Section 1

Title: Multiobjective Optimization of a Public Supply Wellfield using an Artificial Neural Network and Non-Linear Programming

Revised Title: Optimal Pumping Policy for a Public Supply Wellfield Using Computational Neural Network with Decision-Making Methodology

Section 2

Principal Investigator(s) name(s) and university:

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Section 3

Congressional district of university where the research was conducted:

Fifth

Section 4

A. Problem and Research Objectives:

Many public supply wellfields are located in urban areas where releases of contaminants into the subsurface are all too common. The resulting groundwater contaminant plumes are often captured by pumping wells, contaminating the drinking water supply, and constituting a potential risk to public health. Even though the Safe Drinking Water Act requires routine water quality monitoring of public supply wells, and, if detected above the maximum contaminant level(s), contaminant removal, the distributed drinking water may still contain potentially harmful compounds presently not regulated. In fact, while there are over 75,000 chemicals produced in the United States, only 80 are currently monitored for in drinking water.

Many compounds are not regulated simply because the effects on human health from exposure are not known. In 1997, The Environmental Defense Fund released a report alleging that there was a lack of publicly available data on the health effects of 2,700 US high production volume chemicals. Because many contaminant plumes consist of a myriad of compounds, many public supply systems are distributing water that, while meeting the requirements of the Safe Drinking Water Act, contain non-regulated contaminants at relatively high concentrations.

The area over which a pumping well captures it water, and potentially groundwater contamination, increases with increasing pumping rates. Because many water managers are faced with meeting high supply demands, particularly during hot months, many wells often pump at or near their maximum pump capacities. These high pumping rates produce capture zones that extend over large areas and can result in eventual pollution of the well.

The federally mandated Wellhead Protection Program requires States to delineate wellhead protection areas for all public supply wells. Often, these delineated areas are based upon a computed time of travel for contaminants to the wellhead, for times ranging from days to years. Potential and actual groundwater discharges that constitute a potential threat to the well may be regulated to minimize the chance of well contamination. However, this program does not adequately address existing contamination plumes that already pose a risk to the well(s), and whose pumping rate(s) may determine whether or not the contamination is captured. In cases like these, the water manager may want to implement a pumping policy that balances his supply objectives with the objective of minimizing the possibility of well contamination.

With these two conflicting objectives, the resulting water management problem reduces to a multiobjective and conflict resolution problem, where trade-offs among non-commensurable objectives must be identified. Because various stakeholders are involved, often each with difference preferences in the outcome, identifying the best compromise solution is essential for fostering an atmosphere of cooperative understanding and preserving public trust.

In this research, a new methodology was developed for identifying optimal operating pumping policies for a public supply wellfield that balances the conflicting objectives of maximizing supply and minimizing potential human health risks. The new methodology utilized a Computational Neural Network (CNN) to simulate the behavior of a real-world drinking water aquifer under variable pumping and climatic conditions. The results of this research demonstrate an efficient and accurate alternative to traditional groundwater management optimization methods. In addition, the CNN method provided the information necessary for conducting a formal and rigorous multiobjective and conflict resolution analyses of the water management problem. This enabled identification for an optimal pumping policy for balancing risk with supply in accordance with the preferences of the various stakeholders.

B. Methodology:

The feasibility of training a CNN to learn the behavior of a numerical groundwater flow model under changing conditions was first explored using a hypothetical but realistic test case. Twelve distinct CNN's, each corresponding to a separate month, were individually trained to estimate the final monthly groundwater elevations at specific locations of interest in an aquifer, given some initial state of the system, monthly pumping rates, and the monthly areal recharge rate. The twelve monthly CNN's were then linked to predict the monthly time-evolution of the head field at locations of interest in response to changing pumping and areal recharge rates over an annual planning horizon. The resulting CNN architecture, a condensed linear approximation of the finite-difference groundwater flow equations, was embedded into a multiobjective linear programming problem, and non-dominated pumping policies, in the form of a Pareto frontier, were identified. The Pareto frontier is the trade-off curve that depicts water supply (total well pumpage) versus total risk (predicted hydraulic gradients at select locations along the contaminant plume boundary). This Pareto frontier served as the basis for both multiobjective and conflict resolution methodologies.

