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Software prototype for optimization of monitoring and data logging in water distribution systems

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Abstract

Collecting field data is a vital task for efficiently managing and operating a water distribution system. A field data collection program can be long-term permanent monitoring and/or short-term data logging for capturing hydraulic (pressures and flows) and water quality characteristics. The challenge for water utilities is to determine how many and where to place the data loggers, which hydrant and how many hydrants to flush for flow test, where and how many water quality sensors needs to be placed in a system. This paper reports the development of a unified method and an integrated software prototype for optimizing pressure logger placement, hydrant selection for flow test and conventional flushing, and water quality sensor placement, and also elaborates on the application of the tool for each type of data collection optimizations. It is illustrated that the tool is easy to use and the methods are effective for practitioners to come up with a technically sound field data collection program that can be long-term permanent monitoring or short-term data logging, hydrant flow testing and conventional flushing.

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Keywords: Monitoring, field data collection, flushing, model calibration.

1. Introduction

In order to improve the efficiency of water distribution system operation and management, water companies and utilities are increasingly embarking on long-term monitoring program or conducting short-term data logging to capture the hydraulic and water quality characteristics throughout a water network. The data collected can be used

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for many purposes. For instance, pressure and flow data can be used for detecting anomaly events, predicting water consumption, calibrating hydraulic model, identifying new and long-lasting leakage hotspots, water quality data can be used for calibrating water quality models, flow testing program can improve the quality of field data collection and also cleaning up (flushing) the pipelines. Therefore, monitoring and field data logging are vital tasks for water companies and utilities.

Previous research focused on sampling design for hydraulic model calibration [1-2], and optimizing water quality sensor placement for detecting contamination events [3-4]. More recently, Farley, Mounce and Boxall [5] developed an approach for selecting the most sensitive location for placing pressure loggers for detecting new pipe bursts. However, due to the limited budget and the large scale of the water distribution systems, the challenge is to determine how many and where to place the pressure loggers, which hydrant and how many hydrants to flush for flow test, where and how many water quality sensors must be placed in a system. This paper, based on the previous works by the authors [6-9], presents the development of an integrated software tool for optimizing pressure logger placement, hydrant selection for flow test, and water quality sensor placement. The methods and tool have been applied to a number of real cases with the results to demonstrate that the developed method and tool are useful for practitioners to come up with a good field data collection program for hydraulic and/or water quality model calibration.

2. Methods in a nutshell

Monitoring or data logging is common practice for water companies. Supervisory control and data acquisition (SCADA) system has been used for recording flows, pressures and the other desired attributes at the critical facilities, such as system entry points, pump stations and system boundary connection points, together with water levels at storage tanks and pressures at the key control devices e.g. PRVs. Such a SCADA logging system is good but not adequate for achieving the best operation efficiency. Additional field data is required for maximizing the cost efficiency and improve the water service.

A water network monitoring or data logging program can be conducted by permanently installation or placement of data loggers, so-called long-term monitoring program, or by temporarily (one week or so) placing the data loggers in a system.

2.1. Pressure logger placement

Pressure logger placement is defined to search for the locations for placing the given number, noted as N_p, of loggers, so that the pressure change, due to any abnormal event, e.g. pipe burst or new leak, can be detected or covered by at least one pressure logger. Thus the effectiveness of the pressure loggers can be evaluated by defining a coverage rate given as:

$$CR = \frac{NS_{detected}}{NS} \tag{1}$$

Where $NS_{detected}$ is the number of detected events and NS is the total number of events, each of the events can be randomly generated by adding an extra demand or emitter to a node, and analyzed by calling the hydraulic network solver to evaluate the pressure changes at nodes. Thus an evaluation database can be created for the given network [6].

