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Darwin Calibrator—

Improving Project Productivity and Model Quality for Large Water Systems

Water distribution modeling has proven to be a practical tool for the design and operation of efficient and reliable infrastructure systems by water utilities, consulting firms, and government agencies. Not only is modeling software easy to use, it also offers powerful capabilities for storing, managing, analyzing, and presenting water asset information. The purpose of a model is to encapsulate the knowledge of system hydraulics and water quality characteristics and enable engineers to identify sound solutions by evaluating "what-if" scenarios.

Because of the large number of possible scenarios, it is nearly impossible for engineers to develop cost-effective solutions for complex tasks such as system expansion, rehabilitation, and system security without the assistance of a well-calibrated water distribution model. Over the past 20 years, the public and private sectors have invested hundreds of millions of dollars in advancing water resources modeling technology and a variety of asset information systems. Feature-rich commercial models typically allow for the integration of geographic information system (GIS) and AM/FM information system technologies through open database architecture, opening the door for the civil engineering community to take advantage of numerous types of state-of-the-art computing technologies. However, with so many options, determining how to best leverage a simulation model can be a daunting task. Optimization modeling provides engineers with a flexible and intelligent tool to achieve their water supply goals in the most cost-effective manner.

An optimization model embeds a hydraulic simulation model as a domain analyzer and couples it with an intelligent search algorithm to automatically generate and evaluate "what-if" scenarios. It arrives at a number of top solutions (optimal and near-optimal) for solving a practical problem such as model calibration, system design, or pump scheduling.

Some case studies on optimization modeling have been conducted by specialized consultants in the field. These studies have been and will continue to be used to demonstrate how this technology benefits the water resources community. Although a number of off-the-shelf optimization tools have been developed for civil engineers and modelers, most water utilities do not commonly use optimization modeling in the decision-making process. By evaluating optimization modeling and uncovering the essence of this practice, the industry may move a few steps closer to understanding its benefits and challenges.

Guayaquil, with its population of 3 million people, is the largest city in Ecuador and is one of the fastest growing cities in South America.

OPTIMIZATION MODELING

Over the past 40 years, thousands of technical papers have been published on water distribution optimization. A variety of optimization techniques have been developed. In general, genetic algorithms have been found to be the most effective and efficient at solving the optimization problems of model calibration and system design. The optimization technique, a traditional and evolutionary method, is a strict mathematic algorithm that solves a problem (represented by a set of equations) for the solution that gives the extreme value (minimum or maximum). The solution is often referred to as the "optimal" solution. This concept and algorithmic perspective have planted the belief that the optimization method can automatically find the optimal solution for an application.

Finding the single optimal solution has been the consistent goal of mathematic optimization methodologies. This approach is theoretically and academically correct for advancing the research front, but directly matching the mathematician's perception to the engineer's is dangerous for the industry. The danger arises because no practical problem can be automatically solved, a true optimal solution remains unknown for a practical problem even if a cost-effective solution is identified for a particular set of circumstances. What, then, is the true value of optimization technology for the industry?

Envirosoft Engineering & Science Inc. applied Haestad Methods' Darwin optimization technology, based on a competent genetic algorithm, to calibrate a water distribution model for the city of Guayaquil, Ecuador. Guayaquil has a population of 2.3 million people and one of the highest growth rates in South America.

In 2001, the city entered into a 30-year agreement with Interagua, an international water company based in London, England, to operate and manage Guayaquil's water and sewer systems. Some of the main challenges faced by the concessionaire included a significant water supply deficit, interrupted service, low-pressure areas, and a high percentage of unaccounted-for-water (UFW).

Downtown Guayaquil is Ecuador's up-and-coming hot spot for travelers.

The concession contract stipulates that Interagua must install 55,238 new water and sewer connections in the first five years and improve the level of service in areas such as hydraulic pressure and supply continuity throughout the water system. According to Interagua's Commercial Department, in June 2002 the water and sewer network coverage for Guayaquil was approximately 65 and 43%, respectively. The UFW was approximately 75%. To meet these challenges, the city hired Envirosoft and its local affiliated company Aquatec S.A. to develop an effective action plan for various tasks, including:

- an expansion program to manage installation of the required water and sewer connections;
- the design of new water and sewer networks;
- 30-year master plans for the water, wastewater, and drainage systems; and
- an action plan for the reduction of UFW.