Following development and testing, the method was then applied to the Parkway Wellfield, located in Toms River, New Jersey. The wellfield consists of six high-capacity public supply wells that draw their water from the regional unconfined aquifer. Two of the supply wells were contaminated from a groundwater contaminant plume that originated from a neighboring Superfund site. The two contaminated wells are being used primarily to capture and remove contaminated groundwater. Because of a suspected cancer cluster, the treated water is distributed for consumption only under drought conditions. The four remaining non-contaminated supply wells, also in close proximity to the groundwater contaminant plume, are at risk to contamination if pumped at sufficiently high rates.

The supply requirements of the community must be balanced with the potential health risks associated with the contaminated groundwater. Various stakeholders within the community have different interests in the outcome, and their preferences must be consolidated to arrive at an acceptable compromise solution. The stakeholders are the Water Company, the public who consume the water, and the chemical company whose waste contaminated the aquifer.

The New Jersey Geological Survey developed a multi-layer groundwater model to simulate the regional unconfined aquifer and pumping effects at the Parkway wellfield. As in the hypothetical case, this model was used to develop a linked CNN to estimate the effects of pumping on the groundwater system at locations of interest. The linked CNN was embedded within a multiobjective model and linear programming was used to identify the Pareto frontier, again representing the set of non-dominated set of solutions between risk and supply.

As in the hypothetical case, this frontier served as the basis for both multiobjective and conflict resolution methodologies. For the three stakeholders, weight preferences (relative weighted importance to both risk and supply) were assigned by experts familiar with the case. In addition, power factors or the relative strength of each stakeholder in the decision-making process were also assigned. The weight preferences and power factors were then used in conjunction with the multiobjective and decision-making methodologies to identify the best compromise wellfield-management solution.

C. Principal Findings and Significance:

In this research, it was found that the developed CNN methodology, in combination with multiobjective and conflict resolution methods, could be used for identifying the best pumping strategy under the conflicting objectives of maximizing water supply while minimizing potential human health risk.

A number of findings of significance came out of this research. The first is that the construction of a CNN, which, after sufficient training, could serve as a highly accurate approximation to the finite-difference flow model, while having significantly fewer variables and a less complicated structure. These features facilitate embedding the CNN architecture as part of the constraint set into any optimization model.

The second is the development of a multiobjective decision support system in which a compromise solution was found between the conflicting objectives of water supply and potential health risks. Distance-based methods served as the multiobjective tool and the trained CNN served as the physical model. Distance-based methods have flexibility in selecting the type of distance and the particular weights. Using the developed methodology, a complete description of the compromise solution could be obtained, while incorporating the conflicting preference orders of the different stakeholders or interest groups into the model.

The third is the development of a decision support system based upon conflict resolution methodology. The most important conflict resolution methods compute either an optimal solution of a composite objective or find the solution of a certain non-linear equation. As with the multiobjective case, the constraint set consisted predominantly of the CNN equations.

Most importantly, however, this research demonstrated the theoretical possibility of training a CNN directly from field data, and directly optimizing management of the system without having to rely upon a numerical groundwater simulator. This could result in significant savings in both time and money, while possibly increasing the accuracy of the optimization efforts. In fact, subsequent work has demonstrated that a computational neural network can be trained to estimate aquifer water levels in response to variable pumping and climatic conditions significantly better than a well-calibrated numerical groundwater flow model. A paper presenting these results is currently being prepared for submission to Water Resources Research.

In conclusion, the CNN methodology and decision support systems were applied to a complicated and real-world groundwater management problem in Toms River, New

Jersey. Numerical simulation of the optimal pumping policy identified by the CNN approach verified that the solution achieves an acceptable compromise between the conflicting preferences of the stakeholders. Representatives of the NJGS believe this approach and the results may serve as the basis for their decision-making process.

Section 5

Publication Information:

None to date. Five articles submitted.

Section 6

Student Support:

Ph.D. completed by Emery A. Coppola Jr., December 2000.

Section 7

Notable Achievements and Awards:

The University of Arizona filed for a patent on the methodology developed in this research. Specifically, the patent is for application of the developed computational neural network/optimization methodology to management of subsurface fluid flow, including water, natural gas, and petroleum.