimize the cost of cutting the TCE plume at the TAD northern boundary (POE 5 ppb constraint, Figure 4). For Formulation 1, USU decided that it would use extraction to cut the plume at the POE. Predominantly using injection would push contaminated water (>5ppb) into formerly clean aquifer (<5ppb)—not something that we thought environmental regulators would condone (SSOL, 2002b). USU's most acceptable Formulation 1 strategy required installing 3 extraction wells, yielding $14.14M cost (3% improvement over the trial-and-error approach).

Formulation 2 was the same as Formulation 1 but had additional containment constraints along an internal Point of Compliance (POC) boundary (POC constraints, Figure 4). Strictly adhering to Formulation 2 made it likely that contamination would be pushed into formerly clean aquifer. Therefore, USU developed a modified Formulation 2 by adding an additional 5 ppb constraint zone (Zone 4) to prevent the plume from bypassing the POC on the west (Figure 4). Because USU formally added these constraints its result is not reported by ESTCP. The result, about two weeks after the first optimization deadline, was a cost of $15.73M (3% improvement from the trial-and-error approach).

Formulation 3 is the same as Formulation 2 but had a temporally declining source term, an additional 50 ppb cleanup constraint, and limits on the numbers of wells that could be built. The formulation was infeasible, meaning no solution can satisfy all the constraints. Before the final date for submitting results, USU changed the well-limit constraint and presented a $17.93M strategy.

During TAD out-briefing, a TAD agent asked what would have been the result if bounds on individual well pumping rates were relaxed. As a result, USU developed Modified Formulations 1 and 3 by allowing more than 380 gpm pumping per well along the POE, by adding 5 ppb constraint zones (Zones 4 and 5) west of the POC and POE to prevent westward plume expansion (Figure 4), and by relaxing the limit on total well numbers. The optimal solution for Modified Formulation 1 yields a $12.62M cost. The Modified Formulation 3 yields a $16.98M cost, and requires just one well along the POE. This is a more or less satisfactory conclusion for a difficult situation. It emphasizes the need for interaction between designers, clients and regulatory agencies. A conference call could have early determined whether pushing contaminated water (> 5 ppb) into relatively uncontaminated aquifer (<5ppb) was acceptable or not, and whether the formulations needed revision.