In undertaking the challenges of this service work, Envirosoft adopted

FIGURE 1 WaterGEMS-simulated pressures at junctions for the city of Guayaquil

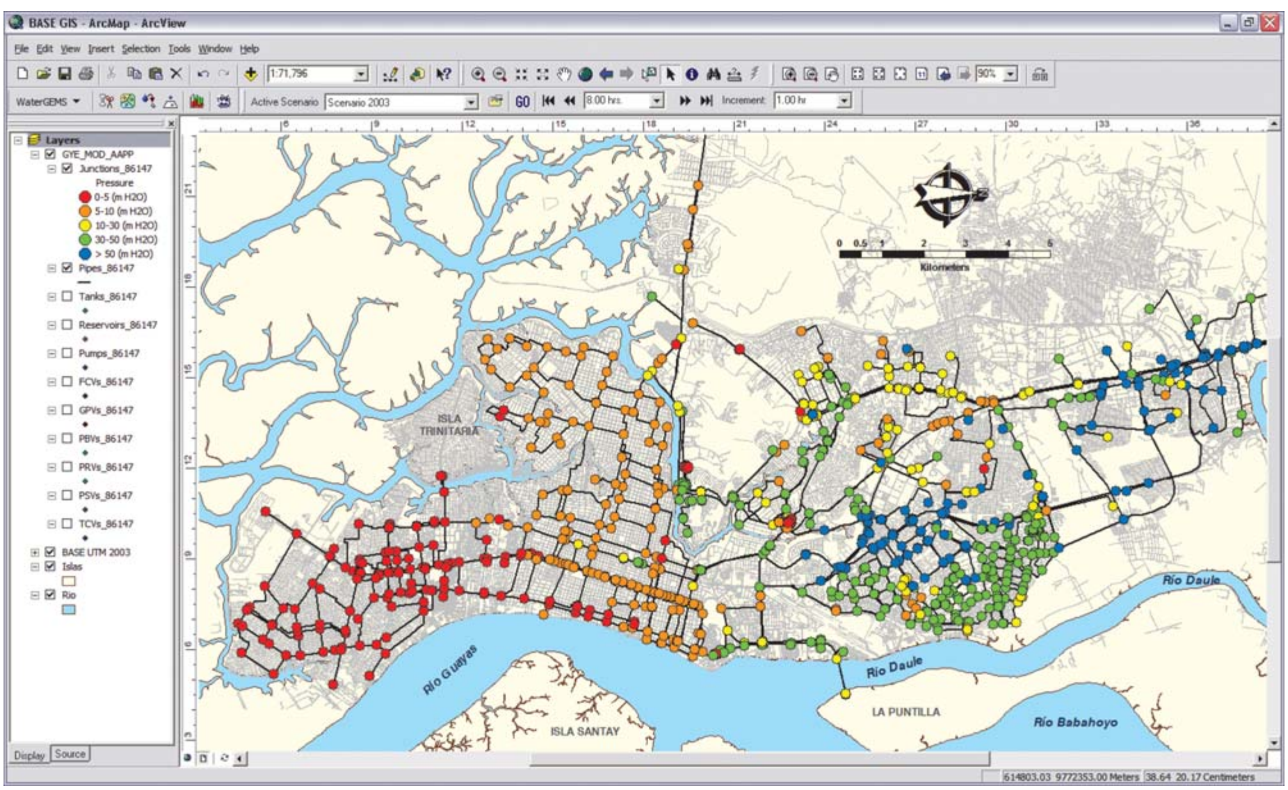
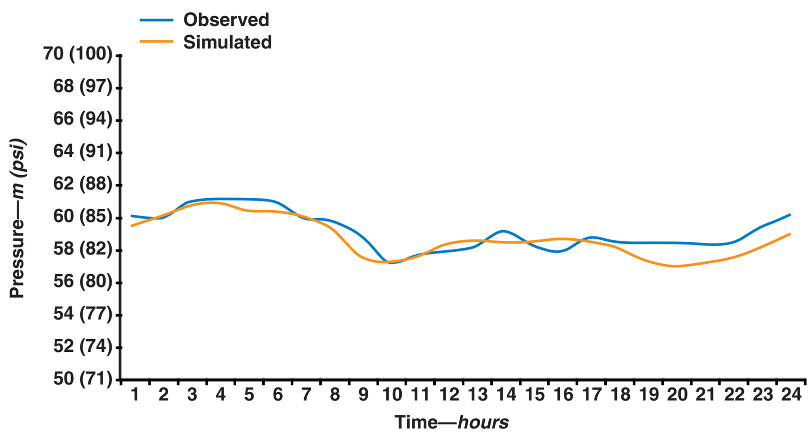