2.2. Hydrant selection

Hydrant selection is formulated to search for a list of flow testing or flushing events, each of them is represented by a hydrant and the corresponding flushing flow rate, such that the length of the pipes, which are effectively impacted or cleaned up by at least one hydrant flowing, is maximized. The overall effectiveness of *N* hydrant flushing events is given as flushing rate, defined as:

$$FR = \frac{\sum L_{i_{flushed}}}{L_{total}} \quad (2)$$

Where L_{total} is the total length of all pipes in a system and $L_{i_{flushed}}$ is the length of pipe *i* that is considered to be effectively impacted or cleaned up by at least one flowing hydrant. For one flow test or flushing event, e.g. a hydrant with the given flow rate, a hydraulic model is conducted to evaluate each pipe by user-selected one of the three criteria, including (1) the minimum required head loss increase; (2) the minimum required flow velocity increase and (3) the minimum required flow velocity. Using Mont Carlo method, a large number of hydrant flowing events can be generated, each event is simulated by the hydraulic model, the simulation results are used for evaluating if a pipe is effectively flushed by a hydrant event, thus an evaluation database can then be generated for optimizing the hydrant selection [7-8].

2.3. Water quality sensor placement

Water quality (WQ) sensor placement are placed to capture the data for WQ model calibration, which is primarily concerned on the pipe wall reaction coefficient. Thus it is of great importance that the water quality variation due to adjustment or calibration of pipe wall coefficient must be detected or covered by at least one data logger. Otherwise pipe wall coefficient calibration is irrelevant to the water quality data recorded by the sensors. Consequently, the water quality sensor placement is formulated to maximize the coverage rate, noted as *CR* given as:

$$CR = \frac{\sum L_{i_{detected}}}{L_{total}} \quad (3)$$

Where L_{total} is the total pipe length in a system, and $L_{i_{detected}}$ is the length of pipe *i*, in which pipe wall coefficient adjusted and the water quality change can be detected by at least one sensor. Similarly, using Mont Carlo method, a large number of scenarios, each contains wall coefficient change of the randomly selected pipes, are created. Each scenario is simulated by calling the water quality solver, and the nodal WQ results are compared to those obtained with base scenario without pipe wall coefficient adjustment. Thus an evaluation database can be generated for optimizing water quality sensor placement.

3. Implementation

The problem is solved in two phases, as shown in Fig. 1, including (1) generation of the evaluation database and (2) optimization of the data logger placement based on the evaluation criteria as given in Eq. (1) – (3) for the corresponding application . The integrated solution method is implemented by using the Darwin Optimization Framework [10] a generic parallel optimization tool.

For a given number of loggers to be placed or hydrant events to be selected for flow testing or flushing, Darwin Optimization Framework is applied to search for the combination of the data logger locations or the hydrant events so that the performance is maximized. Fig. 1 shows the conceptual integration of Darwin with the data logging or flow testing/flushing performance. For any new solution generated by Darwin, it is passed to the evaluation module to compute the performance indicator using the database. The calculated performance indicator is assigned as the fitness value that is passed back to Darwin for the corresponding solution, which is optimized by searching for the combination of logger placements or hydrant events so that the performance is maximized.

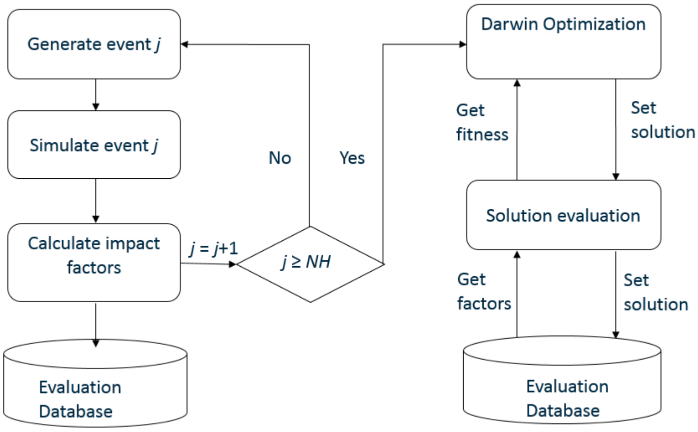

Fig.1. Unified implementation framework for Darwin Sampler

4. Application work flows

As elaborated above, Darwin Sampler is developed to help engineers to optimize pressure logger placement, hydrant selection for flow test and/or conventional flushing, and also water quality sensor placement. The application work flow for each of the tasks is outlined below.