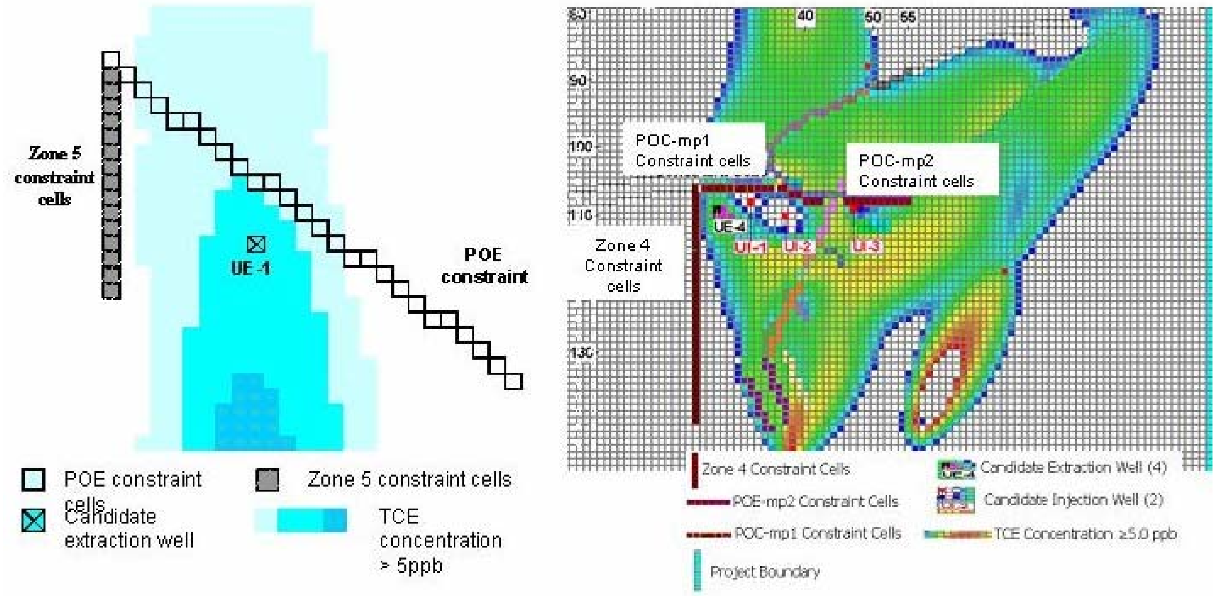

Figure 4. TAD imposed constraints and additional constraints

Cache Valley Stream/Aquifer System Planning

Cache Valley (Utah) model site includes 82 rows, 39 columns, and 6 layers (Fig. 5). Its hydrologic system includes basin fill aquifers and hydraulically connected rivers. In valley upper reaches, streams provide recharge to the aquifer. In lower reaches, flow direction is reversed. The largest river, the Bear, flows from Bear Lake through the valley on its way toward the most urbanized part of Utah. Groundwater pumping depletes flow in the rivers, causing conflict with downstream water users. As water resource and county managers plan future development, they must consider the flow between surface and ground waters. For different management scenarios, SOMOS easily computes maximum sustainable pumping strategies that do not unacceptably cause river dewatering, spring drying, or groundwater declines. Figure 6 shows a tradeoff curve between groundwater pumping and river dewatering (Das, 2002).

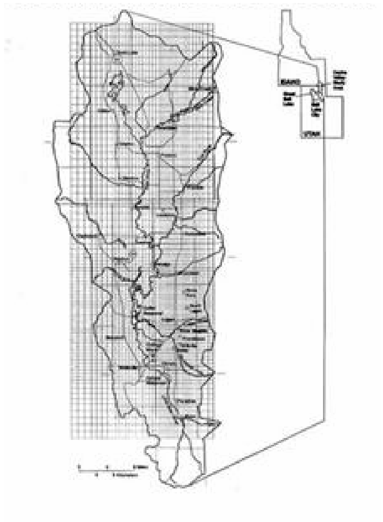

Figure 5. Cache Valley study area

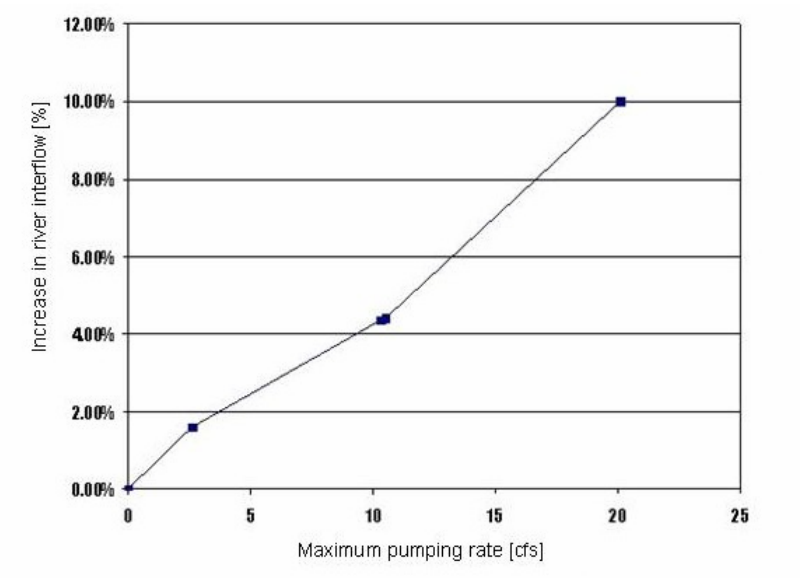

Figure 6. Groundwater Use–Stream Depletion Trade-off

SUMMARY

SOMOS makes it easy to dramatically improve groundwater and conjunctive management strategies. We have demonstrated its application to numerous complex problems. One can generally expect about 20% improvement in objective function value, although 50% or greater is also possible. We invite those interested in such abilities to apply SOMOS to their most challenging problems.

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