FIGURE 2 Darwin calibration illustration of comparison between the observed and simulated pressures over 24 hours



WaterGEMS and Darwin software for hydraulic network simulation and optimization modeling. Both programs were developed by Haestad Methods, a subsidiary of Bentley Systems. The goal of the project was to build an accurate hydraulic model of the water distribution network. Using both simulation and optimization modeling tools proved to be the most effective and efficient means of achieving this goal. An accurate model can reflect real system conditions and enables engineers to analyze current supply conditions, identify critical water loss areas, and evaluate expansion scenarios for the next 30 years.

As shown in Figure 1, the initial analysis using the uncalibrated model showed that low pressures were prevalent in the southern portion of the system. The low pressures in this area may be the result of both its distance from the source and the higher flows resulting from UFW. To identify the amount of UFW in the system, cost-effective improvement solutions, and an operation strategy for minimizing UFW, the hydraulic model was calibrated to accurately reflect the real system. The Darwin calibrator was used in performing the model calibration tasks.

DARWIN CALIBRATOR PRAGMATICS

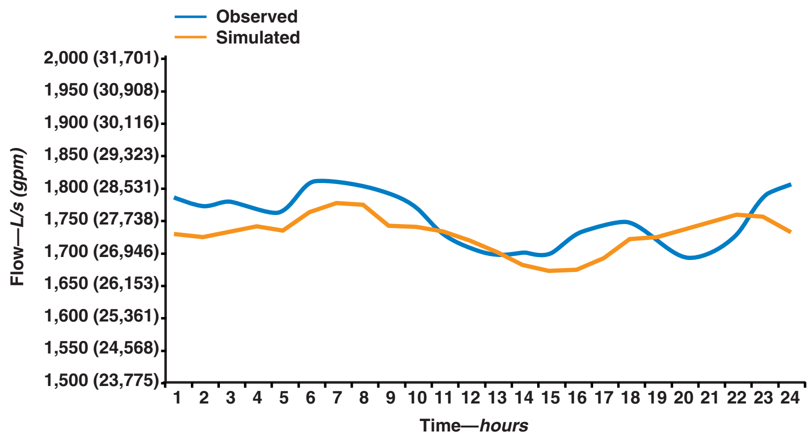
Model calibration consists of adjusting a set of parameters such that the observed values (e.g., flows and pressures) match the model-simulated values. Manual calibration can be a tedious, trial-and-error process for the modeler. The Darwin calibrator uses a competent genetic algorithm as the core search engine to identify the optimal model parameters. It has been developed as a user-friendly and fully integrated tool for water distribution model calibration.

Model calibration depends on adequate field measurement data. In Guayaquil, flow and pressure data were collected using data loggers at appropriate locations. Envirosoft designed 30 new monitoring stations, and Interagua implemented the data-collection program over eight months. Continuously recorded field data—including flows for 10 trunk mains, pressures at 30 locations, and water levels in 7 storage tanks—provided sufficient field data for model calibration. A total of 1,128 data records were entered into the Darwin calibrator to capture the dynamics of the system hydraulics over a 24-hour period.

Following the careful analysis and screening of field data, calibration groups were established, and calibration runs were conducted with the goal of matching measured and modeled flows and pressures. Calibration groups are the groups of elements (pipes or demand nodes) for which Darwin is permitted to adjust model parameters during the calibration process. Items in a single group were transformed in the same way. For instance, pipes in a single adjustment group will have their roughness values set to the same new value during calibration or will have their original roughness values multiplied by the same factor, depending on the option selected by the modeler. One calibration run can be set up for user-selected calibration groups and corresponding field data sets, which effectively represent a portion of the entire system. The Darwin calibrator automatically minimizes the differences between the observed and simulated flows and pressures for the part of a system in one run. Because the calibration tool is so easy to use, many calibration runs have quickly been conducted for the whole system. Using Darwin's powerful combination of genetic algorithm technology and hydraulic solver, hundreds of thousands of possible model parameter solutions were automatically generated and evaluated for each calibration run.