3.1 Pressure logger placement

A pressure logger placement can be created from scratch or opened with a previously saved evaluation database file. To start a new project, users need to create a new evaluation database with the hydraulic model that is constructed for the system. By default, all of the junctions are considered as candidate locations for placing pressure loggers. But in practice, pressure loggers are usually placed at the hydrants. A list of hydrant junctions that are accessible and good for placing pressure loggers can be specified as the candidates for pressure logger placement. To do so, users can simply click on “Use Selected Junctions” to modify the candidate junction list, as shown in Fig. 2 (a).

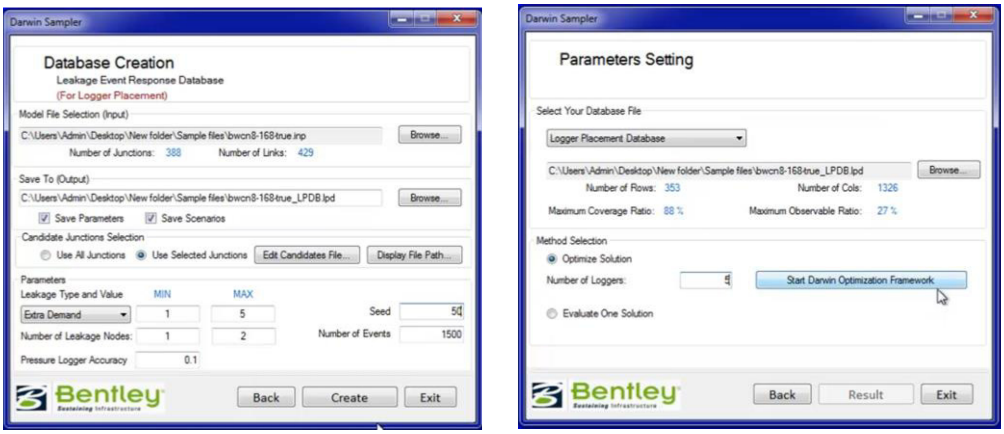

Fig. 2. Pressure logger placement (a) Database creation; (b) optimization parameters

As a pressure logger is to record the pressure in the system, and more importantly to capture the pressure change caused by demand variations caused by abnormal events such as pipe break or leakage. Darwin Sampler allows users to simulate the pressure change in the system using two different approaches, using Extra Demand or Emitter coefficient. Extra Demand simply adds the demand to the randomly selected junction, it is pressure independent analysis while emitter coefficient simulates the leakage as a pressure dependent demand. In reality, leakage is better to be simulated as pressured dependent demand using emitter coefficient. Darwin Sampler generates many scenarios to simulate different possibilities of leakage. All the parameters required to generate these scenarios must be specified. For instance, you can enter the minimum and maximum expected leakage demand or emitter coefficient, also it is possible to have several simultaneous leakages. The minimum and maximum numbers of leaking nodes can be specified as shown in Fig. 1. The number of scenario is specified along with the accuracy of pressure logger equipment. It is suggested that the number of scenarios 2-3 times of the junction number. This is because not all of the events are detectable, and in general the more events are generated, the better the database is to represent the system. Mont Carlo method is employed to generate the scenarios with the input random seed. Each of the scenarios is simulated by calling the hydraulic network solver and evaluated for producing the impact database. Once completed, Darwin Optimization Framework can be launched to optimize the given number of pressure loggers as shown Fig. 3(a). The optimization solution will be summarized with the top solutions, as shown in Fig. 3(b), along with the total number of events, covered and uncovered events and the percentage of uncovered events for each solution, and user can also review the details of each solutions, for instance the list of the nodes that are the optimized locations to put your loggers there and covered events.