With this calibrator, hydraulic model results for each model parameter solution are compared with field observations, and the closeness of the match for each solution is quantified using a "fitness" value. By mimicking the Darwinian natural selection principal of survival of the fittest, the fitter the solutions are, the more likely it is that they will be selected for use in producing the next generation of solutions. A new solution is created by emulating double-helix reproduction of crossover and mutation, allowing calibration solutions to automatically evolve over successive generations.

FIGURE 3 Example of comparison between observed and simulated flows over 24 hours for a large-diameter pipe



For Guayaquil, the calibration was performed by adjusting both nodal demands and pipe roughness coefficients to match the measured flow and pressure values. Twelve roughness calibration groups were created, including four groups of main distribution lines and eight groups based on pipe material and age for the rest of the system. Six demand groups were based on major population distribution zones presented in the city's master plan.

Calibration was conducted in a progressive manner. The Darwin calibrator first focused on matching the total demand supplied by the treatment plant. Roughness and flow parameters were selected and automatically optimized for four main distribution lines to match average flow and pressure for these lines. The demands were also adjusted to match average flow for five pipes connecting the north system to the south system, allowing engineers to quantify the UFW in the south system. Thus, a macrocalibration of the transmission mains was established, and it served as a stepping stone for optimizing the roughness values and demands to match pressures, flows, and tank levels for 47 data sets over 24 hours.

Many manual calibration runs were executed to gain insight into the hydraulic dynamics of the system and the parameter sensitivity before undertaking Darwin optimization runs. More than 20 optimized calibration runs were then made to explore the potential calibration improvement until a point was reached at which additional runs yielded no noticeable improvement. Figure 2 shows a good correlation between observed and simulated pressures over 24 hours at a critical junction. Junctions with very low pressures are located in areas with high UFW levels, and the observed hydraulic grade line is in general greater than the modeled results. A good fit for pipe flows both at the peak hour and over the 24-hour simulation was achieved for the full range of pipe sizes (Figures 3 and 4).

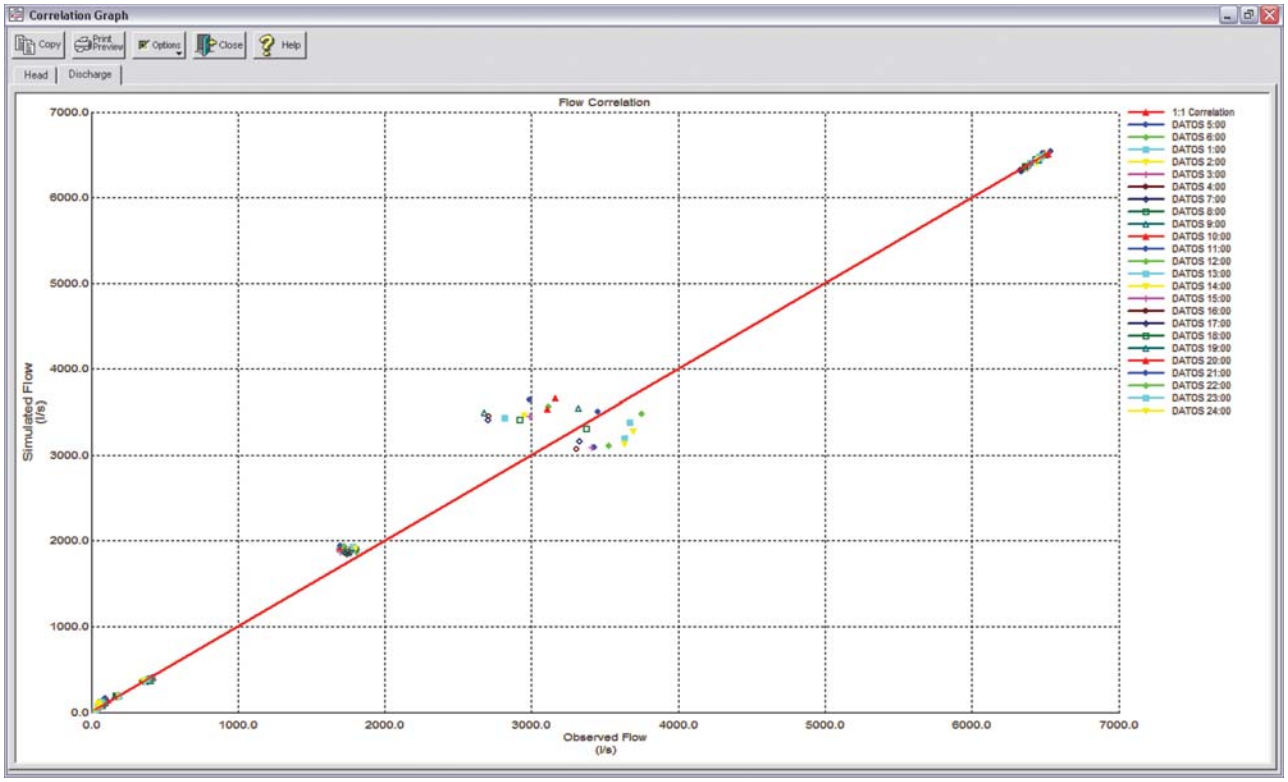
The Darwin calibrator significantly increased productivity on the Guayaquil project. It took approximately 2 hours to set up, execute, and analyze each calibration run, with a total of 40 person-hours for the calibration process. It is estimated that performing a similar level of calibration using manual adjustment methods would have taken at least four times as long. Further, because the Darwin calibrator automatically evolves and evaluates hundreds of thousands of possible trial calibration solutions (a feat not possible with conventional trial-and-error modeling practice), it efficiently enhances the quality of the modeling work. Finally, the tools available in the Darwin calibrator, such as the correlation plot and formatted output tables, help to identify potential errors in the data or abnormalities in the model.

BENEFITS OF USING THE DARWIN CALIBRATOR

Guayaquil now has a well-calibrated model of its water system. Use of the Darwin calibrator has improved the confidence in modeling activities and has helped Interagua in its evaluation of a wide range of scenarios for improving current and future system conditions and identifying and estimating water losses in the system. Specific accomplishments of the modeling exercise are described as follows.

- Darwin calibration analysis showed that the pressures in the northern part of the system are generally higher than 30 m (98 ft), while the pressures fall below 5 m (16 ft) in the south. Significant water loss was identified in the southern portion of the system.
- Darwin calibration simultaneously optimized multiple parameters, including pipe roughness and junction demand, resulting in a well-calibrated WaterGEMS model. The project team was then able to link this model to the commercial database in order to identify the cause of water loss. In this activity, the model-predicted flows were compared with the actual billing records for the study area, which was divided into 25 sectors. This analysis identified 9 of 25 sectors where the model showed actual consumption exceeding the billing consumption by 80% or more. Only three of 25 sectors had modeled consumption that exceeded billing consumption by less than 50%. This analysis confirmed the results of the pilot study, which stated that the sig-

FIGURE 4 Correlation between observed and simulated flows at peak hours



nificant head losses in the system were likely the result of either unmetered water use or estimated billing.

- The model was used to simulate water loss in low-pressure zones of the system and to plan system improvements. This exercise helped Interagua to identify areas where the network needs to be replaced or rehabilitated, simulate the effects of future expansion projects on the network, and allocate water demands for future development and growth in the study area.
- The model was used to develop a system operation and management action plan. A more comprehensive water balance was developed for the system by identifying several unknown water loss components, analyzing the impact of potential operation scenarios, and delineating the action plans for areas of high priority.

CONCLUSIONS

The use of Darwin optimization for system calibration facilitated the model calibration process for Envirosoft. A great deal of uncertainty was associated with demand allocation and pipe roughness estimation in the Guayaquil system, which made it difficult to develop action plans for system improvements. Applying the Darwin calibrator to the project enabled the engineers to not only identify the areas having excessive UFW, but also to quantify it. This enabled better decisions to be made for system remediation.

The efficiency of the optimization tool saved Envirosoft many person-hours of trial-and-error analysis and freed the modeler to "think outside the box." This application of the Darwin calibrator demonstrates that the true benefit of optimization is not just automatically locating a single optimal solution but also a range of top solutions in an expeditious manner. It enables a higher level of insightful analysis and better strategic planning than using only a traditional hydraulic simulation model. Optimization modeling equips engineers with intelligent modeling technology, leverages the engineer's intellectual power to achieve better solutions in a cost-effective way, and provides the water industry with a new means of increasing productivity and enhancing decision-making quality.

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