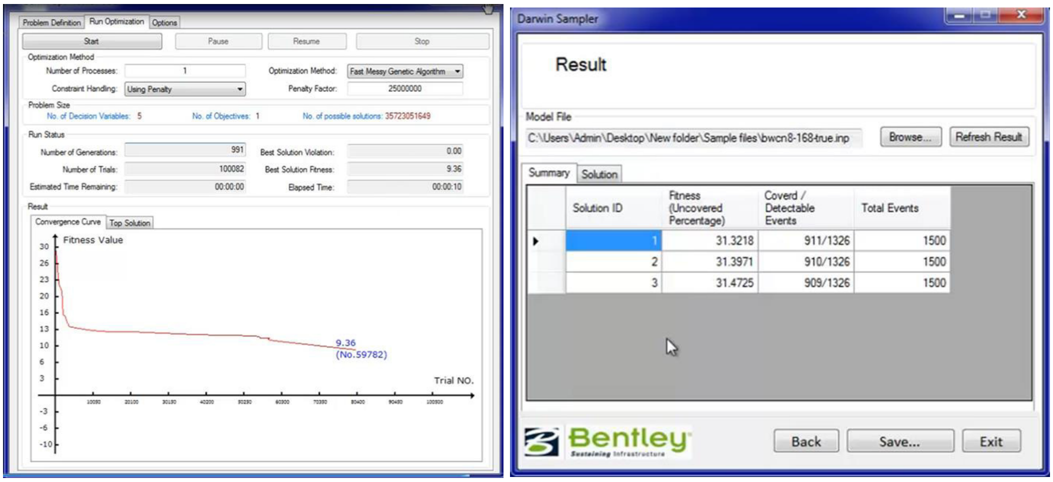

Fig. 3. Pressure logger placement (a) Darwin Optimization Framework; (b) solution presentation

3.2. Hydrants selection

Hydrant selection optimization works in a similar way to the pressure logger placement. Users start by creating a new evaluation database or open a previously generated database. To create a new evaluation database, as shown in Fig. 4(a), users need to specify the list of hydrant junctions. By default all the junctions can be treated as hydrants, but a list of junctions where hydrants are actually located or directly connected, modellers can chose the option "Use Selected Junctions", and then edit the junction list to just keep those junctions that are considered as hydrants.

Hydrant flow test or flushing could be simulated as an extra demand on the junction or as an emitter flow by specifying the emitter coefficient. For the selected flow type, enter the range and specify the interval for hydrant flow. A hydrant flushing is evaluated by the threshold value of the evaluation criteria, users can chose one of three criteria, including pipe head loss change, flow velocity change and minimum flow velocity. For instance "Flow velocity change" criteria is applied to evaluates if the flow velocity change in each pipe, due to the increased hydrant flow, is greater than the specified threshold, e.g. with 0.5 m used for the head loss criteria, if the head loss difference for a pipe before and after opening the hydrant is greater than 0.5 m, the pipe is considered to be flushed effectively by the hydrant flow test. To quantify the impact of all the possible flow tests by all the selected hydrants, the scenarios are generated to represent each selected hydrant with different flows, and simulated to quantify the impact of the flushing events.

To optimize the hydrant selection, users just specify the number of flowing hydrants for flow tests, as shown in Fig. 4 (b), and then simply start the "Start Darwin Optimization Framework" to search for the combination of hydrants with the corresponding flows to maximize the effectiveness of the flushing or flow test. The top solutions will be saved at the end of the optimization run and the details of each solution is also presented in a table.

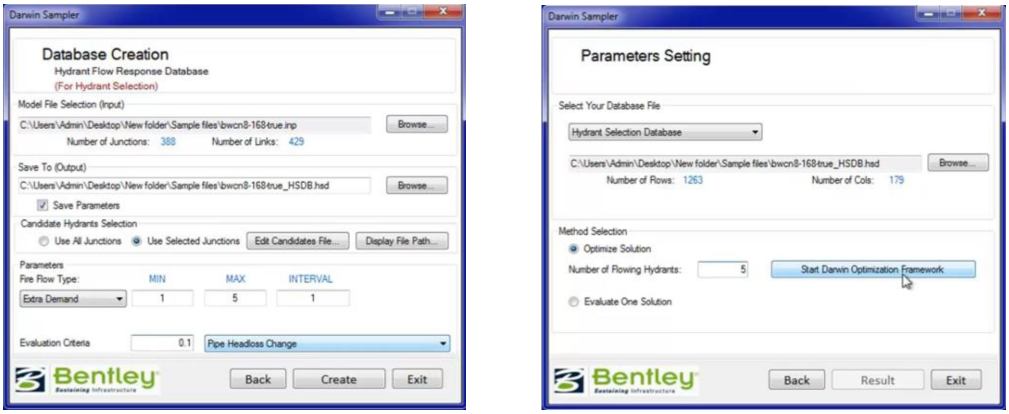

Fig. 4. Hydrant selection optimization (a) database creation; (b) optimization parameters

3.2. Water quality sensor placement

Water quality logger placement is a little bit different from the pressure logger placement and hydrant selection. Although the steps are similar but users have more control on generating water quality scenarios that are usually simulated for an extended period of time. The larger a network is, the longer period is required to run. As a rule of thumb, the simulation time should be more than the time that is required for the chlorine to reach the furthest point from the source. For instance if it takes 48 hours for chlorine to reach the furthest point in the system therefore simulation time should be no less than 48 hours.

Generally, a water distribution system consists of several pipe material types, for instance PVC, Cast Iron, and Concrete pipes in a system. Each pipe material has its own characteristics and wall reaction coefficient which can impact the water quality analysis. As shown in Fig. 5 (a), Darwin Sampler provides the user with the ability to categorize the pipes in a system. This will help the user to produce events that are closer to the reality. You may categorize or group the pipes based on their materials or based on their age. Multiple groups can be specified with the range for wall reaction coefficient. If no wall reaction coefficient is specified for the pipes in a model, Darwin Sampler can generate a wall reaction coefficient value for them by selecting the absolute value. If a good estimate of wall reaction coefficient is made for the initial value for the pipes. The scenarios can be created with the wall coefficients relative to the initial value by using the option of relative value.

Monte Carlo simulation is used to generate various scenarios. By selecting the various priorities for different groups, Darwin Sampler will choose the pipes in the same group with the same priority. However a pipe group has a high priority, the pipes in this group have more chance to be selected in the Monte Carlo simulation than pipes with lower priority. Users can also manually assign a wall reaction coefficient group for each pipe. This is however very tedious if you do it for all pipes so you have the option to select many pipes with group editing. All the scenarios are simulated with the specified period and the evaluation database will be generated accordingly.

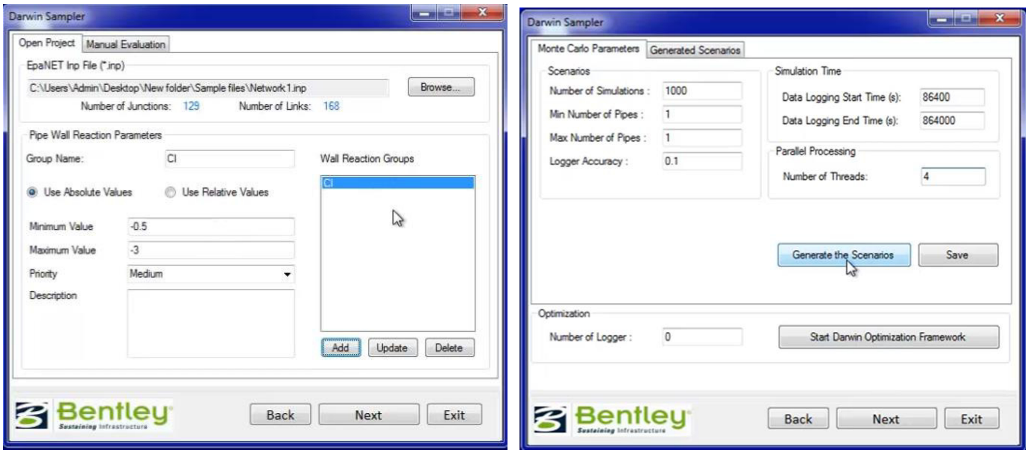

Fig. 5. Water quality sensor placement optimization (a) pipe grouping; (b) water quality scenario parameters

Similar to pressure logger placement and hydrant selection, Fig. 5(b) shows that water quality sensor placement is also optimized by starting Darwin Optimization Framework for the given number of water quality sensors. Apart from reviewing the top solutions at the end of optimization run, some additional post processing has been developed by creating a model map showing where the sensor locations are and the pipes are effectively covered by the sensors.

5. Conclusions

A fully integrated software prototype tool has been developed for optimization of hydraulic and water quality data logging programs, which include pressure logger placement, hydrant flow testing, conventional flushing, and water quality sensor placement for model calibration. Each of the applications is formulated to maximize the data logging (or flow testing) coverage, which is defined accordingly for the application. The tool is relative easy to use and tested with a number of real cases, and proves to be effective at improving data logging efficacy in practice.

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